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Development and Prototyping of Motion Capture Hand Cluster using 3D Printing

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Motion capture is being used to analyze the pitching motion of Mississippi State's softball pitchers. The motion capture requires that the athletes be covered in clusters of reflective markers for the cameras to track their movement. The current cluster responsible for tracking the pitching hand of a softball player is continually being destroyed as the outer edge of the pitcher's hand and the cluster contact her thigh. A new cluster was designed to only cover a small portion of the back of the hand, which eliminated the risk of breaking the cluster during pitching. The hand cluster was produced using an SLA 3D printer with flexible tough resin that lowered the cost, production time, and weight of the cluster compared to the original. In addition to each of those improvements, the number of pitches before breaking increased by over 1500% from 10.5 pitches to 172.

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CHAPTER I

INTRODUCTION TO PROJECT AND NOTABLE SUBJECTS

1.1 Project Overview

To improve upon any task, knowledge of the activity is needed to know what is already ideal and what needs further development. Picking out minute faults is not easy, but it becomes more difficult when the task being studied is the 1.5 seconds of a collegiate softball pitcher's windup. Trying to perfect the intricacies of a softball pitch requires more than just a set of coach's eyes on the pitcher, which is why Mississippi State University utilizes a motion capture lab to analyze the pitching motion of its softball pitchers. The system relies on clusters of highly reflective balls located on specific parts of the athlete's body to track the three-dimensional (3D) movement of the person, but the current design of the hand clusters can interfere with the natural motion and skew the data. In the standard motion of a softball pitch, the pitching arm collides with the pitcher's thigh to create a more forceful release, but because of the design of the cluster on the pitcher's hand, the cluster also connects with the thigh. The consistent battering from repetitive pitches caused the hand cluster to break after ten to twelve pitches, which halted data collection while a new part was ordered and outfitted. The repeated breakage of the hand cluster called for a new form factor to be created that would mitigate the risk of the cluster colliding with the thigh and breaking. The design and prototyping of a new hand cluster using 3D printing would allow the part to be more durable, accessible, and affordable than the current design.

1.2 Motion Capture

Motion capture has a wide field of use ranging from projects in animation to research studies on biomechanics. Motion capture uses a combination of special cameras and reflective markers to record human movement (Mark, 2022). Reflective markers are fit into clusters which are then placed in designated spots on a person's body to correspond to that body part in the software. The cameras capture the field of view completely around the person, so that the clusters can be tracked in three-dimensional space. A software then interprets this data and plots the motion onto an animation that represents the physical subject. For Mississippi State's motion capture lab there are twelve cameras that surround the person. The cameras are trying to detect four uniquely spaced markers per cluster, which have been predesignated as a specific body part. When properly synced, the software provides real time tracking of the motion of the clusters.

1.3 3D Printing

3D printing is a form of additive manufacturing that converts a computer aided design (CAD) into a physical 3D model by successively building up thin layers of material that are each less than a millimeter thick. In contrast to additive manufacturing, there is subtractive manufacturing where material is removed from a larger block to create the final object. While both types of manufacturing are suitable for prototyping, additive manufacturing is particularly useful for early conceptual modeling because it can quickly produce intricate designs at a cheap cost whereas subtractive would be more ideal for larger batches of simpler shapes ("Additive vs Subtractive", n.d.).

The beneficial qualities of additive manufacturing determined that the new design of the hand cluster would be physically created using a 3D printer, but there are numerous types of 3D printers that utilize different methods to create the model. For this project because of their readily availability, the two competing types of 3D printers would be fused deposition modeling (FDM) and stereolithography (SLA).

FDM printers extrude plastic filament through a hot nozzle onto a bed in thin lines, one layer at a time. Like filling in a coloring book, the nozzle must fill in the lines of the layer by extruding a thin line that covers the entire shape of the layer before moving on to the next layer. SLA printers use a laser to cure resin onto a build plate using photopolymerization, which is a process of using ultraviolet light to create a chain of polymers in a cross-link pattern, converting the liquid resin into a solid ("Photopolymerization", 2021). Once one layer has cured onto the build plate, the plate is peeled from the bottom of the resin holding tank and then lowered back into the tank for the next layer to attach to. Unlike FDM printers, in SLA printers, an entire layer can be cured at once no matter the size of the layer.

