Development of Device to Reduce TMD Pain From Eyeglasses

A Interdisciplinary Qualifying Project (IQP) Report
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Abstract

Temporomandibular joint disorder is a condition suffered by approximately ten million Americans. In mild cases it presents as occasional soreness or a clicking jaw; however, for a minority with more serious symptoms, it can cause headaches, a locked jaw, or extreme referred pain in the head and face. For those suffering from more extreme TMD, a simple pair of eyeglasses can be agonizing to wear for prolonged periods of time. Due to the low profile of TMD in global awareness and the small minority affected there exist no current working solutions to allow TMD patients regular use of eyeglasses.

In this project, our team of undergraduates set out to analyze this situation combining differing insights and doctrinal approaches to inform the design of a solution. By analysis through the lens of business and humanitarian studies, we informed the prototyping and design of 3D printed attachments or modifications to a pair of glasses intended to reduce pain in TMD patients. The interdisciplinary nature of our approach helped to address the true needs of the market and ensured that we approached with understanding and compassion the needs of a community all too easily ignored by many.

Acknowledgements

This project would not have been possible without the work of Anastacia Simpson, an undergraduate student at WPI, who was a member of the project team from its inception. They contributed to our background research and our understanding of the demographics of TMJ, along with being a key member of the design team by contributing to design ideation while also being responsible for one of the design paths we prototyped for evaluation.

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2 Introduction

As engineers, it is easy to see the world as nothing more than a list of problems to solve; swoop in, make broad sweeping generalizations, identify what you think the problem is then lock yourself away in a room and work on solving it. This detached attitude is the institutional arrogance of the profession. When you start believing that the only role 'people' have in the process is as possessors of interesting problems; you risk failing to understand the difference between the solutions people actually want and the solutions you think they need. The strength of an interdisciplinary approach lies in its ability to highlight different perspectives. By approaching this project not just as engineers but also as economists and humanitarians we gain the crucial context for the engineering problems.

2.1 Project Objectives

The project seeks to create a product to prevent jaw pain from glasses in people with TMD. The team will use business analysis to gain an understanding of the users, use engineering design to make three prototypes and use disability studies to analyze the project within a broader social context.

2.1.1 Understand Users Needs

The first objective is to do business analysis to understand the potential users' needs. This section provides a complete analysis of the problem space and offers metrics to evaluate the engineering design.

2.1.2 Create Prototypes

The engineering portion of the project will create three design prototypes to prevent jaw pain from glasses. These designs will be created in solid works and work on most glasses. The devices should meet the requirements set out by the business analysis and decision table.

2.1.3 Disability Studies Critique

Lastly, a look at disability studies will provide a holistic contextualization of our project. A few themes that help provide context for our project will be explored, followed by a critique of the project where the project acts as a case study for disability studies.

3 Background

3.1 The Anatomy of the TMJ

The temporomandibular joint (TMJ) is the connection point between the jawbone and skull, responsible for both the hinge and sliding motions critical to chewing and speech. This joint is unique in its combination of movements referred to as ginglymoarthrodial for the combination of hinging (ginglymus) and sliding motion (arthrodial).

Like most significant joints in the human body the TMJ is synovial, this means that the joint itself relies on a cushion of a viscous non-Newtonian fluid to allow free movement between the two bones [20]. The fluid is contained by a joint capsule consisting of an outer layer of fibrous membrane and an inner layer of synovial membrane. The anatomy of a synovial joint relies on the cushioning effect of the synovial fluid to allow frictionless movement and greater mobility. It is worth noting that the joint capsule alone is often not strong enough to maintain joint alignment and limit range of motion alone and usually requires external tendons or ligaments to reinforce it.

The TMJ is bicondylar, meaning that it has two distinct points of contact, in this case, the left and right sides of the jaw both interact with the skull; unlike other bicondylar joints in the human body such as those present in the knee or vertebrae, the TMJ exhibits a large separation between contact points that increases the risk for stress arising from misalignment. This duality does create some degree of confusion in the literature as both left and right contact points can be collectively referred to as the temporomandibular joint, yet often when referencing or discussing TMJ a symptom or specific pain can present only on the left or right side of the joint.

A significant factor in the uniqueness of the TMJ is the use of fibrocartilage rather than hyaline cartilage to cover the articular surfaces. The articular surfaces are the faces of the bones that must slide against each other within the synovial joint; to ease this and prevent binding these surfaces are covered by a cartilage intended to slide smoothly against itself, lubricated by the synovial fluid. Unlike other synovial joints in the body, the TMJ does not use hyaline cartilage but instead fibrocartilage, fibrocartilage being significantly tougher and better suited to sustaining the high occlusal loads generated by the chewing motion[45]. Though the two substances fulfill the same purpose, the difference in composition, primarily the inclusion of Type 1 collagen, means that fibrocartilage is significantly tougher whilst less smooth than hyaline cartilage. The effect of this unique composition is to reduce the insights into TMJ disorders generated by the study of other joint issues.

The TMJ's unique ginglymoarthrodial movement also necessitates a unique anatomy. Most synovial joints contain a single synovial cavity, broadly allowing for one type of movement between the two bones. To allow for two distinct movement types the TMJ has two synovial cavities separated by a biconcave membrane of fibrocartilage. This membrane referred to as the articular disc is shaped vaguely like a peaked cap separating the joint into a larger upper chamber responsible for sliding motions and a smaller lower chamber that handles the hinge motion[5]. This articular disk contains blood vessels and nerve endings and is connected to the lateral pterygoid the muscle responsible for depressing and protruding the jaw. The failure or dislocation of the articular disk is often involved in disorders of the TMJ.

The ligament structure around the TMJ comprises three ligaments around both the left and right TMJs these ligaments serve individually to restrict motion around the specific contact point. Due to their role in restraining the TMJ, these ligaments can often be a source of pain for a patient. The major ligament of the joint referred to as the temporomandibular ligament consists of the thickened lateral portions of the joint capsule that is primarily responsible for preventing motion of the jaw too far backward [11]. The first minor ligament is the sphenomandibular ligament, located forward of the TMJ this ligament is slack when the jaw is closed becoming taught when the jaw is about half open, the sphenomandibular ligament primarily serves to limit the distension of the mandible, and is broadly responsible for the increase pivoting motion experienced in the second half of the jaw's range of motion [26]. The second minor ligament of the TMJ is the stylomandibular ligament, located behind the TMJ this ligament is lax when the jaw is closed and only loosens as the jaw is opened. As such it is generally considered without function [26]. All three of these ligaments are labeled in Figure 1. It is worth noting the presence of two additional ligaments the discomallear and malleomandibular which connect respectively from the articular disk and mandible to the middle ear [15]. Though the two ligaments are commonly understood to serve no function in adults it is worth considering the interconnectivity of TMJ and the middle ear in the context of the relationship between TMJ disorder and pain in and around the ear. By studying the ligaments surrounding the TMJ we gain an understanding of the areas of the face where external pressure from eyeglasses may cause pain.

The final significant system of anatomy surrounding the TMJ are the muscles of mastication responsible for the movement of the jaw. Broadly these muscles can be separated into two categories abductors to open the jaw and adductors to close it, due to the demands of mastication the adductors are generally larger and stronger[5]. The primary adductor is the masseter, the large muscle that runs from the zygomatic arch (cheekbones) and down the back of the jaw. The masseter is complimented by the medial pterygoid, a muscle that runs along the inside of the mandible and terminates above the pallet. Together the masseter and medial pterygoid form a sling around the back of the mandible, and the balance of tension between them

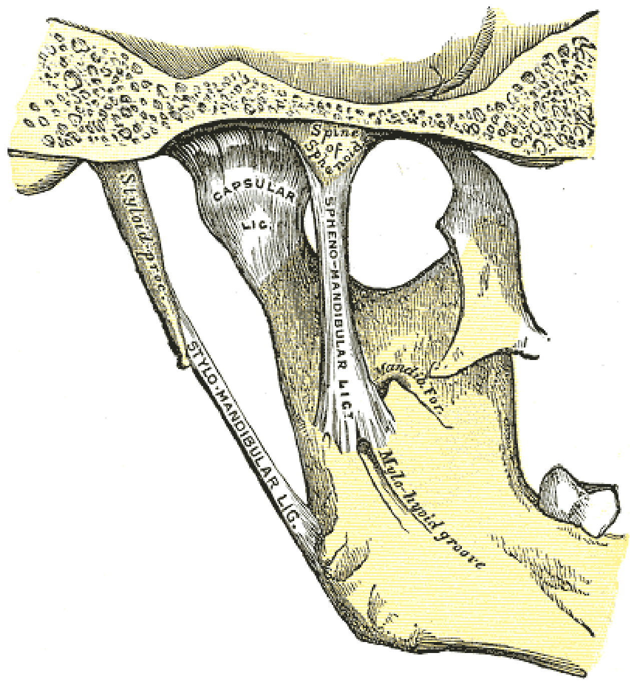

Figure 1: The ligaments of the jaw

Source: From Anatomy of the Human Body, Gray 1918. Accessed via Wikimedia Commons [49]

serves to keep the jaw aligned. The final adductor of note is the temporalis the large fan-shaped muscle that runs from the temples to the jawbone. The masseter and temporalis are external muscles just under the skin as seen in the left half of Figure 2. The temporalis is most used in smaller jaw motions and can be connected to headaches caused by subconscious clenching or grinding of teeth[39].

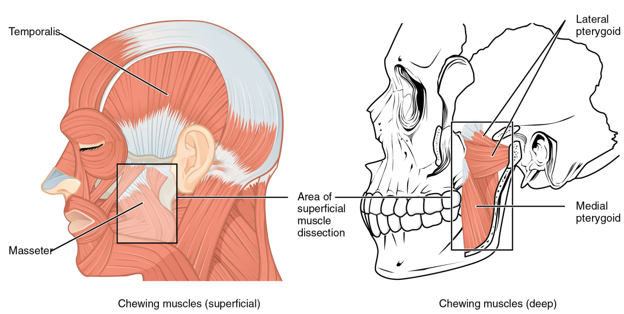

Figure 2: The major muscles of mastication

Source: Accessed from Wikimedia Commons [51]

The protrusion and lateral motion of the jaw while chewing is produced by the lateral pterygoid muscles which pull forwards from the upper mandible beneath the zygomatic arch [5]. The lateral pterygoid muscles do not only pull forwards on the mandible as they also connect to the articular disk and are responsible for sliding it forward along with the mandibular motion. The lateral pterygoid is visible in the cutaway section of Figure 2. Due to the sliding and pivoting nature of the mandible, the lateral pterygoid also serves as the primary abductor responsible for the initial motions of opening the mouth. The lateral pterygoid is assisted by the digastric muscle, this muscle is located below the mandible and connects to the hyoid bone, which is the thin horseshoe-shaped bone that maintains the shape of the throat [26]. While the hyoid itself is subject to another broad array of muscles themselves key to breathing speech and chewing broadly speaking when the hyoid is held stationary the contraction of the diagstric serves to hinge the mandible open. The digastric muscle and the hyoid bone are highlighted in Figure 3.

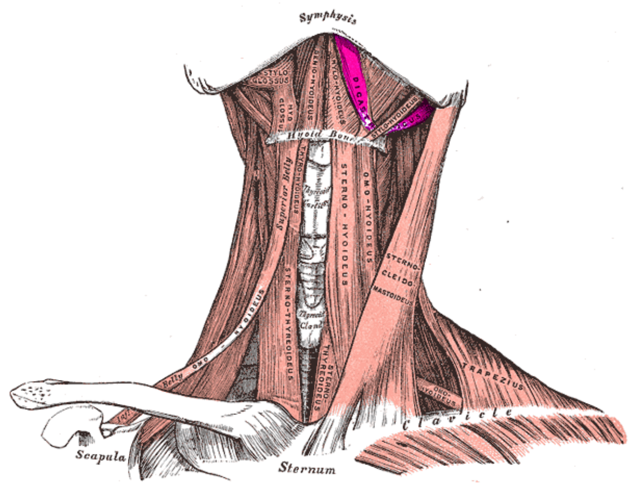

Figure 3: Anterior view of the digastric muscle

Source: Accessed from Wikimedia Commons [50]

Muscular disorders are considered one of the major contributing factors in TMJ disorder [31]; in the context of our project, an understanding of the musculature is crucial to effective design. Understanding the location and function of the muscles that affect the TMJ joint designs can be made that avoid exerting pressure on those muscles, and through them on the TMJ.

3.2 TMJ Disorder

Temporomandibular joint disorder (TMD) refers to a cluster of conditions relating to dysfunction of the TMJ, commonly characterized as conditions sharing the symptom of pain in the TMJ, musculature, or in related soft and hard tissues. Symptoms of TMDs are present in an estimated 6 to 12 percent of the adult population [29], with general oral facial pain sometimes reported in as high as 25 percent [30]. In most instances symptoms are rare and usually minor enough to be manageable, however in a small minority persistent and serious TMJ pain is reported. While it is not the goal of our project to treat TMD understanding its causes and symptoms is key to effective design. Without a clear understanding, a design could unintentionally fail to mitigate or even worsen some symptoms.

The classification of TMD generally can refer to any one of or a combination of diagnoses: muscular disorder in the muscles of mastication, displacement of the articular disc, and arthritic conditions caused by deficiencies in the joint itself. A study of a population of those seeking treatment for TMDs revealed an occurrence of muscular disorder in 38%, disc displacement in 52%, and arthritis in 53%, with an even distribution of individual and combined conditions [31]. The broad distribution of specific disorders combined with the frequency with which patients present with combinations of disorders seems to indicate that TMD has multiple causes.

One potential cause for TMD is the mechanical loading of the joint itself, subject to trauma or the aberrant mechanical loading of a nonstandard chewing motion the TMJ joint can begin to show degeneration. As would be expected, the significant shock loading of traumatic events can cause damage to the TMJ; studies on patients that suffered whiplash have noted an increase in immediate post-accident jaw pain [14] and an increased future risk for developing TMD symptoms [38]. While the consequences of trauma are obvious sustained aberrant mechanical loading can present just as much danger to the TMJ. The jaw is one of the parts of the human musculoskeletal system that sees the most cycles of motion; activities such as eating or talking require near-constant repeated cycling of the joint. Unfortunately, the motion of the mandible is also highly sensitive to external factors; studies on rodents in 1986 revealed significant deformation of cartilage and reduction in bone density caused by the filing of incisors or a change to a soft diet[28]. Notably, this study saw damage to the mandibular joint caused not just by the physical adjustment of the mastication motion but also when mastication forces were generally reduced through the means of a soft food diet. In many cases, aberrant loading of the TMJ is unavoidable; changes as small as a chipped canine or dietary preference can have significant effects over time. This information is crucial to effective design. Even though symptoms may only be present on one side of the jaw; any device must be symmetrical in effect. Reducing the pressure of eyeglasses on just one side of the face could inadvertently cause damage to the opposite joint.

