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HeadStrong: Concussion Reduction Using Biomimicry

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HeadStrong
Concussion Reduction Using Biomimicry

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The objective of this project is to address the concern of traumatic brain injuries, which include concussions, by designing a product to better protect the head from damage upon impact. Concussions impact the quality of life for those who suffer one (or many), both in the short-term and long-term phases of their life. Current protective equipment on the market fall short of addressing the urgent need for higher quality and reliable headwear to reduce brain injury. Recently, high tech solutions for football helmets are under development, due to the public exposure of the risks and long-term disabilities that can evolve from concussions in contact activities. It is encouraging to see efforts being made to reduce concussions, and my hope is that these solutions be put into practice as soon as possible to minimize this problem.

My project aims to address the issue of concussions through a unique avenue. Although I respect the use of technology to monitor, record, and analyze data, I felt that a solution exists that could use an organic approach to reducing brain injuries. The goal was to design, develop, and manufacture a product that could offer an improvement to the existing headwear for impact sports, as well as all other applications which experience head trauma during activities. My approach, as described throughout the rest of this paper, relies on biomimetic influences, physical analysis, material research, and manufacturing methods to achieve a viable solution desperately needed to protect the mental well-being of our society, both near term and in the future.

Ultimately, the deliverable for this project will be the documentation of my research and findings, as well as a complete prototype showcasing the materials and design that evolved from the development process. The prototype is a physical, tangible object representing the crucial aspects of head protection uncovered through my studies of medicine, nature, athletics, and physics.
Concussions, and all traumatic brain injuries, are not limited to impact sports. Although football, especially at the professional level, has been in the social spotlight in recent years, this issue has wide spread impact in many other ways. Concussions can happen anytime, anywhere, and to anyone. Certainly, playing an impact sport greatly increases the risk of obtaining a concussion due to the nature of the game, but there is a risk nonetheless for everyone living their daily lives. Just like there is a risk of accidentally breaking an arm, or stubbing a toe, there is a risk of getting a concussion without expectation simply by doing normal activities.

That being said, I am designing a product. So, for the time being I will narrow the field from "everyone" to those that are directly involved with activities and applications with increased risk of head injury. Included are impact sports such as football, which involve repetitive, aggressive physical interactions. Because of the repeated impact to the body and head, it is no surprise that players of these sports experience a high rate of concussions. It is not my goal to change how these sports are played, but rather let them play and create the protective means to reduce the harmful risk of concussions. Concussions cannot be prevented, however they can be reduced by a large margin.

Outside of impact sports, protective headgear can be used in applications where head injury is a concern. Industrial environments, such as construction sites, foundries, machine shops, etc. could all benefit from having a reliable piece of protective headgear. Recreational activities, such as skateboarding, skiing, snowboarding, ice skating, biking, etc. could use this product to improve safety while enjoying the hobby.

Other applications exist, the list goes on. The point I am trying to drive home is that through the development of this project, a design solution is evolving that could be applied to numerous applications with very little variation in the product. As a result, the beneficiaries of this product expands greatly from solely football players, to the large masses of those in need of head protection.
Concussions

To design a product to address concussions, the first step was to research the topic to get a better understanding of what they are, how they occur, what are the short-term and long-term side effects, how they are treated, and how they can be reduced or avoided.

A concussion is a form of a traumatic brain injury (TBI). The Centers for Disease Control and Prevention (CDC) describes a TBI as a reaction “caused by a bump, blow, or jolt to the head or a penetrating head injury that disrupts the normal function of the brain.” [1]

The science involved with concussions is related to impact forces acting upon the skull, and the physiological reaction of the brain within the skull as a result of these forces. An abrupt acceleration and/or deceleration of the body creates a moment impact force on the head [2]. An external object striking the body can cause the acceleration and deceleration, and it can also be caused through body motions, such as running fast and stopping suddenly.

The forces that impact the head can be linear or rotational, and in most cases consists of a combination of both. Linear and angular accelerations and decelerations on the brain create the “primary” injury. The primary injury is the initial force(s) of impact acting on the head and brain.

The “secondary” injury is created by a re-coil effect of the brain bouncing off of the interior wall of the skull. The human brain essentially floats within the skull, surrounded by a layer of cerebral fluid. Because of the suspension relationship between the skull and the brain, there is little constraint from keeping the brain from “sloshing” within that space. When an impact force (primary injury) acts on the head it pushes the brain against the wall of the skull. And the skull, in turn, pushes back. “Every action has an equal and opposite reaction.” The accelerations and collisions involved in the secondary injury phase are equally damaging to the brain system [2]. Figure 1 represents a basic diagram of these injuries [3].

![Figure 1. Impact Forces causing Primary and Secondary Brain Injury][3]
The American Association of Neurological Surgeons provides information on the health complications that are caused in the aftermath of a concussion. Mild cases can cause temporary effects such as changes of mental states or consciousness. More severe cases have been known to result in extended durations of unconsciousness, coma, and in the worst case, death [4].