Both styles of printers have their intended uses. The resolution of FDM printers depends on the size of the nozzle. The standard 0.2 mm nozzle cannot achieve a perfect connection between each line in a layer, so small gaps can be seen within layers. The same issue can occur between layers making the layer lines obvious instead of a continuous smooth surface. The lacking resolution means that delicate details are not producible, but simpler objects are still feasible. FDM printers also have the slight advantage in material cost because a 1 kg spool of polylactic acid (PLA) filament can be obtained for as cheap as $19.99 versus $25.99 for a kg of standard resin. The cheaper cost and reliance on simplicity makes an FDM printer suitable for quick proof of concept prototypes that do not require smooth surfaces, finer details, or completely solid parts.

Where FDM printers lack in quality, SLA printers excel. The laser responsible for curing the resin makes accurate and precise details that leave a smooth surface on the most complex parts, which can be seen in Figure 1.1. The nature of the cross-linked polymers formed during photopolymerization means that the part will have solid layers and be isotropic. Since the part is isotropic, the orientation that it is constructed in will not affect the strength of the part ("FDM vs SLA", n.d.). Besides the higher cost, the other key drawback to SLA printers is that the resin and its fumes are toxic and must be handled with care. Gloves and a face mask are required to handle the SLA part before it has been washed in 99% isopropyl alcohol to remove excess resin and cured in front of an ultraviolet light. FDM printers should still be used in a ventilated area, but they produce much less odor and their outputs do not require special handling.

Figure 1.1 Surface Quality of FDM and SLA Printers
A figure comparing the surface quality and layer lines of FDM (left) and SLA (right) prints.

Despite the higher cost and health risks, the drastic increase in quality and strength of the parts that come from SLA printers make it the preferred choice for prototyping a hand cluster that is comfortable and can endure strenuous use. For this project, an AnyCubic Photon Mono SLA Printer shown in Figure 1.2 was used to prototype the hand cluster with different iterations using AnyCubic Sensitive Resin and AnyCubic Flexible Tough Resin.

Figure 1.2 AnyCubic Photon Mono

Note. From *Photon Mono*, ANYCUBIC 3D Printing, n.d. (https://www.anycubic.com/collections/anycubic-photon-3d-printers/products/photon-mono-resin-3d-printer?variant=35894750838946).

1.4 Software

To create a CAD model, a 3D modeling software is needed to design the part. AutoDesk Fusion 360 was used to design the hand cluster. The common functions used in creating the hand cluster in Fusion 360 can be found in Table 1.1

Table 1.1 Frequently Used Fusion 360 Functions

Function Name	**Description**
Sketch	Create a two-dimensional geometric outline to serve as the basis of the model
Fit Point Spline	Defines a curve through a series of designated points
Plane Along Path	Creates a construction plane for a sketch along a selected path
Loft	Creates a smooth body that transitions between selected sketch profiles
Thicken	Adds thickness to a 2D surface to turn it into a 3D body
Fillet	Rounds the selected edges of a 3D body
Plane Tangent to Face at Point	Creates a construction plane for a sketch tangent to a surface at a designated point.
Extrude	Like Thicken but can also be used to cut a shape into a body.
Thread	Add internal or external threads to cylindrical shape

Once the 3D model has been created, the cluster can be exported as a 3D mesh, but before it can be used in a 3D printer, it must go through a slicer. The slicer is a software that converts the 3D model into a version that the 3D printer can understand. For SLA slicers, the model is broken down into instructions for each layer, so that the printer knows what areas the laser needs to cure each time. In addition to writing the instructions for the printer, the slicer also allows support structures to be added to the model. Certain overhangs or layers of the model might not align with any previous layers already printed, so supports are necessary to give the new layer something to attach to. The slicer software will also inform the user the number of layers, expected amount of material necessary, time to produce, and estimated cost. Once the model is supported and sliced, it can then be uploaded to a 3D printer. For this project, Chitubox Basic was used to support and slice the hand cluster.

CHAPTER II

DESIGN OF HAND CLUSTER

2.1 Old Design

Similar to how the hand cluster provides knowledge on what is occurring with a softball pitch, it can also provide input into its own design flaws. By analyzing the current design and what causes it to fail, a new design can correct the limitations.