Unfortunately, mechanical issues and wear of the TMJ can be accentuated by other biochemical mechanisms. In a 2005 paper, Dr. Stephen Milam of the University of Texas proposed a cascade failure model by which mechanical stress within susceptible individuals causes the release of harmful molecules referred to as free radicals[32]. The proposed mechanism for this release varied from high magnitude forces within the TMJ itself causing homolytic fission, to sustained action such as jaw clenching causing hypoxia within vascular tissues such as the articular disc.

Due to the increased rates of reported TMD among women of reproductive age it has been postulated that a sex-based determinant such as hormonal levels may be a cause of TMD [45]. Supporting this is the observation of estrogen and progesterone receptors in the TMJ of primates[33] and mice [47]. In 2008 researchers from the University of Connecticut and the University of Michigan identified the possible role of estrogen in managing the release of tissue-damaging enzymes within fibrocartilage[45]. However, it should be noted that the researchers themselves did not identify this factor as conclusive merely a contribution to the risk of disc displacement or the development of arthritic degeneration in the joint itself.

One of the more common forms of TMD is responsible for one of the most noticeable and unpleasant symptoms. A popping jaw is typically characterized as an audible or otherwise perceived 'popping' or 'clicking' sound usually experienced at fairly low angles of mandible separation, often after closing and reopening the mouth. Alternatively, a locked TMJ joint can be much more serious and usually presents as a painful rigidity of the jaw, whereby the jaw cannot be moved; most commonly this occurs when trying to open the mouth though it can happen when closing the jaw. It should be noted that this is separate from the common use of 'lockjaw' in referring to the inability to open the jaw due to muscle spasms historically as a result of tetanus infection. The TMJ joint locking is a result of the articular disc meant to remain between the two bones being displaced too far forward and bunching up preventing the easy sliding of the bones [21]. This is a symptom that can easily build on itself as every time the jaw pops or locks it is stretching the connective tissue responsible for maintaining the position of the articular disc. It is worth noting that jaw popping is a symptom commonly associated with a clenched jaw; this is likely because of the role of the lateral pterygoid in pulling the articular disk forwards in the normal operation of the joint. An increase in tension of the mastication muscles leads to increased applied force by the lateral pterygoid and an increased risk of the articular disk slipping forwards. There is no modification to a set of eyeglasses that will restore the proper position of the articular disk. However, it is important to understand how muscle stress can lead to unwanted pain.

One of the more nebulous symptoms of TMJ disorder is referred pain in the face, neck, and head, many patients suffering from TMJ issues report other pain symptoms in associated tissues. The exact presentation of this symptom varies highly between individuals; the exact nature of the pain and the locations where palpation causes response is not only variable between patients but can be intermittent in presentation. The most common location for referred pain is naturally around the TMJ itself, both as a location of referred pain and an area in which external pressure results in pain [13]. However, the TMJ itself is not the only location where pain can occur; more generally, referred pain from a TMD can occur anywhere surrounding the skull or mandible with areas of anatomy directly related to the joint being hot spots where palpation results in pain response [46].

The diagnosis and understanding of TMJ-related pain are further complicated by the relationship of TMD with other maladies such as general dysfunction of the ear or headaches. The general correlation between TMD and symptoms such as a feeling of stuffiness in the ear, dizziness, or even earache is generally assumed to be a product of their close proximity [12] practically this means that TMD sufferers can additionally be oversensitive to devices such as headphones or earbuds that are known to aggravate ear conditions. A correlation has been observed between patients with persistent temple[39] and cervicogenic [44] headaches. It is unclear if there is a direct causation however treatment for TMD did result in a reduction of headache symptoms in a 2011 study [44].

3.3 Existing Solutions

There are several tools for making eyeglasses more comfortable, yet none are directly intended to solve the complications with TMJ pain.

Glasses straps connect to the end of the temples of the glasses and provide support to keep glasses in place and reduce downward pressure on the ears, but further tightness around the head is something that would generally agitate TMJ pain.

Silicone ear grips provide a tighter fit for glasses as they are positioned so that the ear is touching the grip. It makes it so that the glasses stay in place by providing more tension on the ear and by virtue of being silicone. There are also silicone sleeves that cover the temple of the glasses and provide a more cushioned surface while also increasing friction. Both of these solutions do not address the pressure applied to the head with the glasses.

Glasses with malleable frames are on the market and seem to help move pressure from glasses to other pressure points that the user would prefer. This seemed to have good potential for alleviating TMJ pain and is very similar to one of the designs created. However, the price for such glasses is above average which is cost-prohibitory.

Nose-clipping glasses are glasses that pinch onto the nose and do neither rest on the ears nor touch the area around the TMJ. The issue with this solution is that it can be uncomfortable as it is pinching the nose, and is not wearable with many nose shapes. Getting a prescription for these glasses is challenging and expensive.

Headbands that hold eyeglasses in place from above exist. The glasses are not supported on the ears and do not apply pressure to the TMJ. These glasses are incredibly hard to find and generally not a viable option.

Contact lens is a solution that gets rid of glasses entirely. They avoid the problem from the start. However, for many, they are too expensive or irritating to wear and are not a sustainable solution for many.

LASIK eye surgery, as well, gets around one of the core causes of our problem. The reality is though that this is incredibly expensive and not feasible for many.

Physical therapy for the TMJ is a potential solution that requires a time commitment. It also can be expensive if seeking professional advice. For particularly bad cases of TMJ disorders, this may not be an option. However, reducing baseline TMJ pain and addressing the problem itself is a good action to take.

Another attempt to reduce TMD pain is to get steroidal injections that reduce swelling. This can be detrimental to the joint and runs the risk of antagonizing it further. Also, it can be expensive.

There are no existing medical solutions that directly address pain from glasses from TMD disorders. In a community discussion, the following was brought up as potential solutions.

"[W]e found that having an optometrist adjust the stems (arms) of the frames to make them less tight against your skull may help. There are some frames that the stems attached the front of the frames with springs which can expand should you face swell instead of staying rigid. [. . .] Another thought is perhaps trying contact lenses."

This was found at inspire.com, which enables people who seek help to ask questions and receive some advice and support. In a similar post, it was recommended to "find frames that have a spring feature." If there is swelling in the joint, then the spring will reduce more pressure than if there was just a rigid frame.

In other forums, there are discussions of which glasses manufacturers actually helped with the pain. Material choice is brought up as a complicating factor to this issue with a discussion on a material that is light and not too rigid being discussed. These conversations revealed a lack of direct intended solutions.

3.4 Stake Holders

The main stakeholder for the assistive device are people with TMD who wear glasses. The medical industry is often slow and unavailable for many people. Without insurance people with medical conditions are forced to treat themselves and this can result in people having to treat themselves. These stakeholders want a solution for the pain that is affordable and easy to create.

4 Autoethnographic TMJ Pain Study

Due to the relative lack of academic research on the subject we decided to engage in an autoethnographic study of TMD experience to better inform the design of our glasses attachment. For this purpose, two members of our project team Kell Carlisle and Santiago Tougas recorded their experiences with TMD disorder for the length of a month making use of journals and pain diaries to record any observations or specific triggers.

4.1 Kell Carlisle

My jaw pain developed in high school; however, I was not formally diagnosed with TMD until college. When I grew up, my jaw would often lock or have a reduced motion. Thankfully my jaw never got to the point where it would not open. I went to the doctor several times in high school for jaw pain, but the doctor never figured out what was causing it.

I had immense difficulty getting diagnosed with TMD due to a lack of communication between the doctor and dentist who treated my pain. My jaw pain started in my junior year of high school and got progressively worse. By my senior year of high school, my pain was bad enough that I got medical treatment. I went to my primary care doctor, who did not have experience with TMD. This doctor advised me to see a dentist. I followed the advice and went to my regular dentist. The dentist said my pain was a problem with the jaw joint, and they only treat teeth. I was back at square one. I went back to my primary care doctor to get treatment. Unfortunately, once again, he could not help me. However, he referred me to an ear, nose, and throat doctor. The ear, nose, and throat doctor said my pain was a dental issue.

At this point, I was so frustrated that I gave up trying to get treatment. The constant invalidation of my pain made me hopeless. I felt like the medical industry was playing a game of keep away with me. They did not want to take me as their patient, so they kept throwing me to different medical professionals. It hurt.

During my senior year of college, I began wearing glasses that were causing pressure on my TMJ joint. The stems of the glasses pressed on an area that was already causing me pain, resulting in my jaw locking. The discomfort was severe enough that I sought medical attention.

This time, getting TMD treatment was more successful. Although, I again was thrown between dentists and doctors, I finally found a TMD expert. The doctor who treated me was a specialist in the TMJ joint. I finally got treatment for my pain, and it did not work.

I tried several different treatments for my TMD. I took pills. I did physical therapy. I even tried meditation. Nothing worked. My doctors were out of ideas. I was out of ideas. I was back to square one.

Square one is cozy. I have made my home here. At first, I was angry. I sat down and sulked about how unfair this was. However, the longer I sat in my anger; the more I realized how silly I was being. Ragging at the world rarely gets anything done. Through this self-realization, I calmed down and took a breath. I learned acceptance is much more effective than anger.

4.2 Santiago Tougas

My jaw disorder developed during my high school junior and senior year. I was diagnosed with anxiety around this time, and I believe I was grinding my teeth at night. Around this time I stopped wearing braces which allowed me to pick up the habit of chewing gum. With my stress level high I used gum as a way of alleviating my anxiety; however, I did so by chewing up to five pieces of gum at once and so long that the taste of the gum had gone.

This unhealthy habit continued, and I started noticing that my jaw would click when I ate on my right cheek. I had been chewing mostly on the right side of my mouth and there started to be visible inflammation. It grew progressively worse and opening my jaw started to hurt. At its peak, there were times when the jaw would become locked out to a particular range of mobility. To undo this I would have to move the jaw around and massage it. I looked into possible causes and somewhere I read it included excess chewing of gum. I stopped chewing gum for several months.

I let my jaw rest but the pain while eating and the jaw clicking persisted. I went to see a dentist and it was recommended to wear a mouth guard to prevent grinding at night. When the night-guard is worn the jaw is generally less painful throughout the day.

Generally, it is not a big deal for me. When I eat the pain is generally low enough for me that I don't notice and the clicking sound has gone down in frequency when I eat. If the pain worsens, I increase the hours per week of night-guard use.

5 Business Analysis to Inform Design

The business section of the IQP aims to inform and assess product development. Business analysis will help in product creation by identifying edge cases. Identifying edge cases will involve a qualitative brainstorming session and will be used in customer segmentation. The engineers will use the list of edge cases to develop a more suitable assistive device for the customer segment. The team plans to use customer segmentation to create an assistive device that will not be sold. Instead, the goal is to target a user base that will spread the word and even make the device for themselves. The engineers will use this process to design prototypes that meet specific product-based specifications and assess them using a decision matrix.

5.1 Identifying Edge Cases

Edge case is a term coined for software development that can also be used for physical product creation. The definition of an edge case is an issue that product developers do not anticipate affecting a significant number of users, and, similarly, it relates to problems that may be rare [37].

Understanding the edge cases for the assistive will be used for the product design by understanding the product user. For example, an edge case is the heads of children. Most people, have a much larger head than a child. A device correctly sized for only an adult would accommodate the non-adult portion of the user base. Without examining edge cases, product designers can unknowingly exclude a segment of the consumer base. Listing edge cases will give a designer insight into consumer needs. Examples of how edge cases can help designers are:

- Identifying potential problems: Edge cases can help designers identify potential issues or problems that may not be apparent in typical use cases. By considering how a product might behave in extreme situations, designers can anticipate and mitigate potential problems before they occur [37].
- Ensuring accessibility: Edge cases can help ensure that a product is accessible to a wide range of users, including those with disabilities or unique needs. By considering how the product might be used by people with different abilities or in different contexts, designers can make sure that it is usable and useful for as many people as possible [37].
- Improving overall usability: Addressing edge cases can help improve the overall usability of a product. By designing for extreme situations, designers can create a more robust and reliable product that is easier to use and more intuitive for everyone [37].
- Enhancing user experience: Edge cases can also help enhance the user experience by providing features or functionality that users may not have thought to request. By considering how the product might be used in unique or extreme situations, designers can create features that add value and delight to the user experience [37].

Overall, edge cases are an important part of product design because they help designers create products that are more accessible, more reliable, and more versatile for users. By considering how a product work for edge cases, designers can create a better product that meets the needs of a wider range of users.

For the product design, the team found edge cases that help inform the design creation. A table was created of all the edge cases in the categories of:

- Hair: hairstyles, hair types, and hair texture
- Head: Facial hair, head size, age of the person, and facial structure
- Pain: levels of pain and area of pain
- Clothing: any clothing on or around the head
- Items on the ear: earring, hearing aids, and headphones
- Usage: how many times a week an item is used
- Skin: powders on the skin, skin type, and skin conditions
- Glasses: glasses types and sizes
- Ear: Ear condition and ear shape
- Lifestyle of the user

These edge cases were then evaluated on what aspects of design they would affect. Unfortunately, there is a limitation to the ability of edge cases to include diverse user needs. When products are being created generally abled, financially stable, white, cisgender, men are the default. By using edge cases we want to look at minorities' needs and go beyond the traditional assumed default user. However, by attempting to go beyond the non-minority status quo we are using white male as the baseline and in some ways this has the side effect of framing minorities as "the other." Minorities are not "the other" however to evaluate the traditional biases a baseline of the biases are needed. As a result, minority needs such as the ability for the product to work with Afros are more likely to be outlined than the ability of the product to work with straight hair. The business analysis will outline minorities so product designers can make a product that is not just for white men. Bellow explanations of important edge cases.

