

Design IA

Design Opportunity

References are essential in visual arts, as they provide information on forms, posing, lighting and shadows used to guide a drawing (Chrystal). Although pictures are mostly used as reference, they are limited in variety and restricted by the pose and angle they show. Mannequins are a popular alternative for referencing, as they show a figure from all sides and allows the user to view it in environments and poses that photos don't always provide. Mannequins are also a good learning tool for learners. The main problem is that humans are predominantly depicted. Artists that draw animals have far fewer options and are usually reliant on images and diagrams. The products that partially address this problem, such as ModiBot (modibot.com) and Armature Nine (armaturenine.com) don't provide realistic models that accurately showcase the form and shape of animals and are easily reconfigurable and adjustable. There is a significant lack of adequate models when it comes to depicting archosaurs; the group includes birds, crocodilians and their extinct relatives such as non-avian dinosaurs and pseudosuchians (Britannica). According to a conducted survey, international amateur illustrators aged 15-18 show interest in realistic plastic drawing mannequins and a decent portion depict animals in their works, meaning there is a market opportunity.



Models like the Body Kun figurines have become popular recently.

Figure 1.1
(Body Kun Dolls)

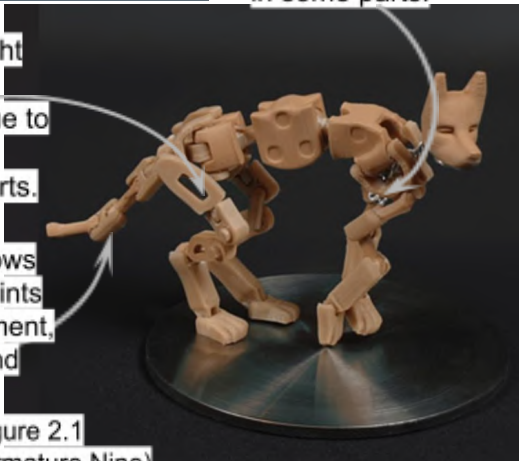
Competitor Analysis

Armature Nine

Regular reconfiguration is tedious due to screws in some parts.

Lightweight yet rigid design due to thin and hollow parts.
Design shows accurate joints and movement, not form and shape.

Figure 2.1
(Armature Nine)



Modibot

Limited use as reference due to simplified parts and joints.

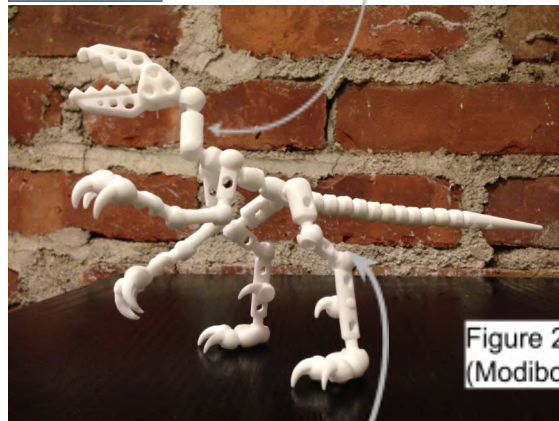


Figure 2.2
(Modibot)

Simple ball joints make for easy assembly and separation.

Beasts of the Mesozoic

Marketed as action figures. Good reference thanks to accuracy.

Modularity is limited, and is only present in specialized sets

Figure 3.1
(Creative Beast Studio)



Figure 3.2
(Creative Beast Studio)



Digital Apps

Some artists use digital programs to make maquettes for flexibility.

Video games like Planet Zoo (Andrew) and Prehistoric Kingdom (Knappe) are used.



Figure 4.1, Figure 4.2 (Wyatts)

Advantages and Disadvantages of Competitors

Armature Nine	Modibot	Beasts of the Mesozoic	Digital Apps (Planet Zoo, Prehistoric Kingdom)
Accurate movement	Limited movement accuracy	Accurate movement	Flexible
Inaccurate shaping	Inaccurate shaping	Detailed texture and shaping	Accessible
Customizable	Customizable	Limited customizability	Time consuming, adjustment can be tedious
Difficult reconfiguration	Easy configuration	Limited to no configuration	Lack of physicality

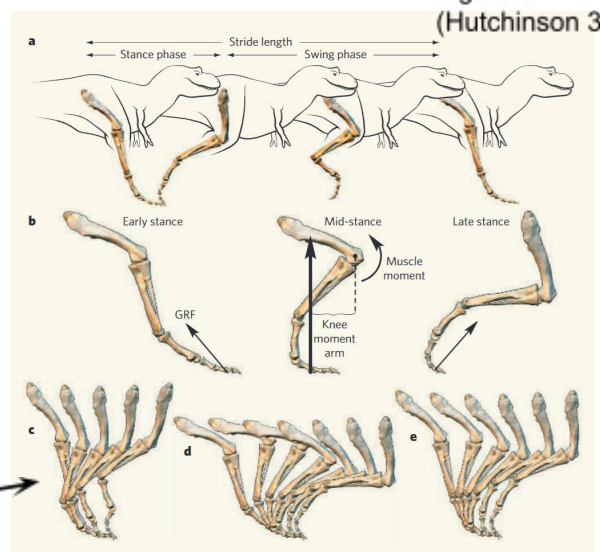
Design Brief

My goal is to produce a to-scale prototype of a modular figurine system for amateur illustrators aged 15-18, where pieces such as limbs and joints are separated and attached as the user sees fit. These pieces would be organized into a **mannequin set**, sold as a collection of parts. Different parts could be organized into a variety of inter-compatible sets. As encompassing all animals would be extremely difficult, this project will focus on creating a mannequin set representing archosaurs. A 3D-printed prototype of a mannequin set for archosaurs will be made. Hypothetical incremental additions to this project would facilitate the creation of other types of animals, such as mammals and arthropods. The model will be highly modular, emphasizing the user's ability to easily disassemble and assemble various models. This would allow users to create their own references for depiction of various animals. The model should reflect accurate form and joint articulation.

Design Constraints and Success Criteria

Mannequins should replicate the locomotion of the depicted animal.

Figure 5.1
(Hutchinson 3)



Stickybones

Posing the mannequin is easy. Mannequin can hold its weight.



Figure 5.2
(Stickybones)

Mannequins use embedded magnets for stability, allowing for more poses.

A poseable rig is used to hold up Stickybones figures.

Magnets are embedded in the palms too.

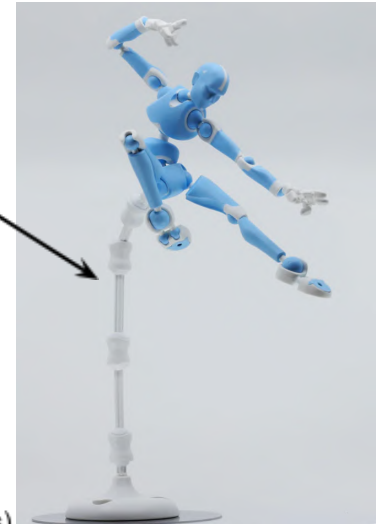


Figure 5.3
(Stickybones)

Should facilitate recreation of archosaur anatomy (basic skeleton and musculature).

Conveys form including musculature and fat, not just the skeleton.