The current design is a black cluster that covers the entire back of the pitcher's hand. The piece is 74 by 68 millimeters with a 14-millimeter height displacement that gently arcs from left to right to match the general contour of the back of the hand. At a thickness of 5 millimeters, the cluster weighs 37 grams. Each corner is rounded off with the two corners closest to the fingers being filleted to a greater degree than those closer to the wrist. The cluster has a Velcro pad on the underside which is attached to a Velcro glove worn by the player. There are also fifteen 4-millimeter holes scattered sporadically throughout the surface of the cluster. On the underside of each hole is a #6-32 nut slightly embedded into the cluster and held in place by the Velcro backing. The nuts are used to secure the reflective markers that are 13 millimeter in-diameter spheres covered in highly reflective tape. The markers screw onto a pin, which is then screwed into the nuts on the cluster. Only four markers are used per cluster, but there are fifteen spaces for markers. Because the hand cluster shape is not unique to just the hand, but identical designs are also used on the arms and feet clusters, variation in the arrangement of the markers is needed for the cameras to identify the correct part. Redundant amounts of holes allow unique combinations to be easily achieved for each cluster. Pictures of the current hand cluster can be found in Figure 2.1.

Figure 2.1 Original Hand Cluster

Although the cluster design works for the arms and feet, the hand cluster continues to break during use. For a right-handed pitcher, the right side of the hand nearest the pinkie purposefully collides with the outside of the thigh to generate more force when releasing the pitch. The issue occurs when the markers attached to the cluster are thrust against the leg, which causes them to act like a lever and pry themselves out of the cluster, shattering the cluster and ruining the datapoint. To alleviate the problem, the new design of the cluster needs to rest predominantly on the left side of the hand to avoid the markers encountering the pitcher's leg. The same problems and solutions arise for a left-handed pitcher, but the focus is shifted to the opposite side of the hand compared to a right-handed pitcher.

2.2 Iteration 1

Prior to designing the new cluster in Fusion 360, the back of the right hand was analyzed to find the proper placement for the new design. The right half of the hand is already removed from contention since that is the source of the original problem. The part cannot interfere with the movement of the hand, so it should not cover any knuckle, finger, or wrist, but there are also extensor tendons that span the entire length of the back of the hand. The tendons' ability to straighten the fingers would not be interfered with, but the movement of the tendons under the cluster could cause discomfort or slight movement in the cluster ("Extensor tendon injuries", 2021). To avoid any interference, there is space between the extensor tendon connected to the index finger and the tendon connected to the thumb as shown in Figure 2.2 where the cluster could rest.

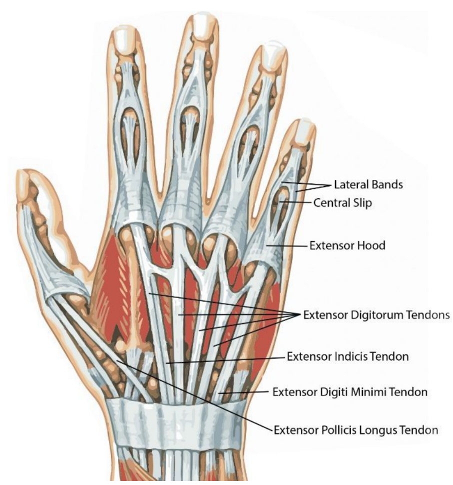

Figure 2.2 Tendons on Back of Hand

Note. From *Extensor tendon injuries,* by Gordon Groh, 2021, (https://www.drgordongroh.com/orthopaedic-injuries-treatment/hand-wrist/extensor-tendon-injuries/).

2.2.1 Modeling Iteration 1

Knowing the general location of where the cluster will go, means that a shape confined to that area can be created. In Fusion 360, a new design was created beginning with a sketch of a 70 mm line that would serve as the spine of the cluster. Using the plane along path tool, five new planes were created along the spine, specifically at either end and 11 mm, 31 mm, and 56 mm from the bottom end of the spine. The specific lengths correspond with inflection points where the outer curve of the cluster will change directions of curvature. Next, an arc was created at each new plane along the spine. Beginning from the bottom, each arc had a length of 26, 36, 28, 18, and 13 mm respectively. The arcs began to decrease in size as they move further away from the wrist and toward the minimal area to the left of the index tendon. Each arc was then connected using the loft function to make a surface that smoothly transitioned from the dimensions of one arc to the next. At this point, the general shape of the cluster was created, but it had no real thickness. To correct this, the thicken tool was used to transform the surface into a 5 mm thick body. The top two corners nearest the index finger were then filleted with a 7 mm radius while the bottom corners were rounded with a 12 mm radius. Mistakenly only three, instead of four, new planes were created on the surface of the cluster using the function, plane tangent to face at point. In each plane, a 4 mm circle was created. Using the extrusion tool, each circle was bored all the way through the cluster, creating three hollow holes. Because of the precision and quality provided by SLA printers, the thread function was able to be used, which incorporated M4x0.7 threads automatically into each hole. The inclusion of threads built into the cluster removed the need to install nuts on the underside of the cluster. To finish the model, the top and bottom edges were filleted with a radius of 2.5 mm to create a smooth edge all around the cluster. The modeling process is pictured in Figure 2.3.