One edge case is head size. The size of the product needed is largely impacted by facial dimensions. An edge case for head sizes is children. A child will have a vastly different head size from an adult. A product sized for an adult will be large for a child. The differences in head dimensions between children and adults will require the product to either have multiple sizes or work well on a wide range of head sizes. Large head sizes present the opposite problem from children's heads. A person with a larger head size will need a larger product. If a product is designed to disperse pressure from glasses on a person with an abnormally large head, the product would need to be bigger than the average head size. To account for both large heads and children's heads products would need to work on a large range of head sizes.

Low nose bridges present a challenge for the product because they change how the product will sit. The most extreme cases for facial structure are people with low nose bridges. Low nose bridges reduce glasses' ability to grip the nose[42]. Without the ability to grip the nose, glasses will often slide around the face or fall off. To account for the low nose bridge, the design will have to either reduce glasses shifting or have a product that does not require precise orientation. TMD can be caused by severe injuries to the jaw. Many people with TMD have a deformation of the jaw and face due to injury(better word needed). This means that to fit more of the consumer base the device should allow for common deformation of the jaw.

The most common area of pain with TMD is the jaw however it is not the only common area of pain. TMD sufferers often have neck pain and facial pain[23]. The edge case of pain areas is people who have more than one area of pain. A product that prevents jaw pain but puts more pressure on other areas of the face will not work for some of the TMD patient population. Avoiding areas of pain by changing how the glasses sit becomes more complex if a person has many painful areas besides the jaw. If a person's entire head and neck hurt, a product that is designed to avoid painful areas will be ineffective. To design for a person whose entire head and neck hurt a product will need to be created to reduce total pressure because of glasses stems rather than change the area that glasses stems sit.

The edge case for usage is a person who wears glasses every day. A daily glasses user will rapidly decrease the durability of a glasses attachment. To accommodate daily users a product would need to be more durable.

Sensitive skin will increase the irritation of products. People with extremely sensitive skin may be unable to use a mildly abrasive product. Medical skin conditions such as dermatitis, a skin inflammatory condition, will increase the likelihood that the consumer's skin will be irritated[34]. The consumer may also need a product that can avoid areas where the skin condition is present. To avoid irritated areas the customer will need a more customizable product.

Ear piercing increases the risk of the product being tangled and can created additional painful areas to avoid. The edge cases of ear piercings are hoops and upper ear piercings. Upper ear piercings such as bar piercings can cause lack of ear mobility when fitting the product. Additionally, people with ear piercings are unable to remove a piercing before it is healed [6]. This could result in a person with TMD being unable to use the product due to having a piercing [6].

Ear conditions are edge cases because of increased sensitivity [6]. Having an ear condition such as an ear infection will increase the sensitivity of the ear. This could cause pain when a product touches the ear. Having ear pain presents a challenge because the product will need to avoid an additional area. Ear infections are only temporary which reduces the importance of this edge case. However, ear infections are still a consideration because being sick should not prevent a person from wearing glasses.

An edge case is curly hair. Curly hair increases the likelihood for glasses attachments to get caught in a user's hair. Getting items stuck in hair is especially the case for dense curly hair. Removing a stuck item from hair has the potential to pull hair and cause pain. To avoid items getting stuck in curly hair the product designers need to avoid sharp corners on a glasses attachment. Any protrusions increase the risk of hair getting caught around the assistive device.

How much hair a person has dictates how well items on glasses can be hidden. For example, a person who is bald would receive less cover from their hair. In this case to compensate for lack of hair, glasses attachments would need to be smaller and/or camouflaged with the scalp color.

Clothing that covers the ears will interfere with the design of placement. For example, hoods, hijabs and ski masks could tangle with or shift in a glasses attachment. To accommodate clothing that covers the ear, a glasses attachment could be small or not shift.

Hearing aids and headphones can reduce the areas on which glasses attachment can rest. Hearing aids often go behind the ears and any attachment that also go behind the ears would have potential to tangle with the hearing aid. There are many types of hearing aids and the most difficult to account for with the product is large hearing aids that go behind the ear. These devices would restrict the placement of the device and the hearing aid could get caught in the product.

Over-the-ear headphones would press a large and inflexible device into the skull, potentially causing more jaw pain. Additionally, devices that require precision placement could be shifted with over the ear headphones.

Allergies to metals and plastics present a challenge for the amount of consumers who would be interested in the product. Creating a product that can be manufactured out of multiple materials allows consumers with allergies to pick another material.

5.2 Customer Segmentation

Customer segmentation is a tool used to decide who a product should be designed for. The process of customer segmentation is defined by the Cambridge dictionary as “ the process of dividing a company’s customers into groups of similar types, in order to plan how to sell to each type more effectively” [18]. The goal of customer segmentation is to better understand the needs and preferences of different consumer groups. After that, a group to design for will be selected otherwise known as a customer segment.

Unlike traditional customer segmentation this project is not seeking to sell a product. Instead the project group is selecting a customer segment that will advertise the product by word of mouth and have the ability to create the assistive device.

Even though the glasses attachment could be adapted for multiple customer segments the group decided to only focus mainly on one for the assistive device. If multiple customer segments were selected the difficulty of product design would be increased. For example, if the team decided to design the product for both children and adults, the product would have to work for vastly different head sizes. Designing for just one segment allows the team to focus on perfecting the design for one customer segment rather than attempting to design a more versatile product.

There are many different ways to segment customers, depending on the industry, the type of product or service being offered, and the specific goals of the segmentation analysis. Some common approaches to customer segmentation include demographic segmentation (e.g., age, gender, income), geographic segmentation (e.g., region, city), psychographic segmentation (e.g., lifestyle, personality), and behavioral segmentation (e.g., purchase history, brand loyalty) [22].

Customer segmentation can be a powerful tool for product development. By understanding the unique needs and preferences of different customer groups, product designers can tailor products to better accommodate a consumer segment.

5.3 Edge Case Utilization

The team is using edge cases in the customer segmentation process to identify customers who do not fit neatly into traditional customer segments or who have unique needs or behaviors [48]. By identifying and analyzing these edge cases, the product designers can gain valuable insights into customer behavior and preferences that may not be evident from looking at the larger customer population.

By examining edge cases, team will increase the precision of the targeting a specific customer segment. The team is only designing the product for one target customer segment. Using edge cases can divide one customer segment into a smaller customer segment allowing the team to pick a small target customer group. For example, children are an edge case. If our product cannot work for people with small heads then the team can remove children from the target customer segment.

In addition to identifying new customer segments, edge cases can also help businesses refine their existing customer segments. By analyzing the behavior and preferences of edge case customers within each segment, businesses can identify areas where the segment definition may need to be adjusted or where new sub-segments may need to be created.

Overall, edge cases can be a valuable tool for businesses looking to better understand their customers and develop more effective customer segmentation strategies. By looking beyond the typical customer segments and analyzing the unique needs and behaviors of edge cases, businesses can gain insights that lead to more targeted marketing, improved customer experiences, and increased customer loyalty.

5.4 Selected Market Segment

The product is a 3D printable assistive device that works on glasses. The marketing plan for the device is to make a 3D printable modeled of the assistive device and will be available online. The way consumers will discover the product is word of mouth. Money will not be spent on advertising the product. Therefore the service obtainable market, the customers that we realistically obtain with our advertising method, will be people who are active online.

The product will reduce pain for people with TMD from wearing glasses. The main target of the customer base is people with TMD or TMD-like symptoms. The product will target people whose people 's pain increases significantly with glasses use. People who either have no or only a minor increase in pain from wearing glasses are excluded from the customer segment due to a decreased need for the product.

Therefore the customer segment we are targeting is: People with TMD pain that is significantly exacerbated by glasses and who are active online. People in this group have a large likelihood to hear about a product through word of mouth and a large desire to have TMD relieving medical devices.

The consumer base we are targeting is people who are active online and in social media. To reach a group of people by word of mouth online the product should be advertised on online forums. A shareable post should be created with a link to the 3D printable device.

The market segment is people who know how to use 3D printer and are experienced with technology.

Targeting a user with technological experience allows the engineers to create a more complex device.

5.5 Weighted Table

A weighted decision matrix is a decision-making tool that helps to evaluate different product designs based on a set of criteria. A criterion is a design requirement for a product. An example of a criteria is the durability of a product. Creating an objective table involves assigning weights to each criteria, indicating their relative importance, and then evaluating each option against objectives [16].

Weighted objective tables are commonly used in business decision-making, project management, and other areas where multiple options need to be evaluated based on specific criteria. They provide a structured approach to decision-making and help ensure that all relevant factors are considered in the evaluation process.

A weighted objective table typically includes a list of products to be evaluated, a list of objectives, and a weight or importance assigned to each objective [16]. For example, if you are evaluating different cars to buy, the objectives might include factors such as price, fuel efficiency, safety, and reliability. The weights assigned to each objective might reflect your personal priorities, such as valuing safety more than fuel efficiency. The total weights of all of the objectives equal one. For a case with two objectives both objectives could have a weight of 0.5 or one object could have a weight of 0.3 and the other 0.7 [16].

Our team chose to use a weighted objective table to evaluate the designs. This allowed the team to use ranked performance and weighted importance to compare attributes of each design. Much of the ranking of a weighted objective table is subjective so detailed scales explaining how to evaluate each design were included. The weighted objective tables provided the team with a means of choosing the best product design.

Overall, the most important aspect of the design is that the assistive device reduces pain. If the assistive device either does not decrease pain, no one would want the product. Therefore reduction in pain is the top priority.

The priorities of visual appeal, market size and cost are all equal priority. Visual appeal is important because of social stigma around disabilities. People with disabilities often do not want everyone knowing that they have a disability. As such, a product that is hidden is important because it retains the person's privacy.

The market size is important because increasing the reach of a product is important. The market size is defined by how well the product works for the target customer segment. For example, if the customer

Category	Weight
Visual	.154
Durability	.154
Market Size	.077
Cost	.154
Pain Reduction	.462

Table 2: Weighted objective table.

segment selected includes people with short hair and the product does not work for people with short hair the market size will decrease because the product cannot meet the needs of the consumers.

The cost is important because the affordability of the product has an impact on the amount of people willing to buy the product.

Least important is durability. The rationale behind ranking durability the lowest is that if the product does not work and the consumer does not know about the product through marketing then how long the product functions is irrelevant. Additionally, with the limited time frame, the teams ability to accurately predict the durability is limited.

5.6 Business Conclusion

Through the business analysis the team has identified the objectives and created metrics for the product design. The team will use the edge cases as a framework for the creation of product design. The edge cases will allow the team to see the extremes of product use and the historically excluded consumer needs. The customer segment will give the team a target who the design is being created. Finally the decision table will provide a metric to evaluate the product designs.

6 Product Design

Over the course of this project the mechanical team set out to design and assemble a array of prototypes and evaluate their effectiveness as assistive devices for those with TMD.

6.1 Design Goal

From our autoethnographic study and a fair amount of decidedly non-scientific face poking, we identified that in our case the primary source of eyeglass induced TMJ pain is a result of the lateral pressure exerted by the eyeglasses arms to the temporal region above and slightly forward of the ear. This revelation led us to define the core design goal as being to reduce lateral pressure exerted by a pair of eyeglasses on a user's head; while a little overly simplistic, this did quantify the ultimate goal of reducing TMJ pain in such a way as to allow the design team to start work on brainstorming and designing prototypes. Unfortunately, the lateral pressure exerted by a pair of eyeglasses exists for a reason being, largely responsible for keeping the eyeglasses centered and level and keeping them from falling of with the motion of the head. Solutions already exist for glasses that have no arms, namely the pince-nez (literally nose pinching) eyeglasses that rely on a clip resing over the nose bridge to remain in place; in addition to being somewhat out of fashion in contemporary times this style of glasses does not lend itself to the kind of constant wear necessary for modern life. Given the analysis of this preexisting, if rarely used solution, the nature of our design goal changed once again, our product should reduce lateral pressure exerted by conventional eyeglasses while not significantly increasing the eyeglasses propensity to shift or fall off.

Given the significant cost involved in corrective eyewear it would be impractical to attempt to replace a set of glasses completely. An eyeglass frame represents a significant investment and one that we can assume our target user has already made so a design that replaces a set of frames entirely would be impractical, therefore any proposed device should ideally represent an addition or modification to an existing set of eyeglasses. The decision to design for compatibility with a large range of frames introduces its own complexities, the existing variety of styles and geometries introduces a level of complexity to a universal solution that puts it beyond the bounds of this project. Fortunately, we once again made use of our market analysis to reduce the scope of the design goals; since the more complex eyeglass styles such as wireframes or stamped sheet metal arms typically come with an increased price tag, we can assume that members of our target market segment are less likely to have complex frames. This design decision is reinforced by the observation that sheet metal or wireframe arms are significantly more likely to be present on sprung hinge or hingeless eyeglasses, both designs which in addition to being significantly more expensive already somewhat address the issue of reducing lateral pressure and thus represent the high cost somewhat effective solution for many with TMJ disorders. Personal examination of eyeglass designs reveals the most common and universaly affordable design is a frame constructed out of a high elasticity plastic with a set of arms of rectangular cross section, therefore our minimum design goal can be described as a product capable of adapting or attaching to a range of generic plastic framed glasses.

Leveraging the business analysis we were able to lay out the fundamental design goals of this project: To design an affordable device that modifies existing plastic barrel-hinged eyeglasses in a way that reduces lateral pressure on the wearer's head while not significantly compromising the eyeglasses ability to remain affixed.

6.2 Design Constraints

Material Selection

Due to the nature of this project we began with some fairly significant design constraints mostly surrounding material and assembly. The intention was to design a product that is both affordable and accessible. From our understanding of the target market, and recognizing the importance of accessibility and self-actualization in the treatment of disabilities; we concluded that the final products should be manufacturable at a per-user level. This meant we were unable to prototype in materials such as aluminum or Delrin; those that most need a solution to this issue are unlikely to share our access to a machine shop. Fortunately, like many others, we identified the rise in popularity and accessibility of 3d printing as an enabler of niche custom manufacture that is not prohibitive in cost or technical skill. The rise of comparatively simple plug-and-play printer brands such as Prusa or Ultimaker means more people have direct access to a printer than ever, this is in addition to the increase in affordable online printing services capable of manufacturing and shipping custom 3d parts without breaking the bank.