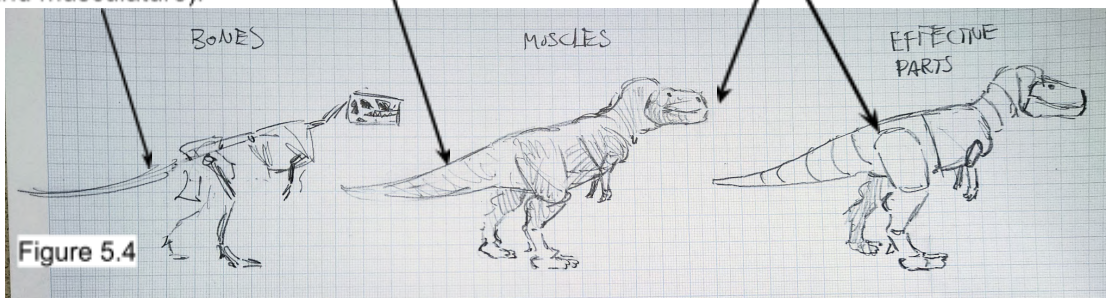


Figure 5.4

Design Specifications

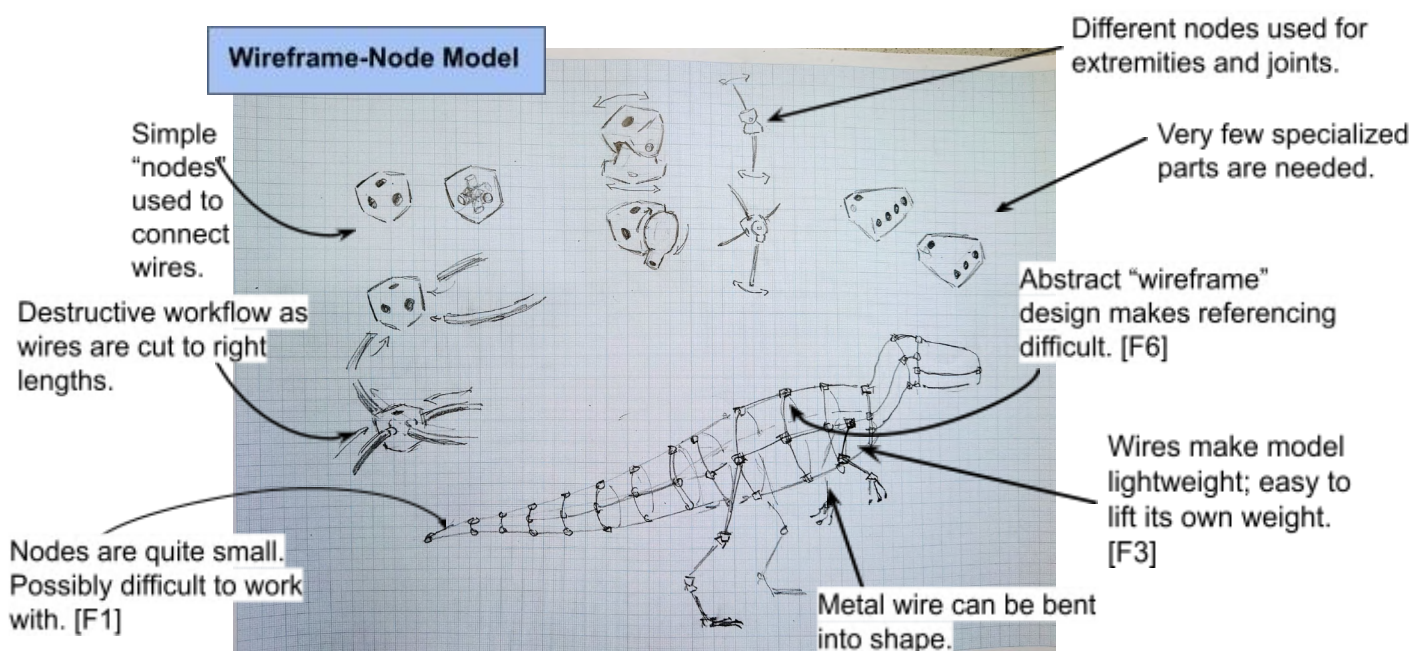
Category and Specification		Justification and Evidence	Testing
Aesthetics		Most other plastic mannequins on the market have these colors (Strike a Pose with the Best Drawing Mannequins for Artists) . Having dull and flat colors allows for easier understanding of the effects of light and shadow on an object as they do not interfere with the color of the shadow or light (Shulke). Being similar to other mannequins makes it easy to understand the purpose of the product.	User trials conducted with prototype models.
A1	Color of the mannequin should be light gray or beige.		
A2	Texture of the model should be matte but not rough.		
Function		One of the ways the product will differentiate itself from competitors is the ability to make varied yet realistic models. It should be easy and fun to rearrange pieces of a mannequin as it happens regularly.	Different joints can be tested in a user trial.
F1	Mannequin should be easy and fun to separate and rearrange.		

F2	Mannequin should be easy to pose and not break easily.	The mannequin's joints should not be too stiff that it becomes difficult to pose. This prevents fatigue or strain when using the mannequin. Also prevents unnecessary force from being applied onto parts as less force is needed to articulate joints.	Different joints can be tested in a user trial.
F3	Mannequin should hold its own weight.	The mannequin will be put into different poses. The joints should be strong enough to hold up the pose for a long duration once it is set in one. This allows the model to be used as reference for the entire period of illustrating.	Can be tested using a prototype.
F4	The mannequin should be posable with the movement range of real animals.	The joints of the mannequin should be able to move within the true movement range of real animal joints. This allows the mannequin to be posed in poses the emulated animal could be in. Movement beyond the range of real animal movement is not an issue.	Can be tested using a high-fidelity prototype.
F5	Joints should not wear easily.	The model will be regularly posed and separated, meaning that it should be designed in a way that the joints do not experience consistent stress which could lead to them wearing down over time, reducing the mannequins function (How to Solve Loose PrintABlok Ball Joints).	Can be tested using a prototype.
F6	Model should accurately show shapes and proportions.	The model should aim to accurately show the shape of an animal when muscles and fat are considered. Accurate shaping means the artist has to do less interpolation on how to draw the subject. It also means light and shadows are shown as intended.	Can be tested using a prototype.
F7	The model should be easy to configure into different forms.	The model should be able to take on numerous different unique forms. Allowing for special accessories will also be important to capture smaller details.	Can be tested in a user trial.
Material Selection		The joints are reliant on friction to stay still. When moving parts, parts of the joint will rub against one another. Pressure will also be applied to the parts to move them. Even the most brittle parts would withstand these forces easily, as they will be applied regularly during use.	Can be tested using a high-fidelity prototype.
M1	Material should withstand regular frictional forces and high pressure.		
M2	The material should be lightweight.		
M3	The material should be weather-resistant.		
Size		As one mannequin is made of many small parts, there is the possibility that parts might be too small to handle comfortably. Small sizes should be avoided as it might make the mannequin difficult to use and observe. Parts are also more fragile at smaller scales.	Variably-sized mock-ups can be tested through user trials.
S1	Model should be large enough to easily handle and observe.		