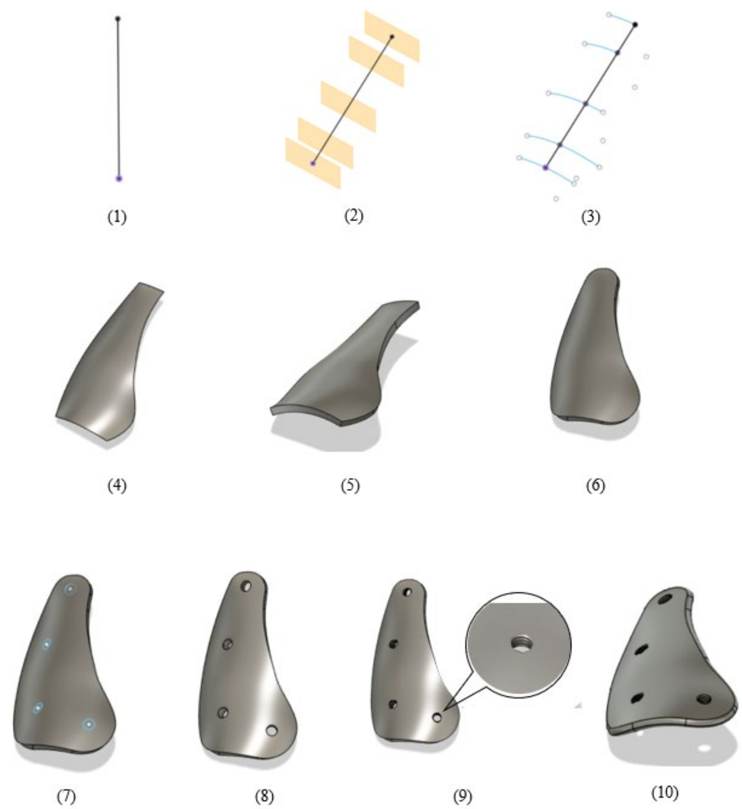

Figure 2.3 Cluster Design Process

Note. Order of design process begins in top left and snakes to bottom right, chronologically.

2.2.2 Printing Iteration 1

After modeling the hand cluster, the 3D model was exported to Chitubox to be supported and sliced. Initially the model rested on the printing bed like how it would rest on the hand of the pitcher as shown in Figure 2.4.

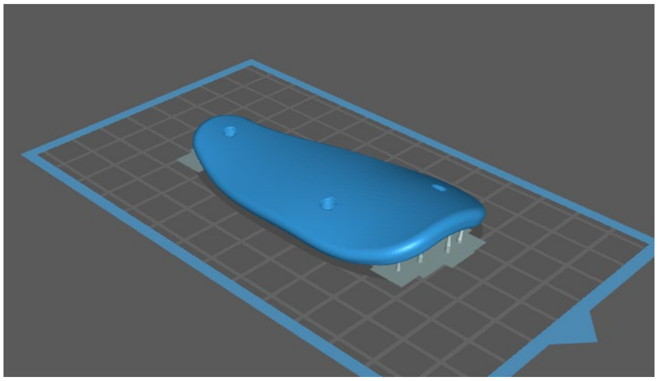

Figure 2.4 Iteration 1 Supported

Ideally, the end points of each arc would be the supports that future layers would be built upon, so additional supports would not be necessary. After filling the AnyCubic Photon Mono with AnyCubic Sensitive Resin, the sliced model began to print. As shown in Figure 2.5, the cluster was not supported well enough, and the part failed to form completely.