Economic factors and an empathetic approach to design for disability meant our design would be created with 3D printing in mind; however, even within the realm of 3D printed parts, there are significant design constraints to consider regarding material selection. By far the most common form of 3d printer is a Fused Deposition Modeling or FDM printer, these printers construct parts by depositing layers of a thermoplastic out of a small heated nozzle. The most common materials for FDM manufacture are PLA and ABS filaments; the two materials are largely interchangeable with most FDM printers capable of working with both materials. However, as PLA is slightly easier to work with, it is the material most often used in hobbyist applications. FDM printing does come with certain significant drawbacks; its surface finish is often quite ugly as the layer lines are visible in the final part. The finish can be improved by sanding or printing with lower layer heights; however, this comes at the cost of time and when using an external manufacturer cost. The layer based nature of FDM printing also introduces planar shear lines within the part; which must be considered when designing features such as pins or pegs into printed components. The dimensional accuracy of FDM printers is also an issue for small parts; with an expected dimensional range of $\pm 0.15\%$ with a minimum tolerance of ± 0.020" for most hobbyist machines. This minimum accuracy can be a significant issue especially when working at the scale of a pair of eyeglasses where certain bolt holes are already as small as 0.060". The final significant restriction of conventional FDM printing is the observation that horizontal surfaces located on the bottom of a part that do not rest on the build-plate itself often have significant inaccuracies in surface and finish. This is pronounced enough that if intending for a part to fit together flush it is often necessary to have no protrusions below that flush surface. These limitations mean that despite being the most common 3d printing option, FDM printing in PLA can introduce significant design restrictions.

While PLA printing is the most common, it is not the only option for additive manufacturing. Given the requirements for fine detail, clean surface finish, and sensitivity to print orientation likely involved in a device meant to fit eyeglasses, it is worth examining resin printing. Resin printing is the name given to a variety of printer designs that produce 3d parts by selectively curing a light-sensitive liquid resin. Ultimately this approach produces parts that are more accurate at small scales, have significantly improved surface finishes, and are much less sensitive to part orientation. Resin printing would be an ideal target method of manufacture for any device intended to work on the scale of a pair of eyeglasses. Resin printing, however, does have its downsides not only is the material used more expensive, but it is also significantly more complex to work with requiring chemical baths and additional post manufacture UV curing. It is because of these reasons along with the necessary complexity of the printer itself that resin printing has not yet reached the inflection point of affordability to be common in the hobbyist community. This means that if we were to design requiring resin printing we would eliminate the convenience and cost savings of users being able to manufacture and assemble this device at home or with the help of a friend. It is worth considering however that resin printing is available from multiple online third-party manufacturers; while significantly more expensive than FDM parts resin prints especially at the scale we can expect are not prohibitively expensive.

Another 3D printing material is worth mentioning. TPE or thermoplastic elastomer is as the name suggests a form of rubber with both thermoplastic (can be melted and recast) and elastomer (capable of stretching or deforming only to regain its original shape when released) properties. TPEs, of which one of the most convenient and easily available is TPU (thermoplastic polyurethane), offer all the benefits of conventional FDM printing while producing parts that are softer to the touch and capable of bending or otherwise deforming without breaking. For an application such as a worn device, the flexibility of TPU would be a major asset in not just preventing sharp contact points but also better fitting the complex curvature of the head in such a way as to distribute pressure. Another appealing advantage of TPU is that it can be printed on any FDM printer capable of working with PLA, so is nominally available to the hobbyist community; however, swapping between PLA and TPU on a single printer can require significant effort to clean print heads and other parts. The major disadvantage of TPU is in its surface finish as the material lends itself to balling of filament, brief failures of adhesion, and other issues which, while they don't commonly compromise the structural integrity of a print often produce an unappealing and uneven surface. Despite the significant drawback in aesthetic appeal, the compliant nature of TPU parts ensures the material is worth consideration, especially where the hard edges and corners of typical PLA would likely cause significant discomfort.

Sourcing COTS components

The considerations of cost and accessibility also affect what off-the-shelf components can be used within a design. For members of the mechanical team, it is natural to source parts or hardware from McMaster; however, for a significant portion of our intended user base accessing that type of online catalog could be considered prohibitively complex or unusual. To increase the accessibility of any final product we established the design constraint that any commercial off-the-shelf component must be sold on Amazon. Fortunately, due to the impressive size of Amazon's catalog, this did not pose much of a restriction; the only significant impact this design constraint created was a push towards metric hardware due to the notable lack of imperial hardware below a #4 screw size.

Complexity of Assembly

When establishing reasonable expectations for the assembly of a proposed device the design team had to again account for their internal bias when considering the average level of mechanical skill and familiarity. The first consideration addressed was hand tool availability. The assumed minimum level is acess to and some proficiency in the use of hand tools common for operating a 3d printer, this includes: needle nose pliers, wire cutters, scalpels or exacto knives, and potentially tweezers. The only necessary tools that we assumed a user would have access to that did not already come with a 3d printing capability were jewelers screwdrivers of the size necessary for performing repairs or modifications to eyeglasses. This was deemed a reasonable exception as eyeglass repair kits containing the necessary tool are readily available both online and in retail. We determined that an eyeglass repair kit was not an unreasonable expense for someone setting out to modify their own set of glasses. It is worth acknowledging the built-in assumption of the fine motor skills and eyesight necessary to work with the quite small hardware involved in mechanisms such as eyeglass hinges. Overall, the assumed level of mechanical competency that we set as a design constraint was to our best estimation that of a potential novice or hobbyist level of tool familiarity but with a willingness to make mistakes so long as they are not too costly.

No permanent modifications or damage

As already noted eyeglasses can be expensive, therefore we set ourselves the design constraint that no design should require irreversible modification or damage to the users eyeglasses. Included in the definition of damage or permanent modification is the use of adhesives such as super glue to attach anything to the glasses themselves. This constraint was formalized with the requirement that any modification we proposed be reversible in a similar time frame and effort as the installation. This constraint was one of the more annoying to work around as issues such as securely attaching to a range of subtly different sizes and shapes of eyeglasses would be significantly easier if they each had a universal boss or feature glued onto them. Despite the frustration of this constraint, we felt it was necessary both to increase the confidence of users in trying the solution and to prevent potential damage or irreversible modification to an important item.

6.3 The Anatomy of Eyeglasses

To better understand the design problem we engaged in a study of eyeglass styles, materials, and mechanical features. A thorough study of eyeglasses allowed us to better understand how our product should function and potentially avoid some pitfalls and mistakes.

The three types of glasses

While there is a near infinite array of styles and fashions to a pair of glasses they can be broadly categorized into three groups by mechanical function. While there are still inevitably outliers this categorization is also indicative of the functional purpose of eyeglass frames. The central part of a pair of glasses: lenses, nose bridge, and surrounding frame, exists primarily to properly position the lenses at an appropriate height and distance from the eye, to achieve this there is a variety of designs: silicone pads on adjustable arms, larger flexible rubber inserts, or even single piece silicone bridges intended to sit snugly against the nose. While the variety of designs and methods in use are interesting and of importance to those with sensitive skin or abnormal nose shapes they are largely irrelevant to the designs we worked on. Of more interest is the hinge and arm assembly that exists primarily to create the lateral inwards pressure on the arms that prevent glasses from falling off.

The first and by far most common category of eyeglasses are those with simple hinges. This category has hinges purely to collapse the eyeglass assembly and as such the hinges themselves exert no moments on the arms. Instead to generate the inwards lateral pressure these glasses rely on the fact that fully open the arms are slightly closer together than the average head's width. Therefore when this category of glasses is put on the hinges are forced open and beyond producing a bending moment in the central frame. The high elasticity of the glasses frame, usually the result of the use of cellulose acetate or the hypoallergenic propitiate, allows the glasses arms to be levered outwards all while exerting an equal and opposite bending moment on the arms that presents itself as inward lateral pressure. This means that the gap between the arms of the eyeglasses is too narrow even when the hinges are fully extended. Due to the high rigidity design of the frame itself and the necessary high stiffness of the plastic this style of glasses tends to produce the greatest lateral pressures; unfortunately, this is also the cheapest to manufacture and most common style.

Figure 4: Top down view of sprung hinge frame

Figure 5: Close up of sprung hinge mechanism

The next category of eyeglasses are those with sprung hinges, these are glasses where the lateral force on the arms does not come from bending the frame itself but instead due to a small spring applying a moment about the hinge itself. These glasses are often identifiable by two characteristics, the arms rest position is approximately perpendicular to the frame and past a certain angle will always spring open, the arms are capable of over-opening with the spring opposing the increase in angle. Examining the pair of glasses in Figure 4 we can see that the sprung hinge frame is naturally just as narrow as the standard hinges; however, due to the hinge's ability to over-open when the glasses are pulled apart to fit around a head, the frame does not bend at all. In addition to allowing alternative materials and constructions the sprung hinge design produces significantly less lateral force as the spring inside the hinge by design puts a lesser moment on the arm. The exact mechanism of the sprung hinge varies between frames and manufacturers due to individual patents however the mechanism in Figure 5 is a fairly prototypical example making use of the stamped sheet metal construction to gently spring the arms towards a slightly squeezing position. Sprung frame glasses with their reduced lateral pressure can be beneficial in reducing pain from TMD however they are quite universally more expensive than standard hinges by a significant magnitude.

The final category of eyeglasses are hingeless frames, these frames have arms with moderate elasticity and a low elastic limit. The intended use for a hingeless frame is for the arms to be adjusted to fit their wearer by exceeding the elastic limit to cause plastic deformation; in theory, this allows for a set of glasses that precisely fit the wearer's head along with highly variable lateral pressure. This is because while the elasticity of the arms cannot be changed their natural resting position can be gently modified in an attempt to closely approach the limit of lateral force where the glasses are as loose on the head as the wearer is willing to tolerate. This style of glasses should be ideal for people with TMD; however, autoethnograpic experience testifies that even though the glasses have significantly reduced pressure the arms are not quite adjustable enough. Limitations on the hingeless frame's arm's length and relatively fixed vertical angle mean avoiding some painful areas is not always possible. While it seems that hingeless glasses may have some potential their price as the most expensive of all three categories means they are not a universal solution; the prohibitive price is in addition to some issues such as the difficulty to repair or the lack of centering force putting extra pressure on the nose bridge. The principles of adjustability inherent in hingeless glasses designs are worth pursuing; however, this is a relatively new design and until time manages to bring down prices and certain durability issues are addressed the design will remain a novelty.

For the purposes of this project we elected to focus our design compatibility purely upon the standard hinge design in order to directly address the largest share of the market that most needs our product. That does not mean that all our proposed designs will only work with standard hinges; however, the thicker arms of standard frames compared to the common thin sheet or wire of sprung and hingeless does present an easier profile for attachment to.

Barrels, bolts, and other non-alliterative components

Even within the category of standard hinged glasses there can be significant variation between hinge designs and because our designs are likely to need to interact with the hinge mechanisms directly we took some time to study the design differences.

The primary distinguishing feature of an eyeglass hinge is its barrel count, the barrel count refers to the number of interleaved pieces within a single hinge. The most simple hinge possible is a two-barrel hinge however on glasses the three-barrel hinge is the lowest used. The three-barrel hinge interleaving two outer barrels with a single inner barrel puts the bolt itself into double shear and prevents twisting or bending moments perpendicular to the hinge axis. Three-barrel designs are quite durable and represent the simplest and cheapest implementation of a standard frame and as such are one of the most common hinges on eyeglasses. There are two common three-barrel hinge designs. The most common design is a separate hinge mechanism embedded into the part when it was injection molded such as in Figure 6; this has the benefit of a stronger and smoother hinge in exchange for the higher cost, and introducing an unrepairable failure mode where the hinge insert itself rips out of the arm. Alternatively, a frame may use an integrated three-barrel hinge where the barrels are modeled directly into the plastic such as in Figure 7, this design is cheaper but requires a generally larger hinge due to the need for plastic to take loads directly, this design is most common in cheaper generally non-prescription eyewear such as safety glasses, sunglasses, or even 3d glasses at the movies. The distinction between implementations is significant in that the different designs tend to have different barrel thicknesses requiring unique geometry to fit each. The three-barrel is the simplest mechanism to allow glasses to hinge open and the most common; while, there are plenty of frames that change the mechanism for style purposes, a device designed to interface with a three-barrel hinge located inside of the arm will with minimal tweaks apply to the majority of cheaper frames.

Figure 6: Inset three barrel hinge

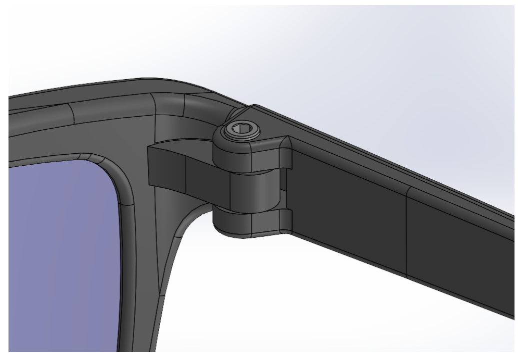

Figure 7: Model of an integrated three-barrel hinge

Given the existence of three-barrel hinges and humanity's general instincts towards bigger numbers being clearly better there is of course five and seven-barrel hinges. Usually considered a luxury or premium feature on a frame these higher barrel hinges are always metal and usually bolt to the arm and frame rather than being cast inside them. The bolt-in design allows for adjustment or replacement while the higher barrel count produces a theoretically higher strength hinge. Overall barrel counts greater than three can be generally ignored as mostly belonging to more expensive frames, though it is worth noting that the bolt-in hinge plate does allow a five or seven-barrel hinge to be replaced with a three-barrel if needed.

The final component of the hinge that can vary from frame to frame is the bolt size. The bolt serves primarily as a shoulder bolt threaded into the hinge to provide an axis around which to pivot. Unfortunately like many things, the world cannot agree on a single standard while almost all eyeware uses metric bolts both M1.4 and M1.6 bolts are equally common. The reason for this distinction seems largely pointless as the slightly larger bolt does very little to increase mechanical strength and the savings in hinge size using the smaller bolt is negligible. Regardless of the reason, this does mean that any design that wishes to connect to the hinge of a frame likely will require two slightly different models, one for the M1.4 bolt and another for M1.6.