Severe brain injuries create long-term effects that impact thinking, memory, balance, coordination, speech, hearing, vision, learning, and emotional stability. Daily activities such as exercise, driving, and working at home or at a job, are all impacted by the disability created by this injury. It also puts a strain on family and friend relationships, as in many cases the disabled person requires attention and assistance [5].

Understanding the biomechanics of a concussion was an imperative phase of this project. As an industrial designer, it is critical to identify and understand the issue to be addressed. Having the knowledge of how a concussion occurs, as well as the health risks created in its wake, provides the foundation needed to proceed with an empathetic design solution.

As shown throughout this section, concussions are a general health concern, and specifically a great concern for impact sports. The physiology of the skull and brain cannot be changed; a protective helmet will not address the fact that the brain is in a suspended state within the skull. However, innovations in a protective head product can reduce the impact forces that reach the skull and brain. In essence, this is the goal of this project. Concussions will never be preventable regardless of the advancements of materials, designs, and technologies.

A unique design approach can offer a solution to increase safety, and create confidence that players of an impact sport do not have such a high risk of brain injury while playing an activity they enjoy. To move forward with the design process, the next phase was to investigate the research, development, and innovation efforts being made to reduce the risk of concussions in activities prone to head impact.
Market Research

Inspiration is sparked in many ways. Not re-inventing the wheel is a major contributor for motivation and inspiration. What already exists? How can I make it better? How can I offer something different? What makes my product unique? All of these questions, and many others, swim around in the head of a designer. Market research offers the information necessary to form these questions. Ideation, creativity, and design thinking are the methods to which these questions can be answered through the design process.

Riddell® is a leading manufacturer of football helmets, and other football protective equipment, used at all levels of football activity. The National Football League (NFL) exclusively uses Riddell helmets [6]. Research and development efforts are addressing the concern of concussions by means of engineering, design, and technology.

Riddell® helmet technologies are systems of electronics that measures magnitude, accelerations (linear and rotational), direction, location and time of impact, tracked in real time. Medical staff, trainers, and/or coaches are alerted instantly when an impact is occurred above a certain threshold [7].

Researching a company like Riddell® was important for the development of this project because it allowed me to become aware of what was already being developed, and what is currently on the market. This awareness provided me insight into what the “experts” in the field were achieving. I could extract the benefits of these features and functions, however would not replicate them. Instead, it would provide inspiration and motivation to innovate a unique solution with the same goal of reducing brain injury risk.

The market research portion of this project led me to investigate products that were not in the football market, but were equally important for head protection in other areas, such as skiing and snowboarding.

Many forces are at play while skiing and snowboarding. The quick side to side motions, accelerations and decelerations, bumps from the terrain, and body to ground impact during a fall, all translate into forces being transferred into the body. Proper head protection will minimize the continuous impact of these forces.

Smith Optics focus primarily on snow activity related products, including goggles, sunglasses, and helmets [8]. Smith is a company actively researching, designing, and developing the next generation of helmet for their market. The construction of the helmet focuses on safety with an emphasis on material selection. High strength and durability are imperative to absorb all types of impact, specifically multiple impacts. Weight is also an important consideration for head protective equipment. Lightweight materials reduce the pressure acting on the head and neck, and also provide a more comfortable, wearable product.

Market research was valuable because there are many ways to approach concussion reduction through design and innovation. Riddell® and Smith Optics exemplify the increased awareness and importance of user safety. The forms, features, materials, manufacturing methods, and design intent, presented through their products will influence the path of my ideation, design, and development processes for this project.
The goal for conception creation was to produce prototype helmets, consisting of the outer shell, as well as the inner padding. To start the process, I acquired used helmets to use as my base product to build off of. Plaster putty was applied to the exterior of the helmet, and a carving and sanding process allowed me to explore options for shell forms. After several iterations of this process, I decided to paint the helmet. Figures 2 and 3 show the plastering/forming and painting processes, respectively.

This was, without a doubt, the most important crossroad for this thesis project. I was dissatisfied with the object sitting in front of me. My intention and motivation was not questioned in my mind, but the direction of achieving my goal was not clicking with the efforts and energy I was expending up to this point. Designing a helmet was leaving a void in my creative inspiration. Companies, such as Riddell and Smith, are producing incredibly innovative solutions to address the concerns of concussions through helmet design and development.

“Fail Fast, Learn Faster” is a slogan I learned at RIT, and it is a phrase of optimism and encouragement. If at first you don’t succeed, learn from the flaws, grow from the experience, and try a new approach. The project had to be re-framed.

The question became, “What can I add, change, create, to make my product effective and unique?”

The answer was, “A helmet may not be the answer.”

This was the critical turning point for this project. My mind was open to new approaches and solutions that weren’t limited to the idea of a helmet. With this new frame of mind, alternative, unique ideas were being explored. The remainder of this paper details the change of direction taken for a design solution, while staying true to my project objective.
Biomimicry

[From Greek: bio for life, mimesis for imitation]

Biomimicry is a method of studying how nature has evolved and adapted to suit its environment, and extracting these natural features and functions to create innovations to benefit human needs.