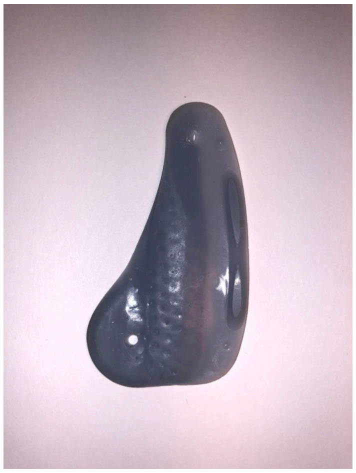

Figure 2.5 Failed Print of Iteration 1

In order to correct the lack of supports, the model was reinserted into the slicer and rotated so that the top of the cluster was face down on the print bed as shown in Figure 2.6. With the arc of the cluster now facing upwards, a larger surface area was now connected to the bed to ensure a strong first layer. Additional supports were added under the overhangs of the arcs on either side to strengthen the model. Reprinting the newly sliced model created the feasible output seen in Figure 2.7 that only had a slight surface flaw where the printer had flattened the top of the arc when trying to create the initial layers.

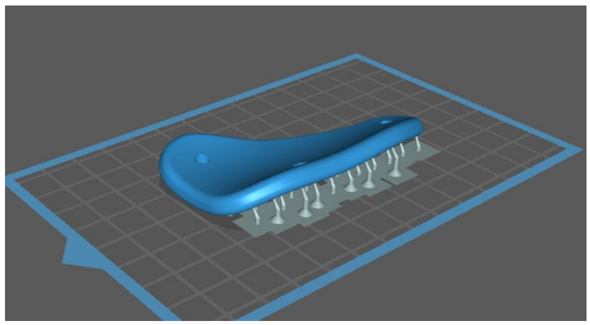

Figure 2.6 Iteration 1 Support Redesign

Figure 2.7 Iteration 1 Print

2.2.3 Iteration 1 Feedback

Although the first iteration of the cluster did not have a perfect print, it was reasonable enough to present to the stakeholder before continuing. Meeting with Coach Josh Johnson provided valuable feedback on the state of the cluster. The 3D printed threads perfectly fit the pin holding the reflective marker. The durability of the resin and quality of the SLA printer created threads resilient enough to secure the pin when inserted but allow for easy removal if necessary. The success of the 3D printed threads meant that attaching nuts to the underside of the cluster would not be necessary. Without the need to embed nuts into the cluster, the next iteration could be reduced in thickness to decrease weight and material usage. Coach Johnson did state that an additional hole was needed for the fourth marker, which had accidently been left out of the model. With two major improvements planned, the next iteration began.

2.3 Iteration 2

Only two modifications were suggested to the first design: reduce the thickness of the cluster and add an additional threaded hole. Making these changes would not be difficult because Fusion 360 has a timeline feature that chronologically tracks each function used and allows the user to return to that step at any point to adjust the settings.

2.3.1 Modeling Iteration 2

Returning to the thicken command on the timeline, the settings were changed from 5 mm to 2.5 mm. The change effectively reduced the weight and material usage in half, but despite the decreased thickness, the rigidity of the resin would not create a cluster that deformed easily. The fourth hole was created by repeating the steps previously done for each hole after the middle hole had been moved closer to the bottom to accommodate space for the new hole.

2.3.2 Printing Iteration 2

To prevent the printing errors that occurred for Iteration 1, the 3D model of Iteration 2 was tilted by 40 degrees as shown in Figure 2.8. Tilting the model does extend the printing time and number of supports required, but it lowers the cross-sectional area of each layer, which reduces the force necessary for the printing surface to peel the cured resin off the screen ("How to Orient Models", 2021). A lesser force means that the print is less likely to warp or fail, and the tilted model reduces the visibility of the layer lines, which makes a smoother surface finish. With the adjustments made to the print settings, the second iteration of the hand cluster successfully printed without any warpage or failures.

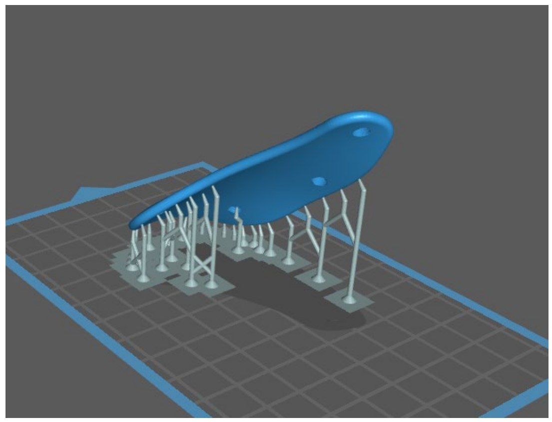

Figure 2.8 Iteration 2 Supported

2.3.3 Iteration 2 Feedback

The latest design of the cluster was once again provided to Coach Johnson to be used by the softball pitchers in practice to test the durability of the cluster. After 172 pitches, the cluster snapped across the second hole from the top, which is shown in Figure 2.9.