6.4 Brainstorming

Once we had established the design goals and set reasonable constraints we next set out to brainstorm desirable features and leading from that identify potential designs of which we picked three to move forward with. The process of brainstorming itself was made a little more difficult as participating in a complete 'abstract requirements to whiteboard product sketches' brainstorming session was a new experience for all but one of the group members. Fortunately, the group's lack of experience with brainstorming was able to be turned to our advantage as some of the features or designs that would otherwise be dismissed and left unspoken by a room full of just mechanical engineers instead were brought up and through discussing their new ideas were generated that otherwise may never have been considered.

We begun the brainstorming process not by proposing designs but instead by proposing features, the purpose of this exercise was not only to identify potentially useful features but to challenge and hopefully dismiss any pre existing images of what the final product may look like. Some of the features generated we wanted to include on a first prototype eg: 'arms that can be bent into any shape', or 'device installation via swapping a set of arms'. Other proposed features were of value but not necessary on initial prototypes 'interchangeable 3d printed outer shells to allow for customization of the devices look' or 'quick swap method for the device between multiple frames: eyeglasses, sunglasses, safety glasses' these features were definitely achievable and would likely enhance any design that could incorporate them but ultimately would be foolish to invest the effort to implement into prototypes that may very well never work for more fundamental reasons. The final category into which we sorted feature ideas were the moonshots, features that would be phenomenal additions if possible but were to our best judgment impossible, impractical, or simply beyond our skill to implement. The moonshots category did end up quite full with ideas such as '3d scanning a persons head to produce glasses that perfectly fit', or 'glasses that can identify their own preasure points and evaluate the force applied' an example respectively of an idea that requires another handful of years of technological development to be possible, and an idea that would provide a benefit that would be minuscule compared to the effort to implement it. The process of generating these ideas and then sorting them based on desirability and feasibility helped us begin to imagine potential designs.

The second portion of the brainstorming session was dedicated to proposing and debating the merits of potential designs. Designs were discussed in the context of a collection of features from the 'need' and 'want' categories that seemed complimentary and then opened up to the group regarding potential designs that would implement those selected features. Unlike the earlier feature focused brainstorming session this time constructive criticism was allowed so long as an idea wasn't dismissed outright. Through the process of debating designs and comparison of current favorites with new proposals the fairly large number of designs were reduced or combined into a half dozen that were all considered possible. To pick three concepts to pursue from the potential designs we finally settled on a set of designs that each optimized for a different potentially significant metric, and assigned those three to individuals depending on interest.

6.5 Design 1: Zygomatic Pod

Despite sounding like a device with which Superman could be trapped by Lex Luthor the zygomatic side pod was selected as a potential prototype for its high compatibility with a large range of eyeglasses without needing serious modifications such as replacing the arms. Given the requirement that the arms of the glasses themselves not be modified the only method available to significantly reduce TMJ pain was to distribute the lateral force of the arms to a different location on the face thus reducing the pressure on the TMJ itself. While numerous options for where to instead have the glasses rest were considered the limiting factor was that any locations where muscles or tendons related to the TMJ had the potential to cause referred pain if the constant low pressure of a pair of eyeglasses were applied. For this prototype, it was decided that it would attempt to dissipate the lateral pressure into the zygomatic arch more commonly referred to as the cheekbone. The location where we intended for the eyeglasses to rest is marked in green in Figure 8

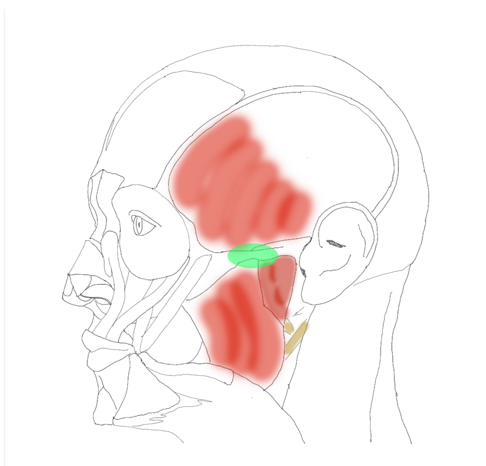

Figure 8: Planned contact location of side pod prototype

The zygomatic arch was selected as the location to attempt to rest a pair of eyeglasses upon due to it being one of the only places on the face where the bone is not covered by significant muscle. While the zygomatic arch does anchor the masseter muscle beneath it the upper portion of the bone has very little direct relation to the TMJ. The theory was that if a significant enough amount of the lateral pressure of the eyeglasses could instead be directed onto the zygomatic arch into the skull itself the fact that the eyeglass arms still passed over the TMJ would not be as significant. The fact that this design theoretically could reduce pressure and pain without modifying the base pair of eyeglasses meant that if it worked it could be applied to the broadest range of glasses without significant modification of the design.

The initial concept for this design was for a slim 3d printed part that is attached to the arm of a pair of glasses and extended down and inwards to rest against the zygomatic arch. Figure 9 contains a diagram indicating the approximate location of the side pod this choice of location was informed by inspecting anatomy diagrams and applying physical pressure to the zygomatic arch in various locations whilst moving the jaw to observe any movement or pain.

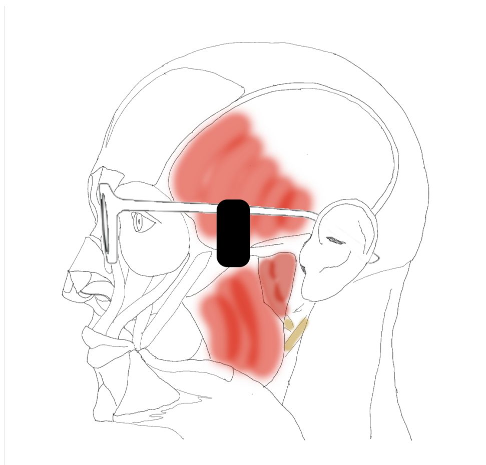

Figure 9: Planned location of side pod

The final significant design decision was for how the assembly would attach to the glasses, ideally the attachment would be solid when in use but allow for easy adjustment when fitting. For this application a slot with a set screw would be ideal; however, the limitations of 3d printing and assumptions about the end users' access to tooling made a set screw non-viable. Instead we settled on a clam shell design; with a close fitting channel such that tightening the clam shell would clamp down on the arm, and loosening it would allow for adjustment without complete disassembly. Figure 10 is a side view of the two printed parts of the clam shell with the rectangular slightly undersized slot visible at the top. To clamp down the clam shell the design uses four flathead #0 plastic tapping screws, plastic tapping screws were used because their thread cutting nature accounts for the inability to print a hole that small and accurate enough to thread conventionally. Incidentally the choice of 0 screws, initially made based on hardware on hand, did violate the requirement that COTS parts must be available from Amazon; however, this could be resolved by simply changing to metric screws of the same size. The final significant feature of the side pod assembly is the point where it contacts the cheek; in order to prevent scraping or otherwise aggravating the skin with the hard edges of the PLA part we instead included a slot into which a length of stickyback foam could be placed to provide a soft contact point. Figure 11 shows the complete side pod assembly with hardware attached to the arm of a pair of glasses.

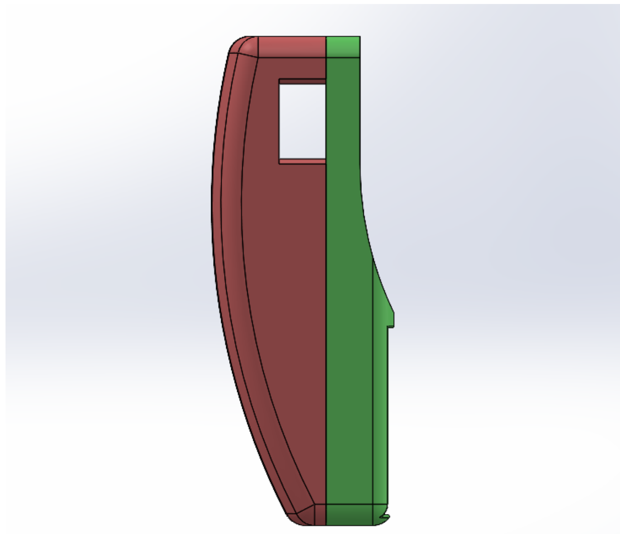

Figure 10: Clamshell assembly of Design 1

Design Challenges

The development of this prototype was not without issues though mostly self induced, when James was making initial observations and tests of the concept he assumed his face represented a representative average. Unfortunately it turned out that his cheekbones were unusually high and prominent, this led to an initial design as seen in Figure 12 which had significantly shorter side pods located about 3/4" further forwards. As a consequence when the various issues with fit and assembly were finally resolved and the prototype was ready to be shared it was discovered that the pod geometry that fit quite tightly for James left the foam pads about an inch above and forward of most peoples cheekbones.

Normally this sort of mistake would be a humorous anecdote and a reminder not to make assumptions without evidence, or at the very least a good reason why testing in progress designs on more than one person is advisable. Unfortunately in this case the initial assumptions regarding the size and location of the side pods led to overlooking a serious flaw in the design. With pods significantly shorter and located further forwards force exerted outwards on the contact pads was directly transmitted into the eyeglasses arms and then into the frame itself bending it slightly as intended. When the design was modified to lengthen the side pods and shift them further back the side pods had become quite significant lever arms. The same force required to spread the pair of glasses applied an inch further back and an inch further from the arm itself didn't spread the glasses open anymore instead it simply produced a bending moment on the plastic arm. If

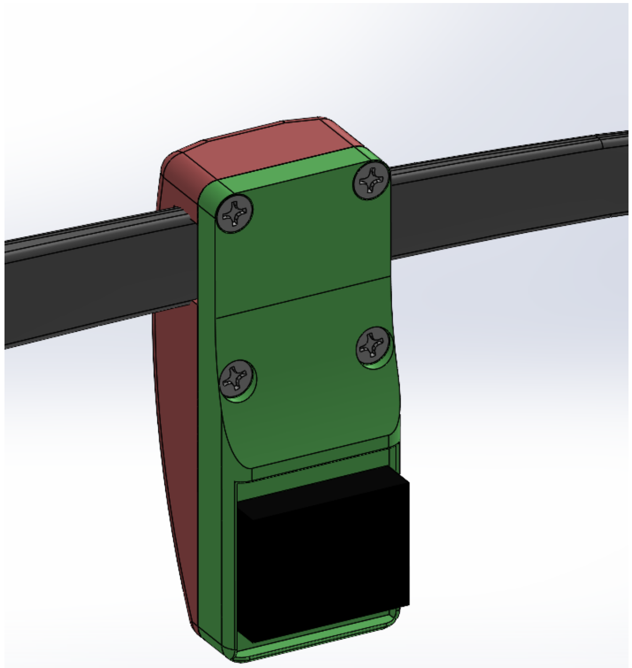

Figure 11: Fully Assembled Side Pod

the time had been taken in the beginning to ascertain a true average location for the side pod then it could have been tested with the same methods that originally confirmed that enough force to spread the frame could be applied through the shorter pods.

User testing indicated that the twisting of the arms would be a serious issue. In direct comparisons Kell Carlisle noted that this design reduced pressure compared to the unmodified control glasses; however, they observed that their normal pair of sprung hinge glasses still felt significantly gentler. Additional observations noted that the foam chosen for the contact points was scratchy and irritating during extended use.

Design Continuation

While the side pod as a simple to install frame independent solution did not achieve all its intended goals it may merit future study. The principle of reducing the lateral pressure of a pair of eyeglasses by dispersing some of the force against the zygomatic arch seems to work. The side pod design can and should work for people with high cheekbones even if it is not a universal solution. If work is continued on this design it will require some changes. The clamshell attachment is far from a universal solution; its dimensions would likely need to be modified for each frame it is intended to attach onto. In addition, the process of tightening and loosening the self-threading screws caused notable stripping of threads. Making an adjustable universal connection may be too ambitious; relaxing the requirements against gluing or otherwise modifying

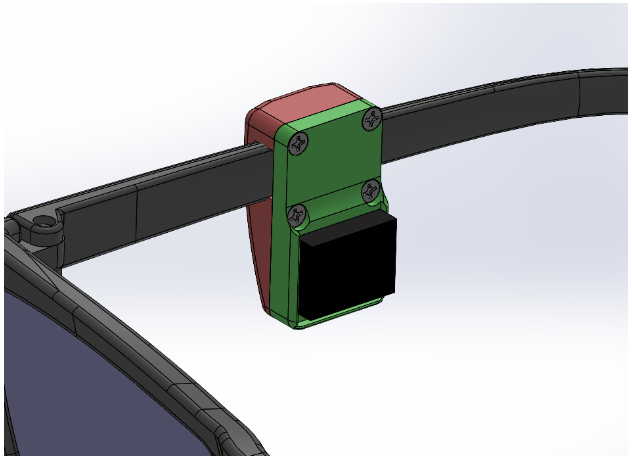

Figure 12: Initial much shorter side pod assembly

the arms of a frame may be necessary. Affixing a stud to the arm via glue would provide a solid point for a side-pod to connect to; alternatively directly gluing or screwing side-pods once correctly positioned would see a significant increase in rigidity. The issue of the foam pads being abrasive is by comparison much easier to address. Softer materials such as felt are available; however, given sweat and other factors a non-absorbant material might be more useful. Materials such as Sugru, a moldable fast-setting silicone rubber, are worth considering.

The concept of distributing pressure onto the zygomatic arch is not limited to side-pods alone. A design worth considering is a solid arm that mimics a conventional hook-over-ear shape while reaching down to rest against the zygomatic. The only immediate concern this design raises is over concealability, unlike other designs that are concealed in part by hair anything that interacts with the cheekbone will be fully visible. The side-pods as fairly small neat capsules while certainly not invisible managed to blend in by looking inconsequential, if the arm of the glasses instead becomes a large triangular gusset on top of impacting peripheral vision it would be significantly more visible at a distance.