“Biomimicry uses an ecological standard to judge the “rightness” of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts.” [9]

As demonstrated in the last section of this paper, my effort to re-design a protective helmet was more-or-less trying to re-invent the wheel. Technology, software, engineered materials, and a large amount of R&D money is being poured into the efforts of creating a “smart” helmet. By having the same end goal, I applaud these efforts with the hopes that the result is a drastic reduction in traumatic brain injuries, in sports and all industries.

So, the question then became: How do I design a unique solution that will differentiate my product from existing products?

It was back to the drawing board. As I started my ideation process, a wise advisor recommended that I take the notion of a “helmet” out of my head, and focus on what I’m really trying to accomplish. The idea of a helmet was restricting my ability to think about the big picture.

The advice clicked. What was I trying to accomplish? I wasn’t trying to design a helmet. I was trying to protect “something” from getting injured by “something else.” When the issue was boiled down to its simplest form, it breathed new life into the ideation process.

So, now that the problem has been redefined, it was a matter of beginning research. The motivation now is to identify and analyze things (the “something”) to understand how they have protection from external influences (the “something else”).

The original purpose of my thesis was to reduce concussions and TBI through design, and that continued to be my goal. To keep true to my goal, and to explore ideation within the new scope of the project, the new question running through my head was:

What other living things and objects experience shock, impact, and repetitive forces? How do these living things and objects protect themselves from incurring damage? What exists that is representative of a human skull and brain system?

The answer is Biomimicry. The remainder of this section will outline my research within this field, and how it relates to the problem statement.

My research began with identifying “things” in nature that are subject to harsh environments, specifically impact forces. “Things” could range anywhere from an animal to a plant, fruit, nut, etc. Nature offers a diverse research market. This diversity made this process of the project interesting because the common necessity of protection has been achieved naturally in several different ways (be it shell, skin, horn, exoskeleton, etc.). Much like in design, there are many different methods and processes able to achieve a common end goal.
Certain foods have natural protection. Part of my research investigated things that were commonly consumed that appear to have a layering or resistance to damage. Perhaps it was the pile of orange peels on my desk that motivated me to look at fruits, such as oranges, melons, and others with an outside skin.

Most share a thin membrane layer that protects the interior, fragile fruit from bruising and damage. Figure 4 below is a Pomelo fruit, similar to a grapefruit, which is mainly found in Southeast Asia [10].

![Figure 4. Pomelo Fruit](image)

As can be seen in Figure 4, a “mesh-like” network of walls and membranes compose the protective layer. This particular fruit can fall from trees at heights greater than 30 feet, and show no signs of damage. The structure of the pomelo fruit is currently being developed in an aluminum composite material for safety applications. [11]

Moving on from the world of fruits, I decided to research “things with shells.” The timing happened to work out that the Biomimicry book I was reading, “Biomimicry: Innovation Inspired by Nature,” had a section regarding hard, organic materials in nature. Within this section, the author mentions oysters. An oyster, specifically an Abalone, has a “brick and mortar” style layering that composes its external shell. The “mortar” is a flexible membrane, which when under stress, allow the “bricks” to translate or move as appropriate to dissipate the forces. “As a result, Abalone is twice as tough as any ceramic we know of – instead of breaking like a man-made ceramic, the shell deforms under stress and behaves like a metal [12].” Figure 5 shows a microscopic cross section of the shell layering [13].
The membrane in the pomelo fruit differs from that of the abalone. The stacking of calcium layers in the abalone shell provides a structure that reacts in a slightly more linear fashion than the mesh structure of the pomelo. However, both have proven themselves in nature to absorb impact for protection.

The animal kingdom was my next research target. Much like the other areas, there was a diverse cross section of subjects to research. Nature has equipped animals with necessary physical features based on their habitat and need for survival. Physical features can be used for hunting or gathering food, building housing, defense mechanisms, mating rituals, or camouflage, just to name some examples.

Although there were many examples, I narrowed my focus down to a couple of animals that I found to be most applicable to my study, as it relates to the ability of an animal to protect itself from impact forces given its natural features.

The Ram.

Figure 5. Abalone Shell cross-section [13]

Figure 6. Ram Butting Contest [14]
Butting contests are competitions during the mating season, with the award being the ewe. The ram’s horn consists of a structural bone that grows internally of the outer horn, which is composed of a keratin/protein material. The flexibility of the horn system allow the rams to butt against each other at speeds of 20 mph or greater for several hours. The horn acts as a shock absorber to the impact, with a spring-like exterior and rigid interior. [15]

The Woodpecker.

Figure 7. Woodpeckers hard at work [16]

The woodpecker is a prime candidate for research in the subject of protection from impact. Widely known for repeatedly banging its head against trees and hardwood, the woodpecker is capable of drumming its head at a rate of 20 times per second at acceleration/deceleration rates exceeding 1200 times gravity [17].

Studies and autopsies of woodpeckers have shown no trace of brain damage despite the repeated impact in endures throughout their lifetimes. Several anatomical features with its skull, beak, and neck structure have been attributed to this resistance to brain damage. Figure 8 [18] shows a microscopic photo of a cranial bone put under mechanical testing [19].

Figure 8. CT scanned images of cranial bone [18]
As Figure 8 shows, the bone has a porous structure. Its “mesh-like” support system is not unlike the membrane in the skin of the pomelo fruit mentioned earlier. Although used in different contexts, a fruit and an animal have similar defenses against impact.