The feedback gathered from this failure was that the second hole was too close to the edge of the cluster and created a weak spot in the design. This weak spot was further compounded by the extreme rigidity of the resin, which did not allow the part to flex under any pressure. While the hand cluster is not intended to have pressure from an outside force applied to it, to be functional in a real-world setting, it must be able to endure accidental collisions or drops without being brittle enough to snap. Nothing in the model design would reduce the brittleness of the material, so a new type of resin was needed to improve upon this characteristic. Both the design and material change would be incorporated into the third iteration of the hand cluster.

Figure 2.9 Iteration 2 Failure

2.4. Iteration 3

2.4.1 Iteration 3 Modeling

Only slight changes were made to the physical design of the model for the third iteration. Once again using the timeline feature of Fusion 360, the sketch of the second circle from the top was moved 4 millimeters toward the center of the cluster. Fusion 360 then automatically extruded and threaded the hole in its new proper location. While not appearing to be a substantial movement, the change doubled the distance from the closest side of the hole to the edge. The technical drawing of Iteration 3 can be seen in Figure 2.10.

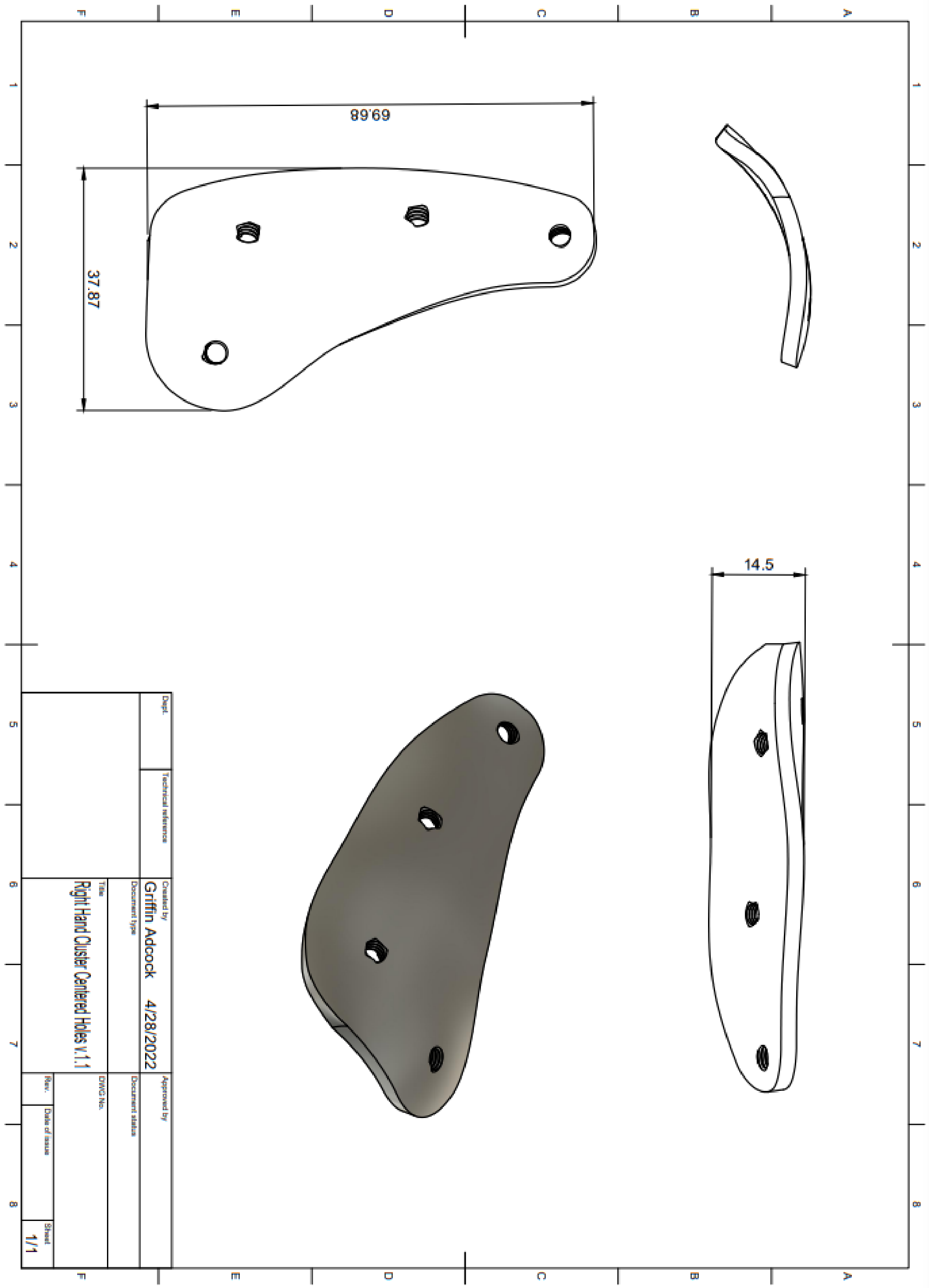

Figure 2.10 Iteration 3 Technical Drawing

2.4.2 Iteration 3 Printing

To reduce the brittle nature of the cluster, a change in material was necessary. Multiple types of resins are commercially available, but currently only a standard resin had been used in prototyping the cluster. While the AnyCubic Sensitive Resin is affordable, it is noted as have little impact resistance and breaking easily. Luckily, AnyCubic offers another resin aptly named AnyCubic Flexible Tough Resin, which is marketed as being able to withstand bending, flexing, and compression, high impacts, and other stresses ("What types of SLA Resin", 2021). Because of the intrinsic compatibility between the resin and the SLA printer since they are both produced by the same company, the AnyCubic Flexible Tough Resin was chosen as the new material for iteration 3.

The Flexible Tough Resin had the same printer settings as the standard resin, so no adjustments were made in the slicer software. The model was still printed at a 40-degree angle with the same supports as iteration 2. The lack of changes in settings reduced the risk of print failure, and the model successfully printed.

2.4.3 Iteration Feedback

The third iteration was once again provided to Coach Josh Johnson for testing with the softball pitchers. The cluster was confirmed to be more flexible than previous iterations, but still sturdy enough to maintain its shape and maintain the proper spacing for the markers to be recognized by the motion capture cameras. The flexibility of the cluster can be seen in Figure 2.11. With over twenty pitches made so far, the third iteration of the cluster has still not broken, so no improvements were made based on feedback from the testing.

Figure 2.11 Flexibility of Iteration 3