S2	The model shouldn't take up a lot of space.	The model shouldn't be very large, as then it would be impractical and take up a lot of space. Many artists value practicality in a mannequin as there was little interest in using it as a display piece. The most convenient size is preferred.	Variably-sized mock-ups can be used to collect feedback.
Dimensions		The mannequin should have mostly accurate volume to the real animals it emulates. Due to modularity, it is very difficult to replicate muscles and fine details, so more general shapes will be the aim. The inside can be hollow as long as the outside is close to the actual animal.	Can be tested using mock-ups.
D1	Mannequin should have proportional volume to real animals.		
Quantity		The high-fidelity prototype can be used for specification F4 and user feedback. Additional parts will be used for destructive testing. Mock-ups and low-fidelity models will also be made.	
Q1	One high-fidelity prototype and multiple additional parts will be made.		
Production		Due to the large variance in parts required by a modular system, 3D printing is the best method of production that fits all the material specifications. Injection molding requires a large amount of molds to be made due to the many parts. FDM printing will be used for the prototype due to availability.	
P1	The mannequin will be made using 3D printers.		
Costs		Most products already on the market are sold for prices of around \$50 or less. Having a price over this would give it a market disadvantage. Many of the surveyed students weren't willing to spend lots of money on art supplies. If the price is too high, consumers might settle for a different mannequin or DIY methods, despite the tedium.	
C1	A mannequin set should cost less than \$50.		

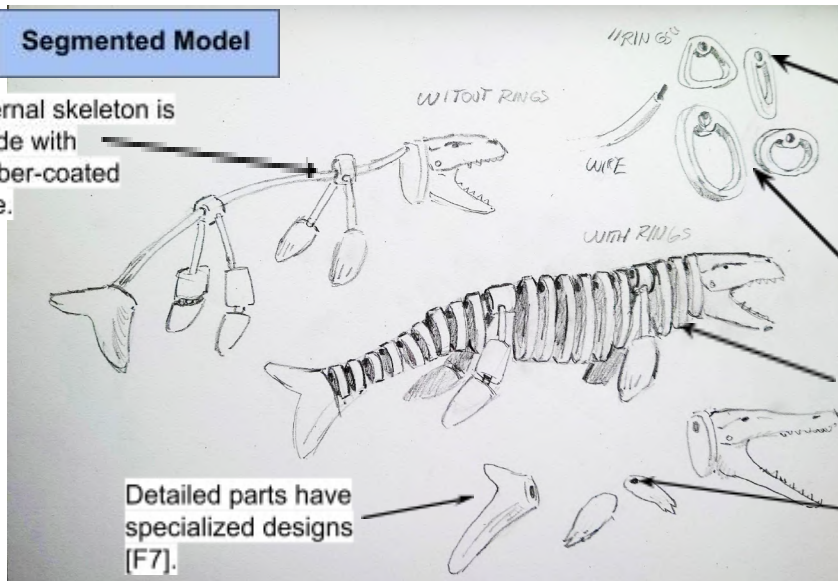
Idea Generation

Note: Arrows in drawings are used to show movement of joints or connection points.



Segmented Model

Internal skeleton is made with rubber-coated wire.



Hollow "rings" ensure model isn't too heavy

Rings come in a variety of shapes and sizes.

Segmented look requires more interpolation when translating to drawing.

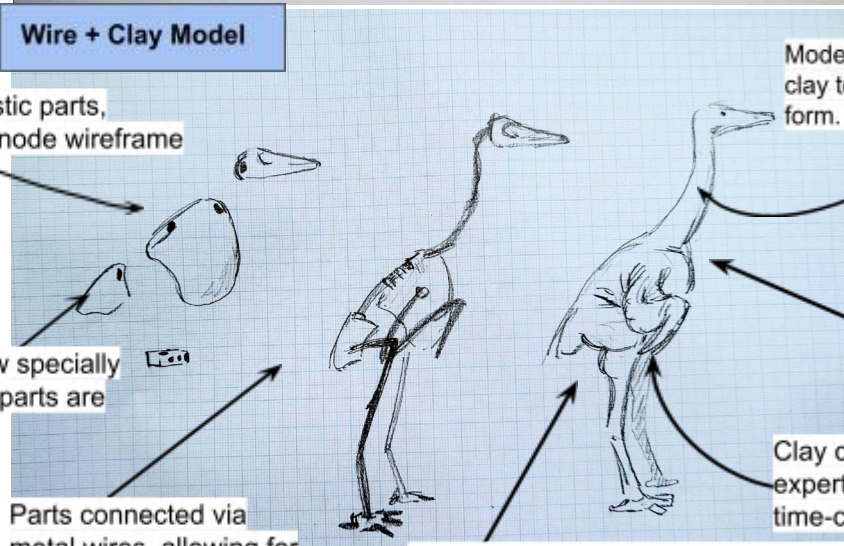
Detailed parts have specialized designs [F7].

Holes allow wire to slot into parts. Rubber wire grips.

Wire + Clay Model

Basic plastic parts, similar to node wireframe mode.

Only a few specially designed parts are required.



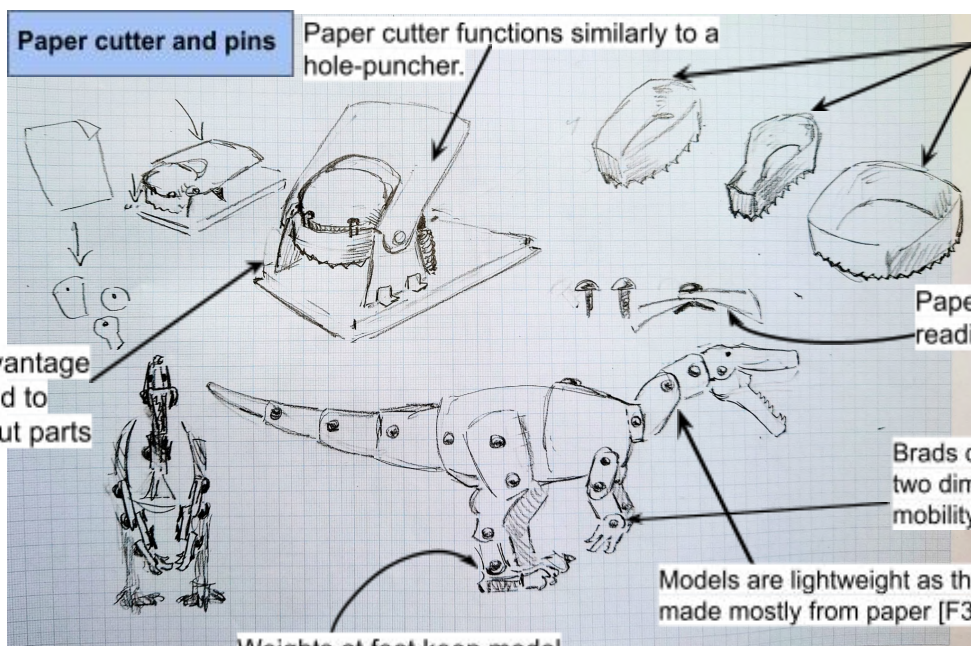
Parts connected via metal wires, allowing for posability [F4].

Clay allows model to be customizable and retain form.

Paper cutter and pins

Paper cutter functions similarly to a hole-puncher.

Different parts can be attached to produce different pieces.



Little advantage compared to cutting out parts oneself.

Paper and brads are readily-available.

Brads can only move on two dimensions, limiting mobility [F4].

Models are lightweight as they are made mostly from paper [F3].

Weights at feet keep model stable.