Researching biomimetic cases led to my discovery that nature has prepared all living things with means to protection. Physical features on these living things have evolved, and have been close to perfected throughout time. All of these examples provide a glimpse into nature’s design solutions for a need.

In this paper, four examples of natural impact protection mechanisms were detailed:

- **Pomelo Fruit**: a chaotic, yet organized, mesh structure in its outer skin absorbs impact as it hits the ground.

- **Abalone Oyster**: a staggered column structure held together with flexible membranes offers rigidity and strength, and absorbs stresses through its linkage system.

- **Ram**: equipped with a horn system that acts as a spring-loaded shock absorber. Thick skulls and neck bones, coupled with the forgiveness of the horns upon impact allow the ram to endure repeated blows to the head without suffering brain injury.

- **Woodpecker**: the amount of impact to the head/neck system, both in frequency and magnitude, that it experiences daily is an incredible figure. A cross section of the skull shows a porous structure, which is one piece to the puzzle as to why it does not experience brain damage despite the repeated drumming.

So, where do I go from here? It was time to narrow my focus.

I was excited to continue my efforts in the realm of biomimetic design, and wanted to direct my attention closer to a specific case study. The woodpecker would be the main influence on this project moving forward. The physics acting on the woodpecker are at amazing levels, and lends itself to an opportunity to explore design solutions for humans based on its physiology.

My ultimate goal is to design a solution to reduce concussions, a subject of repeated impact. I see no better natural example to influence my ideation than the woodpecker. Moving forward in this paper, I intend to detail the anatomy of the woodpeckers’ skull/brain system, and translate those features into a tangible product to help human applications.
Design

As concluded from the last section, my design focus moving forward will be based on the anatomy of the woodpecker. To move forward with design, it was important for me to understand the features and dynamics involved within the entire woodpecker skull structure.

The porous skull was shown in the last section, which plays a part in the overall system, however other factors work in unison to provide the protection needed to preserve brain health. Figure 9 below shows a general scan of a woodpecker head and neck anatomy [20].

![Figure 9. Anatomy of Woodpeck Head & Neck region](image)

Figure 9. shows the brain as it sits within the skull(s). Unlike human brains, the woodpecker brain is “packed” snuggly within the skull, leaving very little room to slosh around as its head accelerates and decelerates. A thin layer of fluid coats the brain, however does not allow significant motion of the brain relative to the motion of the rest of the head [21].

When a woodpecker strikes an object (mainly wood), the high impact force transfers through the beak to the skull. The stress reaches the skull in the frontal region, where it hits a physiological barrier designed to absorb such forces. The woodpeckers’ skull is comprised of a multi-layered structure, with a spongy outer shell encompassing a more rigid, mesh-like bone structure [22]. Figure 10 exhibits a diagram of the anatomy [23].
As impact forces travel through the beak they reach the frontal area of the skull indicated by the red box in the lower right section of Figure 10. Letter “A” is indicating the interior skull, which is porous and dispenses forces in a series of scattered bone structures to dissipate the impact. Letter “B” indicates a spongy, outer layer that acts like a dampener in a shock absorber. Together these two layers act as a primary and secondary line of defense to protect the brain from any residual forces that have traveled through the beak [22].

My goal as a designer is to translate this physiology into a product. To do so, I must replicate the natural substance and biomechanics of the woodpecker anatomy into available, existing materials that are manufacturable. The specific layering and properties of the materials selected will impact the functionality of the product. Figure 11 served as my template during this project, as a basic reminder of how the layers are situated [24].
The Spongy Bone and Skull Bone layering required extensive material research to find appropriate materials to mimic the physical properties demanded to absorb impact. A design consideration that must be kept in mind is that the product ultimately will be used in the context of head protection, and therefore factors such as weight, durability, manufacturability, density, among other things, will enter the picture. The material selection portion of this document will break down such factors to justify the best feasible choice for biomimetic materials.

**Spongy Bone Layer**

The spongy bone is located at the frontal portion of the skull, and takes the brunt of the impact that passes through the beak. The spongy bone is compact, yet has some forgiveness to absorb stresses [22]. The goal was to replicate this portion of the woodpecker skull by researching and selecting a material that had the ability to absorb force, deform, and return to its original form to maintain stability.

In the context of a product for head protection, factors to consider are strength-weight ratio, density, and elastic modulus (Young's modulus). Weight and density are important because a material may have a desirable strength, yet may have a high weight/density. For example, a steel helmet would be strong, but you may get some complaints from the person wearing it about a headache or sore neck. On the other end of the spectrum, a lightweight
material may be attractive for the comfort and mobility factor, yet may be too weak to sustain impact forces. My goal is to find a happy medium that optimizes weight and strength.

The elastic modulus typically describes a material’s ability to stretch [25]. This physical property relates to the spongy bone’s ability to deform under stress and return to its original shape with no fatigue or yield. This material will be crucial for head protection under impact because it will maintain integrity repeatedly. A material that takes one blow and plastically deforms will render useless for applications that experience multiple impacts.