6.6 Design 2: Customizable Wireframe Arm

If the first design was chosen to optimize for compatibility the second prototype was chosen to maximize customizability. The principal is that the independent uncontrollable factors are too varied for any fixed design or set of designs to adequately serve a significant portion of customers. Individuals differing experiences of TMD can mean a pair of glasses that are perfectly comfortable for one person can be agonizingly painful for another, likewise, any attempt in the design to account for more complex factors such as curvature of the head may work for some users but is equally likely to make the device unusable to others. An option for addressing this type of issue would be the production of a matrix of different mesh files corresponding to different measurements and relying on the user to correctly identify the size and or shape of the device that would fit them. While that may be possible the added complexity would likely put this device out of reach of a portion of our intended customer base. The principle behind the wire arm is that if it is impossible to meet the user's exact needs through design the alternative is to enable the end user to customize the product to the extent that they can find the version that fits them exactly.

To achieve this level of customization it was decided that instead of a rigid PLA or soft TPU body for the arm replacement the arms of the eyeglasses would instead be constructed of a single piece of 10 gauge galvanized steel wire. The concept was that the galvanized wires' high plasticity allows it to be bent into virtually any shape and thus achieve a truly custom fit. The initial design called for a printed PLA hinge with a hole for the insertion of a length of wire and on the other end of the length of wire a flexible TPU pad intended to distribute any pressure as seen in Figure 13.

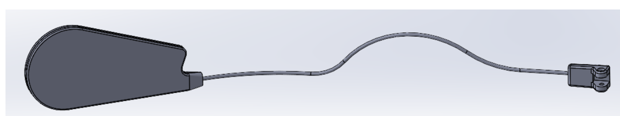

Figure 13: Initial design of the wire arm prototype

This initial design had some quite notable flaws. First, the TPU pad in addition to the difficulty of getting smooth TPU prints; a TPU clamshell design had difficulties remaining attached.. Lamination of both internal layers and the superglue joint was not uncommon, and the TPU pad itself did not serve as the force distributor we had imagined, instead it just produced a few pressure points on its surface where it rested against the curvature of the head. Ultimately the use of a TPU pad to cap the wire arm was a case of excessive designing without considering the existing solutions; if the primary goal was to distribute force and contain any sharp edges, there already exists a solution used for actual eyeglasses. Silicon eyeglass tips can be purchased from Amazon for a very cheap price. The silicone tips are intended to slide over the ends of eyeglasses to cover up sharp edges; these would serve the same purpose as the TPU pad whilst significantly reducing complexity.

The other major issue encountered when working on this prototyping is rather unsurprisingly the only other part in the assembly that isn't simply a length of steel wire. The geometry and manufacture of the hinge pieces intended to attach to a standard 3-barrel hinge presented a rather significant challenge. The first significant issue was in setting the position of the hinge, referring to Figure 14 the quantity marked as 'x' set how far inside the hinge sits this value is quite consistent between glasses and small errors have minimal effect. The more troubling value to determine is the distance marked as 'y', small changes as little as .010” can have significant effects on the angle the hinge is capable of opening too. However, by printing multiple iterations of the part with slightly different y values we were able to determine the side that fit exactly with the glasses we were using for prototyping.

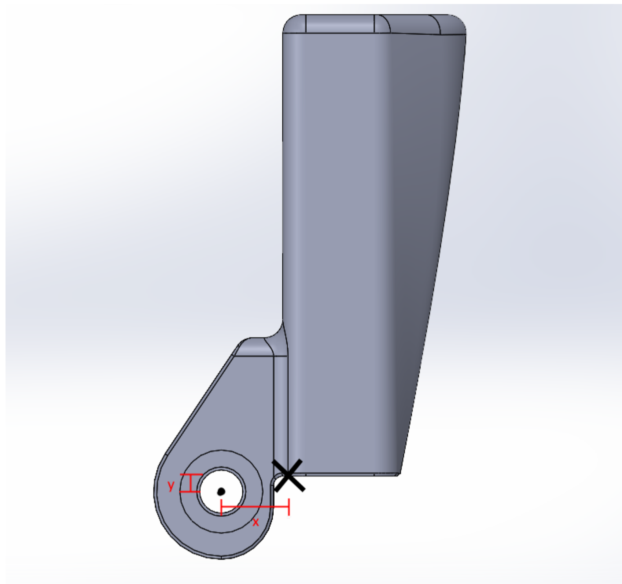

Figure 14: Hinge piece design showing hinge location criterion

The next issue with the 3D printed hinge was with the strength of the printed hinge and its propensity to shatter when dropped or otherwise stressed. The immediate solution to this issue was quite simple, increasing the thickness of the barrels till the hinge was the full height of the arm made the part significantly stronger. It is worth noting, however, that this brittleness issue is rather unavoidable when working in PLA at this size; if we were to consider expanding the manufacturing methods to include resin printing this is an ideal part to benefit from that technique.

The final issue regarding the hinges was not a direct issue of geometry but instead a misunderstanding of how the wire arms should grip the head. After determining the correct hinge geometry we printed and assembled a complete set of arms for evaluation. This assembly had the hinges exactly matching the geometry of the frame much like a simple hinge frame, this meant that the wire arms whilst mostly unbent were too tight to properly fit around a wearer’s head. Unlike a normal set of eyeglasses attempts to stretch the wire frame arms around a head simply resulted in them bending and dog legging outwards. The cost of an arm that is as easily customizable as the galvanized wire is that it has virtually no stiffness. Depending on the point of view this deficiency is actually a benefit of the design, it is impossible for the wireframe arms to exert any significant force on a wearer’s head and thus less likely to aggravate a TMJ disorder. However, despite this convenient property, the glasses we had in hand were still uncomfortable because the wire arm's natural position is simply too tight. To resolve this we printed another set of hinges where the hinge's location was brought further forwards than a perfect fit; a movement of 0.020" increased the range of motion of the hinge from 90deg to approximately 105deg. This meant that the wire arm glasses were able to over-open much like a sprung hinge frame; except unlike a sprung hinge, there was no force pressing the arms back in at maximum extension.

This unique setup without any capability for lateral force meant significant changes in how a set of wire arm glasses had to fit. First how they were put on, unlike most pairs of glasses where they are stretched open simultaneously by two hands, or put on by stretching left to right or vice versa with one hand, instead the wire arm glasses had to be lifted vertically up over the cranium as this was the only way in which removing or putting them on wouldn't significantly bend the arms. Due to the complete lack of lateral pressure the wire arm glasses instead have to remain in place by curling round to the back of the head to prevent the lenses slipping forwards. Much like a pair of hingeless frames, this does put increased pressure on the nose bridge to keep the lenses aligned.

Design Continuation

The wire arm glasses certainly hold some potential for future iterations, however, they do have some areas of concern. Primarily they are unreasonably fragile, even discounting damage to hinges or printed parts the glasses fit is also very sensitive to nudging or pulling against the wire arms. This fragility is only accentuated by the fact that wire arms are significantly longer than normal eyeglass arms, this means that not only are they less protected when folded they also don't fit in traditional glasses cases or bags. While seemingly only a minor inconvenience the design's oversized form seems like it would lead to other frustrations if an attempt was made to use a wire arm daily. Some of the fragility could be addressed by increasing the gauge of the wire; initially, 20G steel galvanized wire was selected to be certain of easy customizability. Given some experimentation wire sizes up to 16G may be worth considering for their increased resistance to unintended bending. A version of this design using resin-printed hinges and thicker wire may not be small enough, or durable enough for regular wear; however, it might present a viable option as a set of 'relief' glasses. If only worn at home or at the end of the day, much in the same way wearing traditional eyeglasses is recommended for those using contacts, a pair of glasses with wire arms would help relieve pressure without compromising vision.

Ultimately the strength of this design is providing customizability; when treating a disability individual experience matters. By attempting to design a universal solution an engineer inevitably marginalizes the portion of the community for which one size does not fit all. Customizability is a key tool to giving back agency; the act of finding a solution that is 'just right' is something that is all too often denied in conventional medical treatment.

6.7 Design 3: Solid Inverted Arm

The third prototype was selected to optimize the simplicity of assembly, as such the design was envisioned as a direct replacement for a typical eyeglass arm only one that is designed to avoid pressing on the TMJ entirely.

The original inspiration for this design came from the observation by several group members of the habit to tilt up a pair of eyeglasses as seen in Figure 15 to relieve temple headaches or other pain caused by longer periods of glasses usage. Testing this method we found that the lateral pressure of the glasses was redirected to the area marked in green. Because tilting a pair of glasses like that is not much use unless you are looking to inspect the ground it wasn't a permanent solution but it seemed worth further investigation. A simple experiment was devised, by swapping the arms of a normal set of glasses such that they pointed up rather than down as seen in Figure 16 it was possible for Kell to evaluate wearing a pair of glasses that rested on the area of interest above and behind the ear. The evaluation was mostly positive regarding pain reduction however there were some issues keeping the glasses in place.

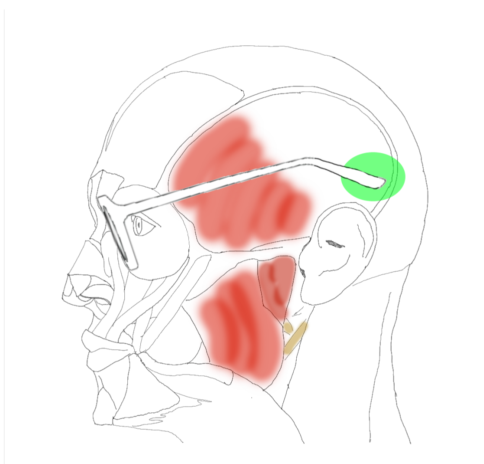

Figure 15: Glasses tilted on face to relieve temporal headache

The third prototype is one most resembling a typical eyeglasses arm. The piece is meant to replace the arm on the side or sides where the user experiences TMJ pain. The design is made up of a long stiff arm, which instead of curving downwards, curves upward into a plate with a high surface area. This item will be made of a stiff material for durability, and for the piece to remain in place. The intention of this design is to redistribute pressure from the glasses on soft tissue to the skull, reducing pain. For assembly, the user will have to remove the arm of their glasses and attach this one. It must be noted that the joint may not fit

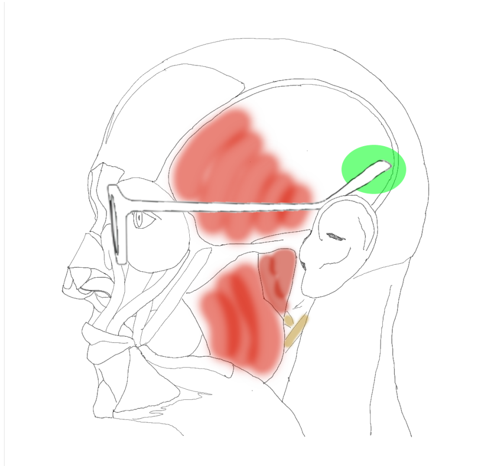

Figure 16: Glasses with inverted arms used to test design potential

every pair of eyeglasses.

As a design intended to replace the eyeglass arm itself this prototype struggled with hinge layout in a very similar manner to the wire arm design. While the work relating to the correct hinge geometry and strengthening of the hinge itself was shared this design is notably different from the wire arms in that it relies on the spring force of the eyeglass frame. This means that instead of moving the hinge location further down to enable over opening of the arms this prototype instead needed the hinge location precisely located to align printed arm and plastic frame.

While designing this prototype, it was noted that the design could be customized in several ways. The most significant is curvature. The design is linear and does not conform to the head. Curvature would improve quality as the device would be more accurate to the shape of a standard glasses arm. Curvature could be added along the length of the device, to where the device rests on the ear, and to the plate that rests on the head. The challenges of matching the curvature of the arm closely to relatively variable head shape is significant, especially because typical plastic glasses arms the PLA print cannot be manually bent to account for individual fit and preference. It may be worth considering a fairly high stiffness TPU for this part as it would be more adaptive to curvature, however the size and visibility of the design means that TPU's tendency to produce ugly surface finishes would be on full display. In addition there exists a further line of development examining the affect of changing the size, shape, and location of the plate.

Due to the constraints of time we were unable to produce a physical prototype of this design, nor iterate upon it to evaluate its viability. It is regretable to have missed this opertunity as there seemed to be potential in redistributing the preassure of glasses onto the parietal portion of the skull. In evaluating the potential of this design it may be worth examining the growing trend in armless sunglasses. These glasses do away with arms all together in favor of a length of cord that wraps around the head. Though armless glasses do nothing to relieve the preasure on the temporal region the tension is atleast distributed to more of the rear of the head. Conversly broader experience and testing may reveal that the rear of the head is not so pain free; while we have two members in our group with TMD neither reported cervicogenic headaches which are known to correspond to TMJ disorders [44].

6.8 Design Retrospective

It would have been nice to stumble into a hitherto unimagined solution to this complex problem, one so simple and elegant that it could be applied universally to great effect; that is unfortunately rarely how engineering works. Motivational posters are fond of quoting Edison as saying "I have not failed. I've just found 10,000 ways that won't work." (the lack of citation can be taken as evidence of this papers authors opinion on Edison actually saying the words) in the case of this project, it may be more accurate to say we found three ways to approach an issue that demands much more work than seven weeks. The work we have done has simply not gone far enough to identify any ideas that simply do not work; however, we have come far enough to recognize some strengths.

Radical customization is a must; any solution must be adaptable to the individual needs of the user. Not only does customization better account for individual experience, but it also empowers the individual to take control of the problem themselves. It is an unfortunate observation that a published design is for the most part unchanging. A design is made, then it is published; often in a format that won't allow or can even support modification or adaptation. Achieving genuine customizability may require rethinking this paradigm. Emerging tools for parametric-driven design may provide an answer. We could attempt to publish 20 different sizes each with 5 different hinge styles, and hope that a user can find one close enough for their circumstances. Instead, a user could input the measurements they need, click calculate, and wait for a model that exactly fits their requirement to be generated. This would take a radical rethink of how we go about defining a design; engineers may need to put down the drafting software and open up an IDE.

During the initial creation of designs, our team focused on additive manufacturing with materials such as PLA and TPU. However, during the design process and meetings we discussed several other materials that could prove to be useful in the design of other TMJ-assisting devices.