CHAPTER III

COMPARISON OF HAND CLUSTER DESIGN ITERATIONS

3.1 Comparison Considerations

The goal of creating a new hand cluster was to produce a design that was more durable, obtainable, and less disruptive of data collection than the current model. To prove the improvements of the new cluster designs, the original cluster and the latest iteration was evaluated on the following criteria: number of pitches, production time, cost, and weight. The original cluster did not pose an issue with data collection in the motion capture system when it was intact, so improvements in that aspect were not considered for the new iterations of the hand cluster; however, each iteration was verified to be detectable and functional within the system.

3.2 Number of Pitches

The need for a new design of the hand cluster originated from the original version not being able to survive enough pitches for extensive data collection. Prior to starting the project, four of the original clusters were broken in only a total 42 pitches, which created an average of 10.5 pitches per cluster.

The second and third iterations of the hand cluster were both tested by pitchers during softball practice to replicate many pitches without having to be in front of the motion capture system. The first iteration was not tested by pitchers since the design was missing a critical hole to make it functional and was almost immediately updated to the next iteration. The second iterations far surpassed the number of pitches than the original cluster with 172 pitches. Iteration

3 is still in testing but has not yet broken at over 20 pitches. Iteration 2 increased the number of pitches thrown before failure by over 1500%. While the third iteration has not had as much testing, the flexible nature of the material should make it far out last even the second iteration.

3.3 Production Times

No matter the design, the cluster is not capable of surviving everything whether it is a stray softball or an unbalanced step that damages the cluster. In unforeseen circumstances, where the cluster is broken, it is vital to be able to replace it quickly so that the data collection can resume. The original cluster was purchased from a company that provided a shipment time of one to two weeks. Disregarding the additional time that would be necessary to follow proper procedures to receive approval for the order or for the company to actually produce the part prior to shipping, one week is still to long to wait when a part is being broken every 10.5 pitches. At that supply rate, only 42 pitches could be accomplished in a month.

Each new iteration has the advantage of being able to be produced in-house in less than three hours with the second and third iterations each only taking 2 hours and 40 minutes to print on the AnyCubic Photon Mono. As long as a printer and resin are available, a new copy of the cluster could be produced in the same afternoon that the other cluster is broken in. The easy manufacturing of the latest iterations through 3D printing makes interruptions to the data collection process a brief respite instead of a dreadful weeklong delay.