Figure 12 [26] is a chart mapping out a variety of materials with relative Strength to Density ratios.

Figure 12 shows several available materials that could be selected to represent the spongy bone. As mentioned before, there is a sacrifice (or compromise) between strength and density. High strength materials also bear high density, and vice versa, low density materials have low strength.

For this reason, I focused towards the central portion of the chart where reasonable strength could be achieved from a relatively low density. Higher strength foams, and polymers/elastomers, offered the traits that could provide the best representation of a spongy bone while also maintaining the performance desired for head protective equipment.
Figure 13 [27] compares Modulus versus Strength of a wide selection of materials.

Figure 13 maps out materials based on their modulus to strength ratio. Like Figure 12, the high strength materials, such as metals and composites, have high strength but would not be a suitable selection for head protection. Lower end foams and elastomers have low moduli, and in many cases, have medium to low strength.

Again, the central portion of the chart drew my focus. The higher end of the foams spectrum, and polymers, provide a balance of the mechanical characteristics that would suit a protective product, while honoring the mimicry of a spongy bone.

Based on the analysis of Figures 12 and 13, my research would hone in on a flexible, medium to low density, medium to high strength material. A range of materials could fit into this category. However, a state of the art material was on the market that offered all of the characteristics that would provide the desired solution.
PORON® is a commercially available material, which is classified as a microcellular urethane foam. It combines the desirable characteristics of foams and elastomers. This material has diverse applications, ranging from sealing, vibration control, footwear cushioning, medical cushioning, and most importantly impact protection [28].

PORON®, which is owned by Rogers Corporation, has a product line specifically dedicated to high impact activities. The engineered material is lightweight, durable, flexible, breathable, and rated to experience repeated impacts. In a general sense, it is a shock absorber made from high performance memory foam [30].

These characteristics meet, and exceed, the expectations I was anticipating while researching materials. Given the proven performance and properties of PORON®, I chose to use this material for prototyping to represent the spongy bone portion of the design.

Skull Bone Layer

The skull bone is the porous, mesh-like structure of bone that resides beneath the spongy bone. It acts as the second element of shock absorbing in the skull, with the spongy bone. This portion of skull is more rigid than the spongy bone, and therefore a material with higher strength, density and modulus would most likely be needed.

Again, keeping in context that ultimately this material will be used in head protective products, the design compromise of weight, durability, and reliability must be considered. With these factors in mind, the goal was to narrow down material selections to best represent the skull bone for use in a product.

To do so, I followed the same steps that I took to analyze the spongy bone material selection. Figure 15 [26] below is the Strength versus Density chart revisited for the skull bone layer.
The mesh structure in the woodpecker skull bone is porous, with high strength, and limited flexibility. Based on the strength vs density chart, the “foams” group has relatively low strength and low density, and therefore would not be an optimal choice. On the high strength, high density end of the spectrum are mostly metal alloys. Although I would not rule out all metals, due to the weight in metals such as steel, lead, and tungsten, it may prove unfeasible to pack into head protection equipment. However, it was noted that alloys such as Aluminum could eventually provide a solution due to their high strength to weight ratio.

Composites, and high strength/density polymers and elastomers, was an area of interest. A high strength polymer or elastomer could provide the structure and rigidity needed, while also providing some flexibility without being brittle.

Continuing the research, I revisited the Modulus vs Strength map [27]. Figure 16 shows the material array for these properties.
Figure 16. Modulus - Strength [27]

The chart shows foams and elastomers with mid-to-low strength and modulus. This does not rule out the use of materials in these groups, however to best represent the physiology of the skull bone a material in the mid-to-high range would be most suitable.

Select foam and polymers could provide the rigidity and strength desired. Composites and metals, again at the upper extreme of the properties, have possibilities given careful consideration and selection.

The skull bone layer proved more difficult to select a material compared to the process for selecting the spongy bone layer. The conclusion from my material research for this layer was that further physical testing would be needed to examine the performance of certain materials in a complex, mesh configuration.

With that being said, my attention shifted towards details of the mesh structure. The complicated web of bone provided the challenge and opportunity to explore both material, and manufacturing processes. Unlike the spongy, which could be represented as a plate or sheet, the skull bone would require a more advanced method of prototyping.
Figure 17 [31] shows a microscopic view of the skull bone structure.

![Figure 17. Mesh Skull Bone Structure][1]

The structure is non-geometric; there is no noticeable pattern or symmetry. Organized Chaos, was a term always on my mind when I looked at these pictures. As a system in nature, it is efficient and reliable. As a product for manufacturing, it is an interesting challenge.

Conventional manufacturing methods, such as milling or casting, would be incapable of producing such a part. However, additive manufacturing technology is available, and offers the potential of creating the complicated structure. The exploration of additive manufacturing for prototyping will be covered in detail in the next section of this paper.

The spongy bone and skull bone layers were analyzed in detail for the head protective product in the spirit of biomimicry. These layers ultimately make up the shock absorbing system for the product.

However, these two layers alone would not complete the entire product. A helmet, or headgear product, will also have an outer shell, as well as an inner liner. Figure 18 shows a basic block diagram of the layering sequence intended for prototyping.