The first was the use of fabrics. It was suggested that a stretchable material, such as polyester, could be used to replace the glasses' arms to form a type of headband that would place pressure on the sides and back of the head. This has the advantage of completely avoiding the part of the jaw that aggravates

TMD. This material would require a different skill set to assemble: the end-user would have to know how to work with fabric, in addition they would have to purchase a larger piece of fabric than is needed. However, this is more accessible than 3D printing.

Craft foam was also considered. Like 3D printed materials the foam could be formed into specific shapes, and would hold that shape. Foam has the benefit of greater customizability, however it requires that the person assembling it understands the shape they are creating. This method is also slightly hazardous as it requires cutting the material. This material shares some properties of softness and flexibility with TPU, and could have been used in our wireframe design.

Finally, modeling clay, of the air dry or baking variety were considered to be options. Like craft foam, it can be shaped how the user likes. It shares some of the same challenges of craft foam, where the user has to know the shape and size they need. This material is low cost and requires minimal skills to work with, making it a more accessible material.

In addition to those listed above, there are many materials that could be viable in devices of this sort. Accessibility, both in price and skills needed, is an important factor in choosing materials for this project.

7 TMD as a Disability Study

7.1 Introduction to Critical Disability Studies

Our project seeks to solve an issue that arises out of disabilities specifically TMJ disorders and eyesight problems. So far it has been analyzed from a Business and Engineering perspective; however, it is imperative to look at the humanities that surround this field. Looking at our project as a case study for Disability Studies provides a framework to understand and critique our project. With this end in mind, an understanding of Disability Studies is required.

The emergence of the term Disability Studies occurred in the early 1980s. However, the groundwork for this movement was an ongoing conversation within the disabled community. Notable communities that represented this broader struggle were the blind communities and those with mental disorders. The struggle within these distinct communities was recognized to be a systemic issue that led to a more unified front among the disabled community. The demands for racial equality during this time were an inspiration for the demands of the disabled community.

More recent writings about Disability studies recognize that this is an intersectional field. Goodley writes in Dis/entangling Critical Disability Studies, "Contemporary disability studies occupy and agitate for what Carol Thomas defines in her book Sociologies of Disability and Illness as a transdisciplinary space breaking boundaries between disciplines, deconstructing professional/lay distinctions, and decolonizing traditional medicalized views of disability with socio-cultural conceptions of disablism." [24].

It is impossible to demand disability justice without embracing other fights for equality such as queer and racial struggles. As marginalized groups all struggle in a hetero, cis, abled, white, patriarchal world, alliances must be formed.

The problem we are trying to solve is at the crossroads of two disabilities. Eyeglasses are a solution to eye problems that fail for individuals that have TMJ issues. This is the problem our project seeks to solve. Looking at our project as a disabilities case study provides a unique opportunity to contextually learn about the field. Understanding research and what it means to have agency be explored in order to offer a foundation preceding the case study. These are challenging concepts that exist in disability studies, and to be contextualized with a project is a chance to challenge established engineering and medical methods of work.

7.2 Research

The act of doing research for many may seem like an innocent and logic-based action. For researchers, there are problems, observation, and the scientific method which seem a neutral way of viewing the world. However, the reality is that there is a need to expand on this definition. To understand the role of research in society.

A more complete understanding of research is that it is not only the act of doing science but also that it provides a guide for how to act and change the world. For example, if a researcher concludes that eating fruits and vegetables increases longevity then they eat more fruits and vegetables. Research is used to tell a narrative. However, if the researcher's methodologies and premises are flawed and biased, then the narrative suggested is wrong.

Now extend this to human research and danger starts to arise. Researchers are in a position of immense power and authority and have pressure to justify their view of their world. Historically this led to research that reduces a particular people's humanity.

Phrenology, the pseudo-science study of head shape and intelligence [35], was a 'research-based' means of justifying dominance across so many different people. It is a clear example of the dangers of flawed research that was used to 'prove' racial dominance. In her book Decolonizing Methodologies, Linda Smith expresses resentment at the "ways in which scientific research is implicated in the worst excesses of colonialism" [40]. In the name of research, "someone measured our [Native Peoples] 'faculties' by filling the skulls of our ancestors with millet seeds" [40]. This abuse is what 'research' means for many people in this world. This sentiment is shared not just in native circles but across marginalized groups.

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The result of 'researched and proven' inferior groups results in two notable crimes against humanity: first, a push for the complete erasure of the group, and second a justification for further abuse. Forced sterilization of Disabled, Native American, and African American peoples was normalized in the US [41]. Women were sterilized at a much higher rate which has an aspect of scientific misogyny. Nazi Germany perfected the odious act of eugenics with the final solution, but they also demonstrated the second kind of transgression. Josef Mengle also known as the Angel of Death was a nazi scientist that performed horrific experiments on children in Nazi camps (attempting to make a Siamese twin by sewing Romani twins together and torturing a family of 5 with dwarfism) [9]. An American example is the horrific abuse of African American men during the Tuskegee Experiment in which those with syphilis were not treated for it even after treatment was widely available. This was research, and while contemporary research is no longer as obvious in its transgressions they are still there.

The scientific, medical model of research is inadequate according to many disability studies authors because it only seeks to answer a problem with a solution. It overlooks the experiences of real individuals. Only looking through a medical lens reduces the individual by imposing a narrative that they have a problem that needs to be solved and ignores what the disabled really desire. There is a prescription of a narrative that neglects to actually interrogate the human in front of them.

A particular example is in the propagation of transmedicalism, the belief that being trans requires gender dysphoria. However many trans individuals argue "that trans self-identification is the only practical means by which we can possibly define a gender identity" [25]. Looking at this example through a disability framework, it is obvious that those in power, with the research, prescribe a narrative of the trans experience to trans individuals while ignoring their lived experience.

Yet another example is found in fatphobic narratives that are impressed on individuals. The common issue is that when individuals that visibly carry more body fat visit medical professionals, they get told to lose weight, and the problem that they came to have addressed would fall on the back burner. Again this is a prescription of a narrative by researchers with the 'research' suggesting the narrative. Research requires a multifaceted approach to change the culture so that narrative writing halts.

7.3 Agency

A common issue that arises within disability studies is the complex differences across the entire field. Bailey writes, "How does one compare the drunk-driving-induced paralyses of a white high school quarterback to the job-acquired carpal tunnel of immigrant women assembly line workers?" [8]. A tool that could illuminate a path out of this dilemma is a critical look at what it means to have agency. Agency is largely understood to be the ability to do an action and get what is desired. Notice that there are two components that contribute to this definition: the requirements to act and the end goal of that action. We will start by analyzing what the end goals generally are in a disability framework and then discuss what are the requirements.

Generally acting with agency results in normative end goals. "Wanting financial success, sating respectable (hetero)sexual desires, [. . .] property ownership and self-sufficiency are but some of the strict normative kinds of desires that are expected." However, disability studies (along with several other fields) find issues with this model for desire.

In Key Concerns for Critical Disability Studies [25], there is an emphasis on analyzing disabled desires. It is noticed that there are two common ways in which people act toward their disability: seeking to integrate with abled normative society while also attempting to reject and change society. Obviously, this is an observation that does not speak for every disabled individual; however, a narrative such as this one helps understand disabled desires and serves as a decent understanding of the end goal of agency from a disability perspective, yet the requirements for agency need exploration.

The language used in the definition of agency, the 'ability' and 'capacity' to act, already raises eyebrows for many within the disabled community. Having ability and being abled should not be a requirement for having agency. Ironically, The very concept of agency unintentionally uses exclusionary language. However, this initial incompatibility with disability studies is part of a more significant dilemma.

The definition of agency as the ability to act already estranges many in the disabled community. Being abled should not be a requirement for having agency. The very concept of agency unintentionally uses exclusionary language. However, this initial incompatibility with disability studies is part of a more significant dilemma.

A more holistic view of agency is that the only thing it really requires is privilege within normative, white, abled patriarchy. An example is the 2005 documentary Murderball in which, generally white, men would play wheelchair rugby called murderball [4]. Analysis of the documentary in the light of privilege displays two acts of them enjoying agency. The first is that they got their stories told. In creating a documentary their experiences are celebrated which humanizes them to the viewer. Secondly, playing this game takes a lot of autonomy (agency) over one's life. Not only is it agency over time, but also there is financial agency if an expensive injury occurs. The game itself costs agency and, by extension, privilege to partake in. It is not being denied that this documentary is doing beautiful work by highlighting the experiences of these individuals; however, it is important to note the male and white privilege that these individuals had afforded to them. A revisitation of Bailey's question through the lens of 'privilege' provides practice in recognizing the differences within disability studies. While the paralyzed quarterback is more physically disabled, the immigrant worker woman still lacks agency compared to the quarterback. The quarterback is still in a more powerful position to affect society and enjoy a meaningful, joyful existence. He will likely have access to good healthcare, while the immigrant worker will find it much harder to find healthcare. Moreover, she acquired the disability out of the need to have financial agency in order to survive. Bailey follows up with this initial hypothetical with a more concrete example. Compare "the intentional lead poisoning of the Black children in Flint, Michigan, with congenital disabilities that are the result of chance" [8]. Violation of human rights is not comparable with random chance. Those in Flint were violated because they were in a socioeconomic position in society that was not cared about and viewed as lesser. They lacked the protection that privilege provides. It is not a surprise that there is a "higher prevalence of disability within Black and other communities of color". It is imperative to acknowledge systematic injustices as a part of disability advocacy.

Research as an Act of Agency

Given the two prior discussions of research and agency, a fascinating intersection of ideas occurs. The assertion is that research is an act of agency. The research acts and then uses that action to justify a particular change in the world. The privileged researcher that concludes eugenics is the best course of action is acting with agency and enacting their desires for the future by sterilizing individuals.

7.4 Project Case Study

The use of our project as a case study for disability studies will hopefully offer constructive critiques of the conventional engineering, business, and medical models of conducting projects

In our project, we assume the role of researchers, and with that comes the responsibility of acknowledging our privilege and responsibly conducting research. We are all privileged college students at an expensive institution. We have access to massive databases online and have faculty and staff that are more than willing to help. Access to affordable 3d printing is also at our fingertips. We have the socioeconomic freedom to be able to spend time working on a project like this instead of working two minimum-wage jobs to feed a family of five.

An interesting lens to view this project is that of a disability-led venture. It is a case of individuals who have experienced disability identifying a problem and seeking a solution. Two of our members have written about their experiences which have guided the course of the project and informed the creation of the devices. While design concepts were being brought up, those with TMJ disorders spoke about how the design would probably antagonize or attenuate their pain. This prevents the issue occurs when researchers impose their perception of the problem onto disabled individuals. While this model was prone to bias due to our small group size, it puts agency into the hands of those directly affected by the disability. Those with the disability are listened to because they are at the helm.

A critique of our project is that academic language makes it challenging to reach broader audiences. This is a problem for most academic fields which also makes reading other academic texts challenging. In the quote used earlier, in which Goodley summarizes Critical Disability studies, a goal is put forward of "deconstructing professional/lay distinctions" [24]. This goal can be aided in the reduction of technical language, yet if language is reduced then there is a risk of it not being taken seriously by other academic authors. This issue extends across our entire project and was a concern that was brought up multiple times with a balance being sought out. However, there is no model to follow across academia that establishes a good balance of this common issue.

Another issue that arises out of the language of academia is the term 'edge cases'. The term grew out of software development and is widely adopted throughout various different studies. However, this is a dangerous way of thinking when it comes to humans as it reduces their experience by suggesting that people are outliers that can be prescribed a list of different variables. Had we had group members that had TMJ pain, glasses, and wore a hijab or had curly hair our comfortability with calling these edge cases would absolutely be diminished. An alternative word choice that is grounded in humanities has the potential to reduce this discomfort. The adoption of the language used to talk about marginalized groups provides a more humane approach to human research. Instead of 'edge cases', 'the margins' provides a better tone. However, this change in language does not solve the problem that devices are not capable of serving everyone with their own unique needs.

When designing the devices the importance of their appearance was discussed (see Weighted Objective Table). The perspective of desire that is presented in this paper is one of reintegrating into normative society with the device being hidden. However in conversations it was established that if the device was visible then customization would be important. This mirrors what Goodley writes about desire. For the disabled "being crip remains a 'hip practice' for some and a distanced practice for others" [25]. Customization leads to the device representing the wearer by being visible and proud (hip), while being hidden demonstrates the equally valid desire to avoid being seen as disabled.

In disseminating our device again we encounter the issue of privilege. In our discussion of agency, it was noticed that those furthest at the margins were most likely to struggle to improve their position. This is again an issue with our device. The two main hurdles are access to time and resource investment and access to technology.

While the devices are intended to be easy to implement and affordable, the time and capital investment is not something that can be overlooked. The time commitment to implement this device is multifactorial. There is a need to spend time figuring out what TMJ disorders are, followed by spending time researching solutions, then spending time figuring out how to order the device with a 3d printing company, and finally putting the device together. This is a multi-hour commitment that is not possible for many who are already struggling with childcare and jobs. Moreover, access to spare capital is not available for many, and spending money on emerging 3d printing technology is not an investment that many would be comfortable pursuing.

Furthermore, access to meaningful 3d printing technologies is not easy for a decent segment of the population. Having internet access is an obvious requirement, but access to a device more capable than a smartphone increases the ability to engage with 3d models. In the US, in 2018, "78 percent of households owned a desktop or laptop" with internet access, and "Households relying only on a smartphone were more likely to make twenty five thousand dollars or less, be headed by someone under 35 years old or have a Black or Hispanic householder" [43]. This excludes 22 percent of the US population from being easily able to print let alone across the rest of the world. Notice that marginalized groups and those with a lack of financial resources are less likely to have the capability to navigate this technological hurdle. Again marginalized individuals are less capable of enacting change in their lives; they lack the privilege and, by extension, agency that we enjoy.

7.5 Actions

This discourse highlights the need that more work needs to be done. Exploration of actions that can be taken will hopefully guide future projects. A revisitation of research and agency, along with recommendations for future action in similar projects is thus necessary.

The Sins Invalid Project is a useful resource that is conscious of the need for action and accountability. Sins Invalid "is a disability justice based performance project that incubates and celebrates artists with disabilities." The group has 10 Principles it demands to be adopted by society in order to demand social change that aids disabled individuals [10]. However, they are not restricted to just disability studies but take a much more rounded look at society. It is highly encouraged to read through the very short overview of each of these principles in the article cited as it takes a few minutes and provides much more insight than a list can provide. These principles will be used to recommend future actions.