Blocky Parts

Model is made from simplistic block pieces.

Ball joints used for wider areas of movement. (F4)

Pin joints only move back and forth, not sideways. (F4)

Large pieces may be heavy, depending on chosen material [M2]

Every piece has one or more ball/pin joint attachments.

Skeletal + Shell system

"Bones" form an internal skeleton

Plastic "shells" are attached to the internal skeleton.

Magnets used for certain attachments.

Model is accurate yet very customizable [F6]

Shells might interfere with movement range.

Shells and bones are quite thin, making the model lightweight [M2]

"Bones" are connected to ball joints for an internal skeleton.

The gracile nature of the parts might make the model brittle [M1].

High piece count but many similar and duplicate parts.

Skeletal + paper shell system

Paper shells and accessories means fewer unique parts are needed.

"Clips" can be attached to "bones" and slot in paper.

Thin parts and paper make model lightweight but also frail [M1, M2]

Special parts might be needed for weight-bearing parts, like hips.

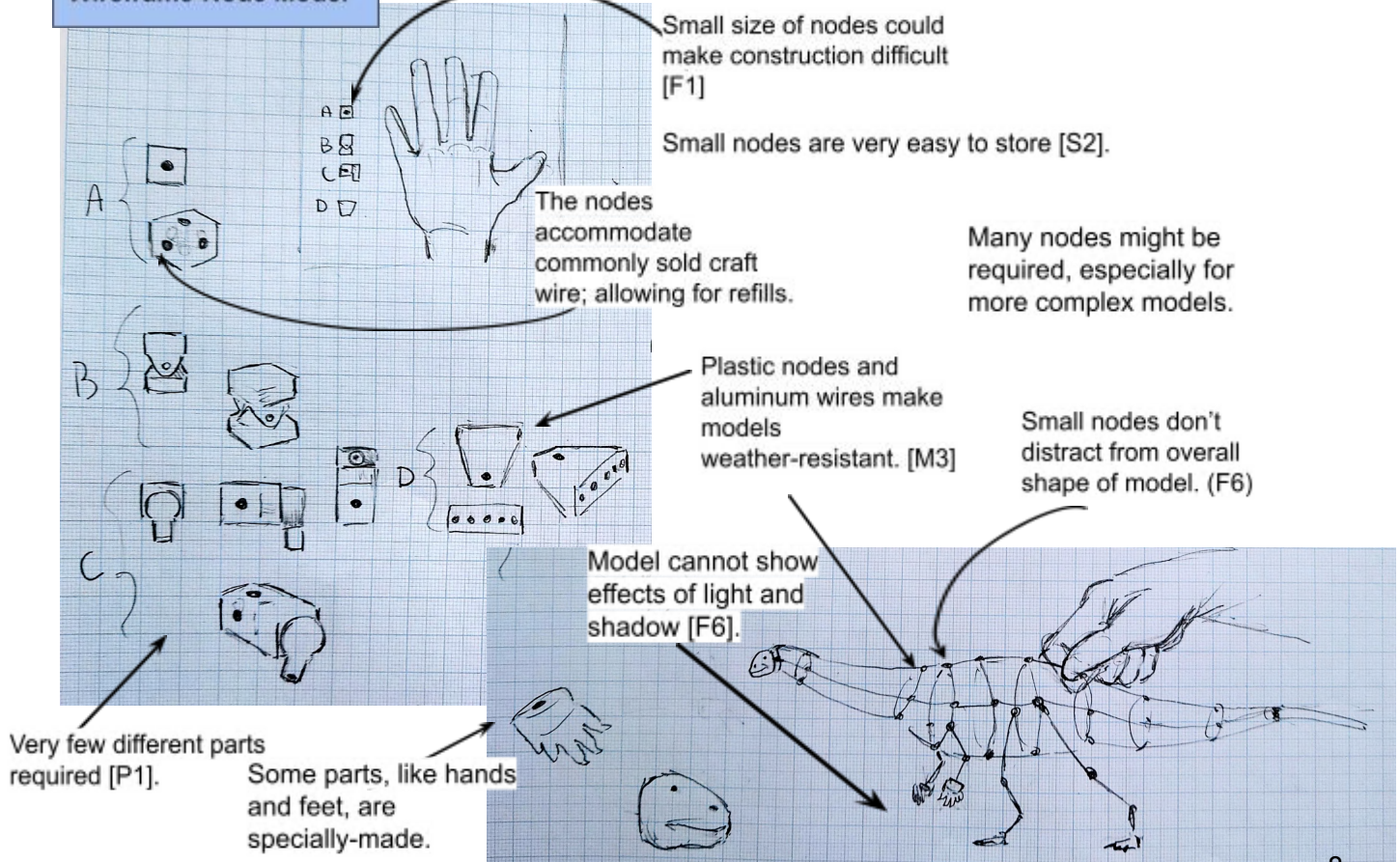
"Hooks" can be attached to "bones" and hook onto paper.

Some unique parts are used for complicated features.

Advantages and Disadvantages of Design Ideas				
Model	[F7]	[F4, F6, D1]	[F1]	[M1, M2, F2]
Wireframe-node model	High customizability	Abstract, does not accurately convey shape	Simple parts, intuitive construction	Durable yet very lightweight
Segmented model	High customizability	Conveys shape, but difficult to understand	Lots of parts can make construction tedious.	Relatively lightweight
Wire + clay model	Very high customizability	Conveys shape	Time-consuming and requires expertise	Not durable, as clay can be deformed
Paper cutter and pins	High customizability	Somewhat accurate form; inaccurate movement	Time-consuming to assemble	Lightweight, Flimsy joints and parts
Blocky parts	Limited customizability	Accurately depicts form	Simple parts, intuitive construction	Pieces might be too heavy if not hollow.
Skeletal + shell system	High customizability	Accurate form, possibly limited movement range.	High piece count makes construction tedious	Thin parts can easily snap or break
Skeletal + paper shell system	Very high customizability	Accurate form, movement not impeded thanks to flexible paper	Time consuming to assemble	Lightweight but somewhat fragile

Idea Development

Wireframe-Node Model



Skeletal + Shell system

Bones need to be made from strong material to anchor shells [M1].

A large variety of different parts, required [P2].

Shells are made from rubber for flexibility.

Joints are separate from bones to reduce wear from separation [F4].

Complicated parts such as heads are specially molded.

Skeletal + Shell system

Some parts left hollow Soft and thin shells can easily detach or break [F2].

Plastic parts make the model weather-resistant [M3].

Model provides good accuracy [F6] but is very complex [F1].

Certain parts can be simplified into basic shapes.

Rubber parts can give the model a naturalistic matte texture [A2].

Lack of transitional parts leads to unnatural jumps or gaps.

Blocky Parts

Made of simple shapes that show generalized form [F6].

Most parts have a somewhat general usage [F6].

Certain parts made for specific animals, such as heads and hands [F6].

Joints wear due to pressure from separation and connection [F5].

Many irregular large parts might be hard to store [S2].

Each model consists of few parts. Construction is simple [F1].

Model is made from hard-plastic; weather-resistant and durable. [M1, M3]

Skeletal + Paper shell system

A variety of complex forms can be created [F6].

Paper parts allow for high customization.

Exposed bones allow attachment points for a rig and accessories [F2]

Internal plastic parts are durable and weather-resistant [M1, M3]

Can accurately depict form and lighting [F6].