![Figure 18. Material Layering Diagram][2]

*Not to Scale*
Layers B and C represent the spongy and skull bones, respectively. Layer A represents the outer shell, and Layer D represents the inner liner.

The material selected for Layer A, the outer shell, was a Polycarbonate Alloy. The polycarbonate alloy was chosen because it has favorable properties in wear resistance, durability, strength, and manufacturability. Riddell, and other helmet manufacturers, currently use this material for high impact applications.

Layer D, the inner liner, will be made from Cork. Cork is very durable and has a high coefficient of friction. Because of these traits, it will survive repeated impacts and will resist wear from rubbing. Cork is extremely flexible, compressible, and elastic, which allows it to return to its original shape after stresses and pressures are relieved [32]. The inner liner will be the barrier between the human head and the material layering. The physical characteristics of cork allow it to form to the various shapes and sizes of a human head, as well as resist the wear from the head rubbing against the material, and will also survive repeated impacts.

In addition to the traits described above, cork is a very sustainable material. It is a natural substance that is harvested from trees without causing harm to the tree. Cork is also a reusable and recyclable material [33]. This opens the door for upcycling cork from old products to produce the inner liner, and will allow the cork from “used” inner liners to be recycled towards other products.
Prototyping

The objective of the prototyping process was to create tangible objects based on the work done through the biomimicry and material research phases. The project began with an ambition to design a new type of helmet to reduce concussions. The goal was, and remains, to lower the risk of concussions and traumatic brain injury by creating “something.” Through the thesis journey, the product (the “something”) shifted from a helmet to a strategic layering of materials. The multi-layered system would act as a shock absorber, with each layer having specific roles.

Biomimicry, mechanical properties, sustainability, and manufacturability were the major factors that influenced the selection of the material layers. Below is a refresher of the material layering, as shown previously in Figure 18.

Figure 18. Material Layering Diagram
*Not to Scale

Layers B and D represent the PORON® Urethane Foam and Cork layers, respectively. These materials are commercially available, and did not require manufacturing or processing efforts. These materials are shown in Figures 19 [29] and 20 [34].
Layer C, representing the mesh-like woodpecker skull bone, provided an interesting opportunity for prototyping. As mentioned in the “Design” section of this paper, conventional manufacturing methods would not be capable of achieving the complex geometry needed to produce the structure.

Advances in additive manufacturing have been growing quickly over recent years. Geometries, forms, and features, that prove very difficult (or impossible) for conventional manufacturing equipment to produce, are now possible due to the development of additive manufacturing processes.

The complicated mesh structure of Layer C lends itself to be a prime candidate for the additive manufacturing process. The bone structure in the woodpecker was porous, with variable bone wall thickness, and multi-directional webs. The goal was to create a prototype through an additive manufacturing process that could somehow mimic, as best as possible, this non-traditional geometry.

Generative Design, in terms of a CAD program, is a parametric based system that uses algorithms to produce 3-dimensional models with complex designs that could be non-computable when processed through other software [35].

Grasshopper® is a program integrated into the Rhino CAD package, which is specifically dedicated to generative algorithm based designs. Through this program, a mesh structure was generated. Factors such as overall size and thickness, amount of “open space” between webs, and thicknesses of the webs were all established and could be adjusted parametrically.

A 3D model was produced through this exercise and exported as an .STL file to prepare for the additive manufacturing process. Figure 21 shows the 3D model as a result of the generative design program.

![Figure 21. Generative Design – 3D Mesh Model](image)
The curvatures and variable thicknesses and directions of the mesh structure members are evident through the model. The open spaces and undercut geometry reiterates that conventional manufacturing tools would not be able to produce such a part.

This would be the first attempt at creating the mesh through additive manufacturing. 3D printing would be the additive manufacturing process to be used to create the physical prototype. This prototype was crucial as a proof of concept of the mesh generative design. It would satisfy the question of “can this be made?” The print completed successfully with no signs of errors or complications.

Figure 22. 3D Print of Mesh

Figure 22 shows some flaws in the design; mainly some connection members were too thin and did not print completely. These broken features were the result of the design geometry being thinner than the diameter of the filament printing them. Overall, this print was very successful as a first prototype. (Note: the circular, pod-like features at the base were not part of the design. They are raft features added as a support structure during printing.)
The next action for prototyping was to create another generative design CAD model with slightly different parameters. Through Rhino’s Grasshopper® application this was a quick effort. Since the program is based on parametric algorithms, it was simply a matter of taking the first model and changing input values.

The second model was similar to the first model, with the exception of overall thickness (the second would be shorter in height), and a slight modification to the spacing of the web elements. Again, a .STL file was created and the second prototype was ready for print.

This prototype offered a second effective representation of the woodpecker skull bone. With two prototypes under my belt, it was time to continue efforts towards a third prototype. Having proven that 3D printing the mesh geometry was possible, it was an opportune time to experiment with features to add complexity.