3.4 Cost

Producing a cluster in-house entails that a material cost and startup cost must be weighed against the ordering cost of the out-sourced clusters. The motion capture suit used by the softball pitchers is composed of fourteen different clusters placed all over the body. Instead of purchasing individual clusters, the entire suit of parts is ordered as a set for a retail value of $300.

Assuming each part was valued equally, the hand cluster alone would cost \$21.43. This is a stark contrast to the production cost of the in-house iterations. The setup costs for in-house manufacturing would require the purchase of an SLA printer, such as the AnyCubic Photon Mono, which retails for \$239.00, and a compatible resin, like the 1 kg bottle of AnyCubic Flexible Tough Resin for \$49.99. The entire setup cost for in-house iterations of \$289.99 is \$11.01 cheaper than ordering a new set of clusters and includes enough resin to create 169 hand clusters. Once setup costs are covered, each third iteration hand cluster produced via SLA printing would only cost \$0.29, which is a 98.5% decrease in price from the outsourced cluster. While the latest design has already proven more durable than the original cluster, an unexpected failure in the part would be much more palatable when it only costs a quarter and four pennies to replace.

3.5 Weight

While some athletes train with leg weights or even add a weighted ring to their bat during practice, the purpose of motion capture is to collect data that is the most comparable to the real-world event. Additional weight added during the motion capture study detracts from the realism and potentially the accuracy of the data. Minimizing the interference of the hand cluster involves preventing physical collisions as well as reducing the load of the parts on the athlete. The original cluster that covered the entire back of the hand weighed 37 grams. At only 5.9 grams, the third iteration hand cluster was less than a sixth of the original's weight. The smaller and thinner design drastically reduced the weight, but still improved upon the strength of the cluster. Without sacrificing functionality or durability, the lighter cluster would be less intrusive than its heavier original counterpart.

CHAPTER IV

CONCLUSIONS

4.1 Limitations

The major limitation during the project was the availability of the softball pitchers to test the iterations of the hand cluster using the motion capture system. The motion capture system is typically used during the off season and training camps, but this study took place during the regular softball season. Since the entire purpose of the cluster and motion capture system is to improve performance for the games, actual practices and games took priority in scheduling over testing new designs in the lab. Without the software to track the performance measures such as the speed of the pitch, claims regarding the improvement of any measures by switching to the new cluster cannot be verified. Although it is reasonable to assume that lowering the weight of the cluster would allow for a faster pitch resembling the real-world action, it could not be tested due to the lack of availability. To compensate for the lack of testing in the lab, the normal softball practices were used to test the durability of the different iterations of hand cluster. The motion capture lab is not necessary to practice a pitch while wearing a cluster, so the practices proved to be very beneficial in testing how many pitches the cluster could endure.

4.2 Future Applications

Breaking motion capture clusters is not a problem unique to Mississippi State's motion capture lab. The common issue of having clusters shatter during data collection means that a durable design that is also more affordable than the standard cluster is a marketable opportunity.

The unique shape and design of the cluster means that a design patent is capable of being filed, which will be pursued after Mississippi State's invention disclosure is completed in accordance with the regulations regarding university related research projects.

The hand cluster has also been in development alongside a project lead by Coach Johnson to create a motion capture suit that can hold all the necessary clusters within the clothing instead of individually attaching the clusters to the athlete. The new hand cluster was incorporated into the glove of the new suit as can be seen in Figure 4.1. The cluster's inclusion in the new suit means that it has potential to be marketed as an entire replacement to other motion capture suits instead of just replacing only the hand cluster.

Figure 4.1 New Motion Capture Suit with Sewn in Clusters

Note. Hand Cluster can be seen attached to inside of glove on right side of the picture.

4.3 Conclusion

Improving upon the durability of the hand cluster was the primary goal, which was achieved by redesigning the cluster to avoid areas of contact on the hand made during a standard softball pitch. This first design change increased the number of pitches from 10.5 up to 172 before breaking. Further refinements and a change in material to a more flexible and impact resistant resin, allowed the cluster to improve to at least 172 pitches. Not only was the durability of the cluster improved, but by producing the part using an SLA 3D printer, the cluster's price, weight, and production time were drastically lowered compared to the original design. The improvements on every aspect of the hand cluster satisfied the goal of the project.

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