Our conversation about research highlights the tenuous relationship between research and many marginalized people within the population. Thus, researchers have an obligation to understand the violations of these different communities and understand their dubiousness of research as a whole. An emphasis on cross-cultural studies should be placed in research settings as it is so common for the historical aspect of research to go unread and criticized. This is a direct connection to the principle of Cross-Movement solidarity.

In a similar way, an emphasis should be put on understanding ethical research. The current model for research uses a lot of legalese which forces researchers to act ethically. Two examples of this phenomenon are HIPAA and the WPI IRB. These are bureaucratic ways to ensure ethical compliance, but what is really necessary is the incorporation of ethics as an inalienable part of research. The act of creating studies has historically lacked ethical components which may be a systemic part of the scientific model for research.

The common solution to all of the aforementioned problems is the tentative incorporation of more individuals in research. People with disabilities, people of color, and women have historically been absent in research which is a systemic problem. However, this alone is not enough. It is played out and can lead to tokenism. The principle that most aligns with this issue is the Leadership of Those Most Impacted, where those in power have actual experience with the issues. This also fixes the problem of medical/researchers prescribing a narrative as they themselves are able to freely dictate their narrative given their vantage of the power of their narrative.

Actions that change the existing culture around agency are more important than changing the culture around research. As analyzed before future actions that increase agency can be understood as the end goal of agency and desire but also addressing the issue of privilege.

In regards to desire a “bifurcated analysis” is recommended for disability studies [24]. Goodley means an understanding that there are two common narratives that disabled individuals generally have of wanting to integrate with normative society while rejecting and demanding societal change. Absolutely this is not an absolute narrative but this basic understanding provides a framework for many to understand and actively engage in meaningful social change that benefits the disabled community.

People on the margins of society know what they desire. Empowering them with meaningful systemic change gives them agency over their lives. Again, looking at the principles outlined, it is visible that anti-capitalist policies offer a means of being empowered as capitalism feeds on those on the margins. Moreover, this would require cross-movement solidarity as agency is so often found by being the normative white, able-bodied, straight, male. Efforts to change society to be more inclusive of a more diverse array of individuals is an effective solution.

8 Conclusion

In this project, the team has outlined the problem space for people with TMD pain from wearing glasses and proposed a solution. The team identified a customer segment, created evaluation methods for the designs, and created three prototypes. The team outlined the problem space for people with TMD pain from glasses. A business analysis found the customer segment of people who were online looking for TMD pain solutions and created a metric to evaluate the engineering designs. The prototypes created three models for users to solve their TMD pain. The humanities section then used this design process as an insight into the systems that make this solution necessary.

When the project was initiated the initial intent was to have a device in hand that would be capable of assuaging the pain caused by eyewear on the TMJ. However, as the weeks went by the scope of what our project had sought to achieve grew into focus. The problem space that we had chosen to pursue was incredibly large. The myriad of different glasses, faces, materials, and other variables would make the creation of a device that could serve a decent portion of the target demographic rather challenging. While the three designs did offer insight for potential future designs, none of them alone met all the criteria laid off for them in the business methodology. However, the use of this project as a case study is still relevant.

The exploration of our project as a case study for disability studies was an in-depth critique of our project as a whole. The writing of humanities juxtaposed with the technical writing of engineers challenges existing project norms that stick to one field of inquiry. The business section used consumer analysis to create an alternative marketing method that escaped the unaffordability of the medical industry. The marketing method selected was word-of-mouth distribution through the Internet. The 3D printable files would be put online so the TMD community could share the device. Word-of-mouth advertising could empower the community by increasing agency and escape some of the predatory practices of the medical industry. The need for alternative medical solutions is especially the case for people with two disabilities, corrective vision needs, and TMD, the medical industry is more likely to fail them. When the medical industry fails people go search online for their own solution.

Edge cases were examined with separate goals: maximizing the user base and incorporating the needs of historically excluded minorities. However, throughout the project, the dichotomy of these goals became apparent. To maximize the user base of a product is to prioritize the needs of the many over the minority. Due to the time limitations of the project the group team had to choose only one customer segment. This resulted in this project falling into the pitfalls of neglecting the historically excluded consumer needs outlined in the edge cases.

Through the lens of business analytics, it is clear that the customer segment with the most people is the best; but through a humanistic lens, the target is more cloudy. The best way to help the majority is often to exclude the minority because incorporating a diverse set of needs reduces the precision of the customer segment. However, including diverse needs is how a product includes historically excluded consumer needs. These conflicting priorities were outlined in the humanities section showing that just because a product is more obtainable does not mean it is focusing on the most historically disregarded people's needs.

This project's customer segment differed from the traditional corporate business tactics because it had no goal of profitability. This project's customer segment was people who were not wealthy enough to get proper medical care but had enough resources to treat themselves. People disenfranchised with the medical system search for their own solutions and an affordable place to find solutions is the internet. Word of mouth escapes the need for paid advertising and makes the assistive device more affordable. However, the limitations of this method hurt the effect on the people most in need. The poorest people do not have access to the internet or time to find solutions. The solution for the people with the least resources needed is a functional medical system, not file online.

By using a humanistic lens, the disability study section analyzed the limitations of the business and design approach. The prototypes created by the team are cheaper than formal medical treatment; however, the device would remain unaffordable to many. Additionally, the obtainability of the device is limited because not everyone has a computer or knowledge of how to 3D print a device. A device that is cheaper in a world that systematically discriminates against the disabled community does not fix the root problem; ableism and lack of universal medical care. Cheaper does not mean affordable. More accessible does not mean accessible.

This research gave a comprehensive outline of the problem space of the intersection between TMD pain and glasses use. There is little research on the intersectionality of these medical conditions. Future research can utilize this framework for understanding this condition.

In the design portion future work can be put into perfecting the three prototypes created by the team. The prototypes are not tested and have several major design flaws. For future research completing these designs could create workable solutions for TMD pain from glasses.

The business analysis approach created a unique method for word-of-mouth advertising. The method of targeting using the internet to make 3D printable medical devices could be applied to other historically neglected consumer needs.

References

[1] Moments in disability history – disability social history project.

[2] Timeline - DRILM - university of california, berkeley.

[3] Tuskegee study - timeline - CDC - OS.

[4] Murderball, 2005. Director-Rubin, Henry and Shapiro, Dana.

[5] Alomar, X., Medrano, J., Cabratosa, J., Clavero, J., Lorente, M., Serra, I., Monill, J., and Salvador, A. Anatomy of the temporomandibular joint. *Seminars in Ultrasound, CT and MRI 28*, 3 (Feb 2007), 170–183.

[6] Angel, E. *The Piercing Bible.* Crossing Press, Feb 2011.

[7] Armstrong, K., Ravenell, K. L., McMurphy, S., and Putt, M. Racial/ethnic differences in physician distrust in the united states. *American Journal of Public Health 97*, 7 (Jul 2007), 1283–1289.

[8] Bailey, M., and Mobley, I. A. WORK IN THE INTERSECTIONS: A black feminist disability framework. 19–40.

[9] Barbier, M. K., and Showalter, D. E. *Josef Mengele—"Angel of Death".* Potomac Books, Inc, 2017, p. 69–100.

[10] Berne, P., Morales, A. L., Langstaff, D., and Invalid, S. Ten principles of disability justice. *WSQ: Women's Studies Quarterly 46*, 1-2 (2018), 227–230.

[11] Bordoni, B., and Varacallo, M. *Anatomy, Head and Neck, Temporomandibular Joint.* StatPearls [Internet], 2023.

[12] Campbell, C. D., Loft, G. H., Davis, H., and Hart, D. L. Tmj symptoms and referred pain patterns. *The Journal of Prosthetic Dentistry 47*, 4 (Apr 1982), 430–433.

[13] Carraro, J. J., Quirch, J. S., and Albano, E. Analysis of patients with temporomandibular joint pain. *The Journal of Prosthetic Dentistry 21*, 6 (Jun 1969), 639–644.

[14] Carroll, L. J., Ferrari, R., and Cassidy, J. D. Reduced or painful jaw movement after collision-related injuries. *The Journal of the American Dental Association 138*, 1 (Jan 2007), 86–93.

[15] Cheynet, F., Guyot, L., Richard, O., Layoun, W., and Gola, R. Discomallear and malleo-mandibular ligaments: Anatomical study and clinical applications. *Surgical and Radiologic Anatomy 25*, 2 (Jun 2003), 152–157.

[16] Courtney, H., Lovallo, D., and Clarke, C. Deciding how to decide, Oct 2014.

[17] Crenshaw, K. Mapping the margins: Intersectionality, identity politics, and violence against women of color. 1241–1299.

[18] Dictionary, C. customer segmentation, Apr 2023.

[19] Drake, R. L., Gray, H., Vogl, W., and M., M. A. W. *Gray's anatomy for students.* Elsevier, 2023.

[20] Dutton, M. *The Musculoskeletal System*, 4 ed. McGraw Hill Education, 2017, p. 3–28.

[21] Farrar, W. B. Characteristics of the condylar path in internal derangements of the tmj. *The Journal of Prosthetic Dentistry 39*, 3 (Mar 1978), 319–323.

[22] Friedman, H. Market segmentation, Aug 2014.

[23] Gil-Martínez, A., Paris-Alemany, A., López-de Uralde-Villanueva, I., and La Touche, R. Management of pain in patients with temporomandibular disorder (tmd): challenges and solutions. *Journal of pain research 11* (2018), 571–587.

[24] Goodley, D., Butz, K., and Schlegel, R. Dis/entangling critical disability studies. In *Culture – Theory – Disability*, A. Waldschmidt, H. Berressem, and M. Ingwersen, Eds., Encounters between Disability Studies and Cultural Studies. Transcript Verlag, pp. 81–110.

[25] Goodley, D., Lawthom, R., Liddiard, K., and Runswick-Cole, K. Key concerns for critical disability studies. 27–49.

[26] Gray, H. *Head and Neck*, 41 ed. Arcturus Publishing, 2016, p. 404–708.

[27] Halley, C. Disability studies: Foundations & key concepts.

[28] Hinton, R. J., and Carlson, D. S. Response of the mandibular joint to loss of incisal function in the rat. *Cells Tissues Organs 125*, 3 (1986), 145–151.

[29] Lipton, J., Ship, J., and Larach-Robinson, D. Estimated prevalence and distribution of reported orofacial pain in the united states. *The Journal of the American Dental Association 124*, 10 (Oct 1993), 115–121.

[30] Macfarlane, T. V., Blinkhorn, A. S., Davies, R. M., Kincey, J., and Worthington, H. V. Oro-facial pain in the community: prevalence and associated impact. *Community Dentistry and Oral Epidemiology 30*, 1 (2002), 52–60.

[31] Manfrendini, D., Chiappe, G., and Bosco, M. Research diagnostic criteria for temporomandibular disorders (rdc/tmd) axis i diagnoses in an italian patient population. *Journal of Oral Rehabilitation 33*, 8 (Aug 2006), 551–558.

[32] Milam, S. B. Pathogenesis of degenerative temporomandibular joint arthritides. *Odontology 93*, 1 (Jul 2005), 7–15.

[33] Milam, S. B., Aufdemorte, T. B., Sheridan, P. J., Triplett, R. G., Van Sickels, J. E., and Holt, G. Sexual dimorphism in the distribution of estrogen receptors in the temporomandibular joint complex of the baboon. *Oral Surgery, Oral Medicine, Oral Pathology 64*, 5 (Nov 1987), 527–532.

[34] Nedorost, S. T. *Generalized Dermatitis in Clinical Practice*. Springer Science & Business Media, Jul 2012.

[35] Parssinen, T. M. Popular science and society: The phrenology movement in early victorian britain. *Journal of Social History 8*, 1 (Aug 1974), 1–20.

[36] Richards, P. L. Disability history online. 45–48.

[37] Sable, P. What is an edge case? meaning and overview, Apr 2023.

[38] Salé, H., and Isberg, A. Delayed temporomandibular joint pain and dysfunction induced by whiplash trauma. *The Journal of the American Dental Association 138*, 8 (Aug 2007), 1084–1091.

[39] Schoenen, J. Exteroceptive suppression of temporalis muscle activity in patients with chronic headache and in normal volunteers: Methodology, clinical and pathophysiological relevance. *Headache: The Journal of Head and Face Pain 37*, 12 (Dec 1987), 3–17.

[40] SMITH, L. T. *Decolonizing methodologies: Research and indigenous peoples*. BLOOMSBURY ACADEMIC, 2022.

[41] Stern, A. Forced sterilization policies in the us targeted minorities and those with disabilities – and lasted into the 21st century. *The Conversation* (Aug 2020).

[42] Ueda, J., and 2022. I'm asian, and low bridge glasses changed my life, Sep 2022.

[43] United States Census Bureau. Computer and internet use in the united states: 2018. https://www.census.gov/newsroom/press-releases/2021/computer-internet-use.html, April 2021.

[44] von Piekartz, H., and Lüdtke, K. Effect of treatment of temporomandibular disorders (tmd) in patients with cervicogenic headache: A single-blind, randomized controlled study. *CRANIO® 29*, 1 (Jan 2011), 43–56.

[45] Wadhwa, S., and Kapila, S. Tmj disorders: Future innovations in diagnostics and therapeutics. *Journal of Dental Education 72*, 8 (Aug 2008), 930–947.

[46] WRIGHT, E. F. Referred craniofacial pain patterns in patients with temporomandibular disorder. *The Journal of the American Dental Association 131*, 9 (Nov 2000), 1307–1315.

[47] Yamada, K., Nozawa-Inoue, K., Kawano, Y., Kohno, S., Amizuka, N., Iwanaga, T., and Maeda, T. Expression of estrogen receptor $\alpha(er\alpha)intherattemporomandibularjoint.TheAnatomicalRecord274A,2(Sep2003),934–941.$

[48] Zimmerman, J. *Principles of Imperative Computation.* 2012.

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Figures Reference

[49] Gray, H. *Anatomy of the human body*, 20 ed. Lea amp; Febiger, 1918.

[50] Häggström, M. Anterior view of digastric muscle., Sep 2007.

[51] OpenStax. Muscles that move the lower jaw, May 2016.