Eventually, the multi-material layering being developed in this project would be inserted into some form of headgear. Therefore, it would require curvature to form to the general shape of a head. The goal for the third prototype was to create another mesh structure, with the added feature of curvature. This would present a more challenging process both for the modeling and printing efforts.
Going back into Rhino Grasshopper®, another parametric 3D model was created. Unlike the first two prototypes, this prototype would not be “flat” but would require a cylindrical curvature influencing the mesh. This was achieved through the design software by creating an oversized model and “cutting away” sections, leaving a model that appeared to have an overall curved profile.

A spherical curvature would have been more representative of the form suitable for head equipment. Complications and errors in the software occurred when I attempted to create a spherical model. Further development efforts in the 3D modeling program would be needed to pursue the spherical form in the future. A cylindrical form was the next best option as a proof of concept that the modeling and printing processes were capable of handling curved geometry.

Figures 24 and 25 show the 3D model produced through this process. Figures 26 and 27 show the printed prototypes created from this 3D model.

![Figure 24. Generative Design – Curved 3D Mesh Model](image)

![Figure 25. Generative Design – Curved 3D Mesh Model](image)
This prototype added confidence to the development of the product. It provided a tangible object that resolved some of the doubts that were floating around prior to creating the printed model. The doubts were questions, such as “Can the mesh structure of a woodpecker skull be replicated into a product, can this layer be integrated into a protective head product, and can this design be manufactured?”

The results of this print were encouraging. The curvature of the mesh did not create complications during the 3D printing process, and verified the additive manufacturing method as a viable option for producing the mesh layer for product use. Given the fast advancement in additive manufacturing technology, the capability to produce variations of the mesh design using a wider selection of materials will be available for future product development.
A high strength to weight ratio is critical to provide the necessary protection to repeated impact forces, while keeping the protective layer lightweight to avoid additional weight forces on the head and neck. The curvature of the 3D print proved that non-linear shapes and forms are possible to create. Down the road, it will be imperative to design the product to fit complex, curved shapes. In this case, it would be the curvature of the human head. Spherical and cylindrical forms will be influential on how this layer is designed and manufactured.

The final layer of the multi-material “sandwich” is Layer A, the outer shell. This layer is not so much related to biomimicry, however addresses the need for an outer protective casing for the product. It is meant to provide a hard, stiff, and lightweight layering as the first line of defense for impact. In addition, it will provide a shell for the other layers to be packed and contained within.

For this layer, I selected a polycarbonate alloy material. The polycarbonate alloy has attractive properties for this application, such as high durability, good wear resistance, and a high strength to weight ratio. Polycarbonate alloys can be thermoformed and machined, which offers an ease of the manufacturing processes. An added benefit is that this material is commercially available.

Thermoforming was the manufacturing process used to mold the plastic into the form of the human head shape. Thermoforming is a common, robust method of heating plastic into a pliable state, at which point vacuum would pull the material (polycarbonate alloy sheet) around the form of the object to be reproduced (in this case, the object was a foam mannequin head).

The process was completed with no issue. This prototyping process was valuable in the respect that it strengthened my knowledge and ability to operate another method of manufacturing. Thermoforming, and the molding process in general, is a process that is imperative for plastics manufacturing, particularly in the field of headgear and protective equipment. Figure 28 shows the formed polycarbonate alloy replication of the foam head.
It should be noted that the “bubbles” that can be seen in the material were unintentional. The rapid heating and cooling process during thermoforming converted the moisture ingrained in the polycarbonate alloy material into air pockets. The voids could compromise the overall strength of the material, and would be avoided for future product development. Baking the material prior to thermoforming would greatly reduce the presence of these voids.

The spherical shape of the polycarbonate mold replicated the general shape of the top of a head. However, for the multi-material prototype the layers have a cylindrical form. To match the profile of the other layers, modifications were made to this component. After some re-work, the outer shell layer was compatible with the other layers. Figures 29 and 30 show the revised form of the outer shell.

![Figure 29. Modified Outer Shell – Polycarbonate Alloy](image)

![Figure 30. Modified Outer Shell – Polycarbonate Alloy](image)
Finished Concept

The prototyping phase for the multi-material layer system was complete, and it was time to build a finished concept. Figure 31 represents the 4 layers of the system, including the curvature.

![Material Layering Diagram](image)

*Figure 31. Material Layering Diagram
*Not to Scale

Layer “A”: Outer Shell – Thermoformed Polycarbonate
Layer “B”: Spongy Bone Replication – Urethane Foam
Layer “C”: Skull Bone Replication – Curved Mesh ABS
Layer “D”: Inner Liner – Natural Cork
“F”: Applied force (external) to the multi-material layers

The objective of the multi-material layer system is to react to impact, represented in Figure 31 as “F.” The path of the impact force is represented by the red arrows. A large external force will impact the outer shell (Layer “A”), which will counteract the force due to the polycarbonate alloy’s strength. The force is weaker, but will transfer through Layer A to Layer B. The urethane foam in Layer B acts a sponge, and will dampen the force. The remaining force will transfer to the mesh structure (Layer “C”). The complex web architecture in Layer C will disperse the force in multiple directions, thus dissipating the force and weakening its strength. The cork liner (Layer “D”) should experience a significantly lower impact at this point. The cork inner liner is the interface to the user’s head. Through this layering system, the impact transferred to the user is minimized.