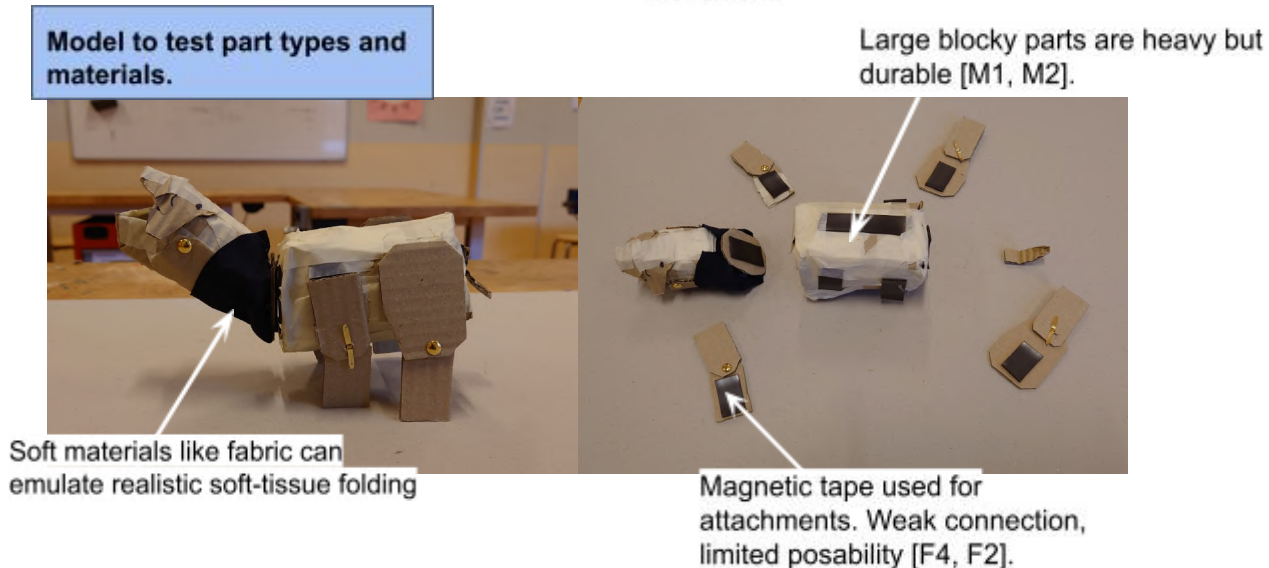
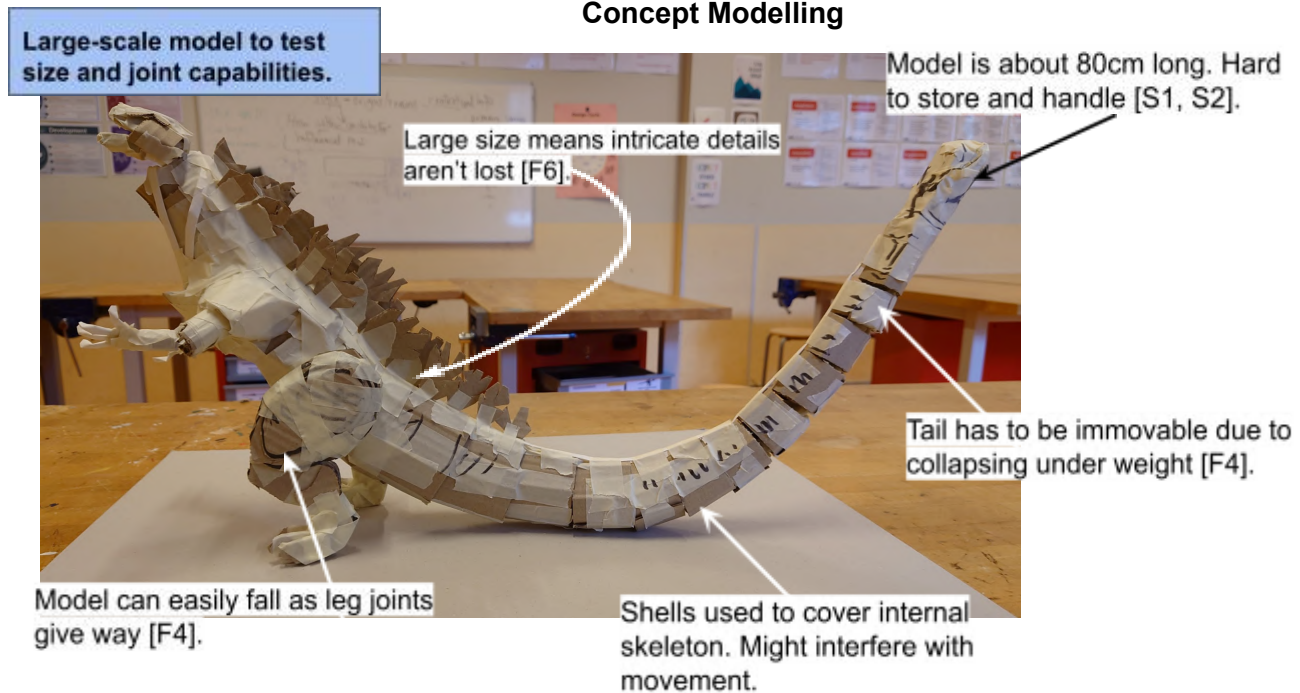
Paper parts are weak but easily replaceable [M1, M3].

Most parts are standardized, with few specialized parts.

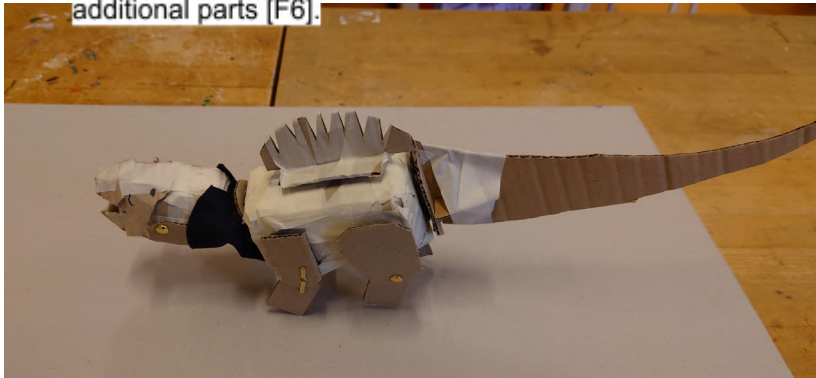
Magnet embedded in foot attaches to metal plate for stability [F4].

Advantages and Disadvantages of Developed Ideas				
Model	[F7]	[F4, F6, D1]	[F1]	[M1, M2, F2]
Wireframe-no de model	High customizability	Abstract does not accurately convey shape	Small parts could be difficult to work with.	Durable yet very lightweight
Blocky parts	Limited customizability	Accurately depicts form	Simple parts, intuitive construction	Pieces might be too heavy if not hollow.
Skeletal + shell system	High customizability	Accurate form, possibly limited movement range.	Numerous parts can make configuration tedious	Thin parts can easily snap or break
Skeletal + paper shell system	Very high customizability	Accurate form, movement not impeded thanks to flexible paper	Cutting out paper and high piece count make construction tedious	Lightweight but somewhat fragile and flimsy

Concept Modelling



Model can be customized with additional parts [F6].



Testing modularity using magnets and seperable joints.

Brads are very weak joints. Struggles to lift lightweight models [F3].

Paper pins are quite weak as joints. Struggled to stand up [F3].

Ball joints needed to accurately replicate movement. Pin joints insufficient [F4].

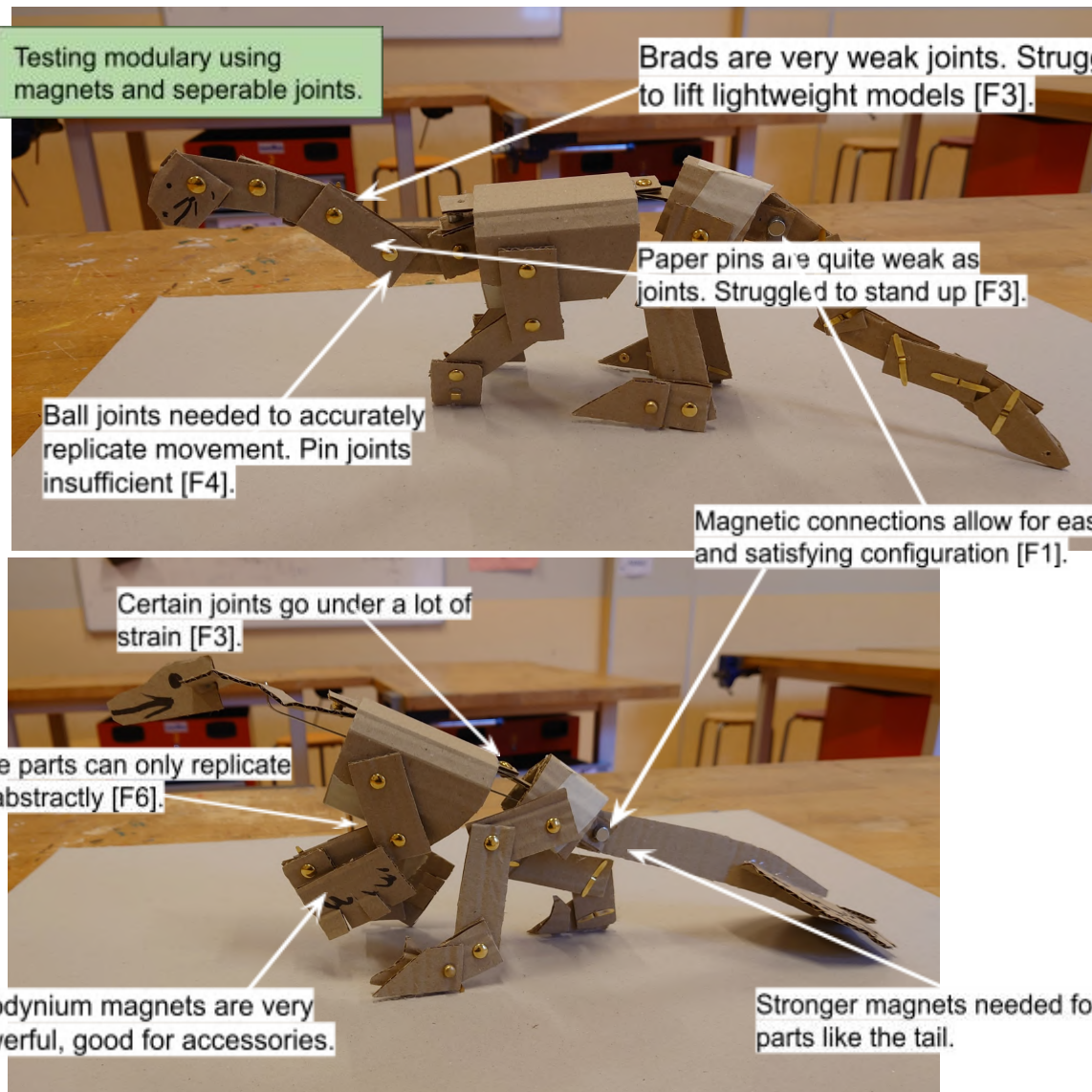
Magnetic connections allow for easy and satisfying configuration [F1].

Certain joints go under a lot of strain [F3].

Simple parts can only replicate form abstractly [F6].

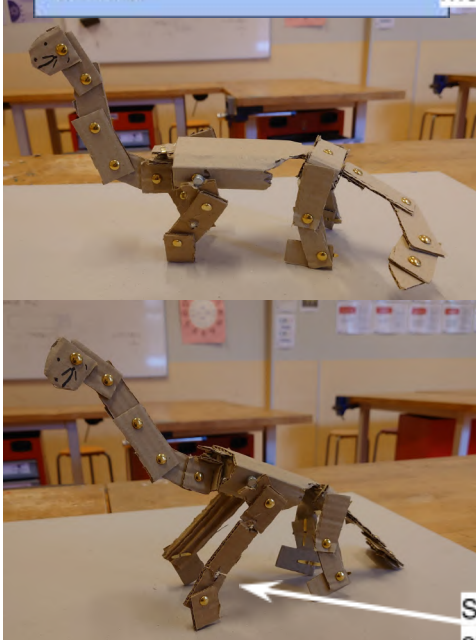
Neodymium magnets are very powerful, good for accessories.

Stronger magnets needed for large parts like the tail.

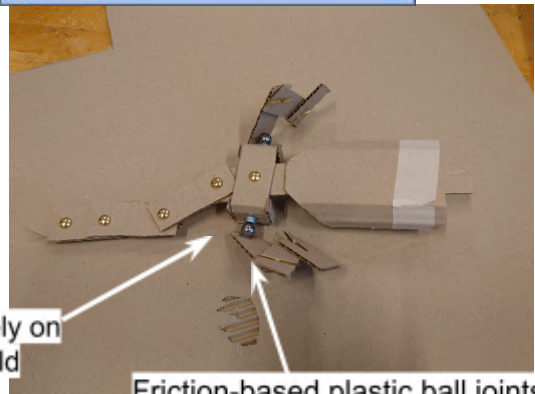


Testing separate joints and bones.

Increased part count but more standardized parts.



Testing metal-magnet ball joints.



Magnet rotates freely on axis. Not able to hold pose [F2].

Friction-based plastic ball joints should be used instead.

Separable joints allow for extensions and varied proportions.

Testing wireframe model.

Only one type of part used leads to simple construction.

Nodes not very useful. Wire alone could give similar results.

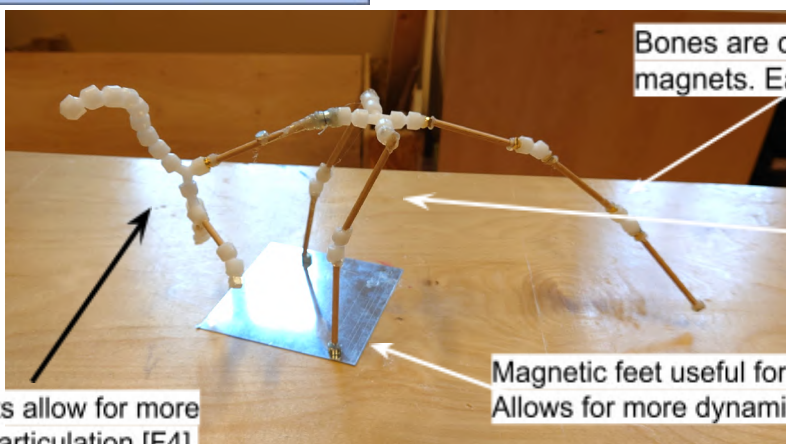
Lack of joints makes model hard to pose. [F4]

Hard to fit wires through nodes, making construction difficult [F1].