The material selections and manufacturing processes were described throughout the previous sections of this document. The finishing process was essentially a matter of adhering the layers into a uniform “sandwich.” To do so, an industrial adhesive was sprayed onto the urethane foam and cork surfaces, which were pressed to fit the contour of the curved mesh. Once the adhesive was cured, the layers were a single unit. Figure 32 shows Layers B, C, and D prior to assembly. Figures 33 and 34 display Layers B, C, and D after assembly.
Figure 32. Urethane Foam, ABS Mesh, and Cork Layers

Figure 33. Urethane Foam, ABS Mesh, and Cork Layering

Figure 34. Urethane Foam, ABS Mesh, and Cork Layering
With the modifications made to Layer “A” (the outer shell), as described in the Prototyping section, Figures 35 and 36 show the entire multi-material layer assembly.

Figure 35. Multi-Material Layer System

Figure 36. Multi-Material Layer System
Identifying a need and framing the problem is the first step in the design process. This step builds the foundation for the entire life cycle of product design. The goal for this project was to address the issue of concussions and traumatic brain injuries ("the problem"), and to develop an effective solution, through a uniquely designed system, to reduce these injuries ("the need.")

The helmet design is intended to address activities where the user experiences repetitive impact forces to the head. Through the design process, it was my goal to make the helmet safer for the user, while not sacrificing beneficial factors like weight and comfort.

To continue the design, extensive research was done to know what helmets were already on the market, and what development efforts were being done to address the concern of concussions. Through the research phase, I discovered that several companies were already heavily invested in creating the next generation of helmets to reduce concussions in high impact activities. Advanced technologies and complex mechanical systems are being installed in helmets to monitor forces acting on the user, with the goal of removing the user from an activity when a concussion may have occurred.

As I began my initial prototyping phase, my focus was still revolved around designing a helmet. I explored various forms for the outer shell, and spent a lot of time trying to create a unique helmet design. The research phase of this project showed that high tech solutions were already being developed. It was at this point that I questioned if my efforts to design a helmet was a worthwhile path.

Reframing the problem is an important part of the design process. In this case, my original problem was framed as “I need to design a helmet to reduce concussions.” But as I found out, the helmet was not the solution. The need was to reduce concussions, and the solution was a product or system that promoted safety through design. The reframing process opened up my mind to ideation and design options that were not necessarily a helmet.

With the new frame of mind, I explored design alternatives that were “outside of the box.” This ultimately led me to the field of biomimicry. Research in this field gave me insight into how nature protects living things from physical harm, specifically protection from impact. Plants, fruits, and animals were studied do understand how they natural protect themselves from harmful impact.

The result was my in-depth research, design, and development of a system based on the physiology of the woodpecker. The woodpecker experiences repetitive impact forces on its skull and brain thousands of times daily, and has been shown to have no brain injury. The amazing natural protection features of the woodpecker would be my inspiration moving forward. My goal was to translate the features of the woodpecker skull system into a tangible, manufacturable product to be used to reduce the risk of brain injuries.
The remaining phases of the project included material research, material selection, and prototyping. Careful analysis was performed to select materials with properties that best reflected the functions and characteristics of the multiple layers in the woodpecker skull. The result was a multi-material layer system using commercially available materials and existing manufacturing methods.

This project has great opportunity for further development. There are many aspects to the concept prototype that can be analyzed and designed to optimize the final product. Much of the development efforts would revolve around material analysis/selection, software and CAD modeling advancement (specifically for the mesh structure), impact testing, and manufacturing methods.

Material analysis and selection would include further exploration into how specific materials react to forces. It would also include factors such as, influence on the environment (sustainability), how the multi-material layers react to each other (physically and chemically), and any concerns of material properties changing, either during the manufacturing process, or over time during use.

Software and CAD modeling advancements can be made to create a spherical form to better fit to the curvature of the human head. The head is a complex shape, and would require development efforts in how the 3D model is created in order to produce an accurate physical product. This effort is primarily applicable to the mesh layer of the system, which is created as a 3D model and then printed using additive manufacturing technology.

Impact testing would prove or disprove the integrity and effectiveness of the multi-material system. Testing would verify if the system in fact absorbs impact more effectively than existing products. Many designs could be tested to optimize material combinations, material thicknesses, and layering positions.

Manufacturing methods is another aspect of the project that could be developed. Most of the layers, at this point, can be produced using conventional methods (machining, molding, thermoforming). The mesh layer offers the greatest window of opportunity for further development. Given the complicated structure of the mesh layer, additive manufacturing is the most viable option. Advances in additive manufacturing technology are growing rapidly, and existing technology has great capabilities. Future development for the mesh layer would be to explore materials such as polymers, soft metals, and elastomers. Additive manufacturing would allow for the desired material to be produced, which would drive development of the entire multi-material layer system forward.

Overall I was very satisfied with the journey of this project. It strengthened my ability to address a problem, and provide a solution through the design process. The lessons learned, such as re-framing the problem and finding inspiration from diverse sources (biomimicry, for example), has given me an appreciation for the power of design, and will enable my personal growth as an industrial designer.
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