Model is very-lightweight but still durable [M1, F2].

Difficult to interpret model. Hollow form doesn't help with shading [F4].

Magnetic Jointed Model

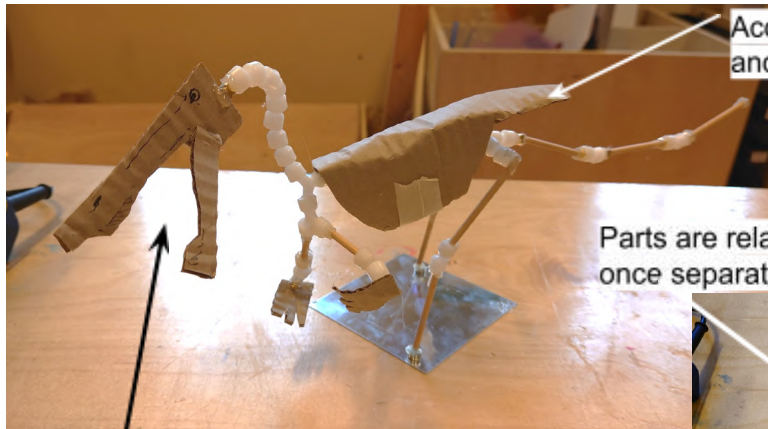


Bones are connected to joints via magnets. Easy to configure [F1].

Simple parts make internal skeleton easy to construct and adjust [F1].

Ball joints allow for more realistic articulation [F4].

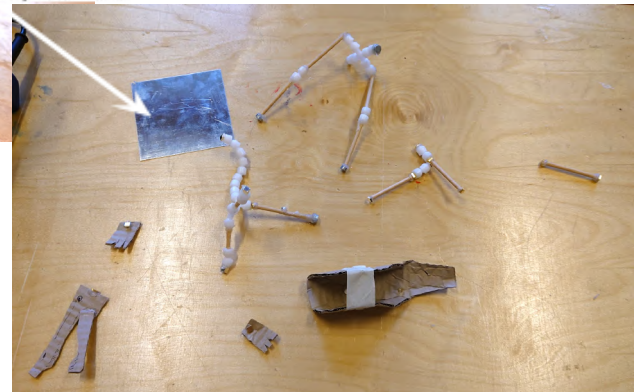
Magnetic feet useful for stability. Allows for more dynamic poses.



Accessories can be easily attached and removed thanks to magnets.

Parts are relatively easy to store once separated.

Specialized parts effectively convey detailed parts like heads and hands

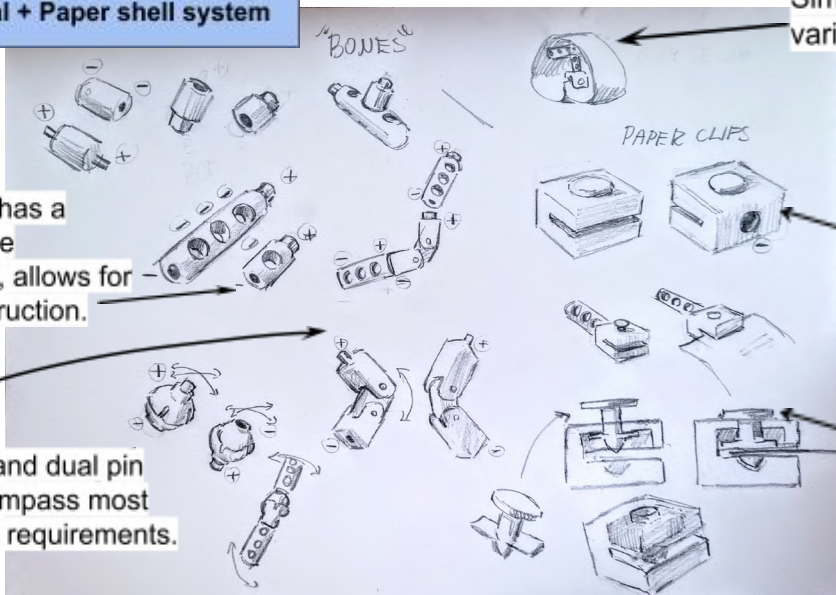


Selection and Justification of Final Design

Skeletal + Paper shell system

Every part has a male/female connection, allows for easy construction.

Ball joints and dual pin joints encompass most articulation requirements.



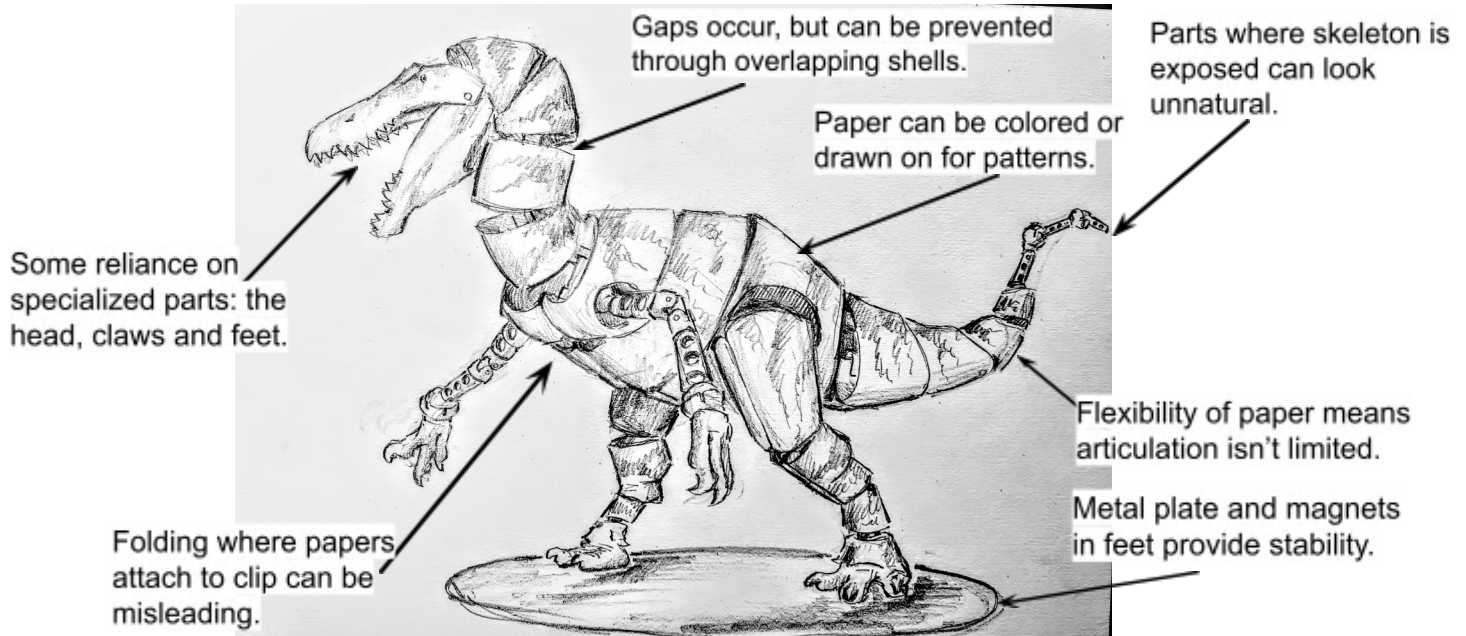
Simple clips can be used to create a variety of shapes [F7].

Reliance on paper shells means very few unique parts needed.

A pin keep papers in place, reducing fragility.

The skeletal-paper shell system provides a highly-customizable and realistic model. It is practical and does not take up much space; especially when not in use as it is made up of small parts that can be easily stored [S2]. One mannequin set is made of many copies of a few different standardised pieces, which makes production simple. Paper is a flexible and commonly-available material; whose range of shapes and forms gives it an advantage over the rubber shells of the skeletal-shell system which is limited in the forms it can depict [F6]. Slots for paper attachment allow the use of different materials, such as fabric. Paper comes in many colours and can be drawn on for further customization. Being made of paper makes the model very lightweight, meaning that the bones and joints don't need to be strained when holding a pose [M2, F3]. Its customizable nature allows for complementary attachments such as a pose rig or magnets embedded in the feet for stability [F3]. The articulation joints being separate from the bones means that they will wear less due to avoiding the forces that would come from "popping" the

joints in and out during construction [F5]. This system provides an accessible modular system that is incredibly customizable. While the model is time-consuming to construct, it is more intuitive than the other highly-customizable designs such as the wireframe model or the wire-clay model. The internal skeletal system provides something new that cannot be easily replicated by DIY methods, which makes the product appealing to artists. The plastic skeleton is quite durable [M1] and resistant to most outdoor situations, such as cold, heat and water [M3]. The paper covering is far more fragile, but can be easily replaced or removed. More durable materials can be used instead of paper as well.



Specification	Advantages	Disadvantages
A1	Differently-colored paper can be used for the shells.	None
A2	Used material can be adjusted.	Might be difficult to find suitable materials.
F1	Simple parts make for intuitive construction.	Lots of parts needed and paper needs to be cut. Can be tedious.
F2	Metal plate helps with posing.	Paper parts can be flimsy.
F3	Hollow bone and paper make the model lightweight.	Joints might struggle to lift a very large model.
F4	Two different joints allow for faithful recreation of animal articulation.	None
F5	The joints being separate to bones reduces the strain during construction.	Joints might wear down over time due to relying on friction.
F6	Shapes and proportions can be easily adjusted.	Gaps in paper might be confusing. Can take time to get things right.
F7	Model is very customizable.	None
M1	Bones are relatively durable.	Paper parts are quite flimsy.
M2	Paper and hollow plastic parts are lightweight	None

M3	Plastic parts are weather-resistant.	Paper parts might get wet or crumpled. Can be easily replaced.
S1	The parts are not very small and simple, relatively easy to handle.	None
S2	Size of a model can be adjusted. Individual parts are small.	None
D1	Flexibility of paper allows different shapes and forms.	Might need folding and tinkering with paper to get the right form.
P1	Parts can be easily 3-D printed.	None
C1	Small plastic parts are quite cheap.	None

Justification of Materials and Manufacturing Process for the Prototype

Part	Requirements	Chosen Material	Method of Manufacture
<u>Singular Parts</u> Small bone, Connector bone, Single-hole bone, Triple-hole bone, Body Panel Clip, Quad Bone  <u>Sub-assemblies</u> 180° Linkage (Male end, linkage, female end), 90° Linkage (Male end, female end), Ball Joint (Ball joint, outer shell), 30° Ball joint (Ball joint, outer shell), Foot (Small end, large end) 	Decent hardness, water and UV-resistant, high stiffness, decent compressive strength	Polylactic acid	FDM Printing
Brads (Amazon) 	Plasticity (in arms), water and UV-resistant	Brass	Purchased as a component
Foot Magnets (Amazon) 	Strong magnetism, high stiffness	Neodymium	Purchased as a component
Disc Stand (Stedaparts) 	Ferromagnetic, high density, high stiffness	Untreated Steel	Purchased as a component

Polylactic Acid (PLA)

Most parts will be made of PLA. Using a single material for most parts is beneficial for modularity, as it's easier to manage the supply required for manufacturing [C1]. PLA is chosen for its low density, (Farah 5) especially when compared to other plastics (Specialchem). PLA has a decent Young's modulus, tensile strength (Ultimaker) and impact resistance (Farah 3). Although less than other plastics suitable for FDM printing, such as HIPS, (Craftcloud), it should be enough for this application. The properties of PLA can

be compared to properties needed during hypothetical calculated scenarios (Appendix 3).

	Tensile Strength at Yield [M1]	Max Compressive Strength [M1]	Gardner Impact [M1]	Flexural Strength [M1]	Density [M2]
PLA	52.5 MPa (Ultimaker)	68.4 MPa (A Kholil 4)	14.0J (Seas3D)	85.1 MPa (Iemai)	1.25g/cm ³ (Farah 5)
Necessary Value	51.7 MPa	49.5MPa	23.2J	49.5MPa	7.44g/cm ³

The table shows that PLA has greater tensile strength, compressive strength, and flexural strength than necessary, allowing parts to be separated and combined without breaking [M1]. Low density, allows for lightweight models [M2]. PLA has low water absorption, only increasing by about 3% in moisture content after being submerged for 5 weeks (Vinoth 8). The model shouldn't get wet frequently, so PLA's water resistance is sufficient without finishes, making it suitable for use indoors and outdoors [M3]. In extreme cases, some parts might break from the model falling or being dropped, due to the Gardner Impact being less than ideal. PLA can be made in various colors, including gray or beige [A1] and a matte texture [A2] (Snapmaker).

FDM is the most suitable manufacturing technique for the prototype as it is cheap and quick and easy to make varied small parts (Cooper). This will be useful when producing parts for destructive testing and iterations. FDM performs best at medium sizes, (Sinterit). A build volume about 230 x 190 x 200 mm allows printing many parts at once (Ultimaker). FDM has environmental benefits: low waste and easy part replacements and adjustments (Sola 1). PLA can be produced from non-toxic renewable sources (Farah 2), reducing environmental impact.

Adhesive

The foot part requires an adhesive to join the magnets to the underside. These parts don't need to be separated, so a permanent joining technique is used. Cyanoacrylate glue is suitable for combining 3D-printed parts and magnets as it is water-resistant (Gradasevic) [M3] and forms strong bonds between metals and plastics (Permatex). Sample calculations show that the tensile strength of the bond can easily hold magnets in place (Appendix 4).

	Tensile Strength
Cyanoacrylate	9.652 MPa (Permatex)
Necessary Value	0.000342MPa

Magnets

Magnets used are neodymium, due to high magnetism (Stanford Materials), allowing it to hold up larger models. While raw neodymium is very reactive, it is coated with oil or plastic to prevent this [M3] (Stanford Materials). Sample calculations here also show that the magnets are strong enough to hold up the model (Appendix 5).

	Maximum Energy Product
Neodymium	342kJ/m ³ (Magnet Expert)
Necessary Value	85.9kJ/m ³

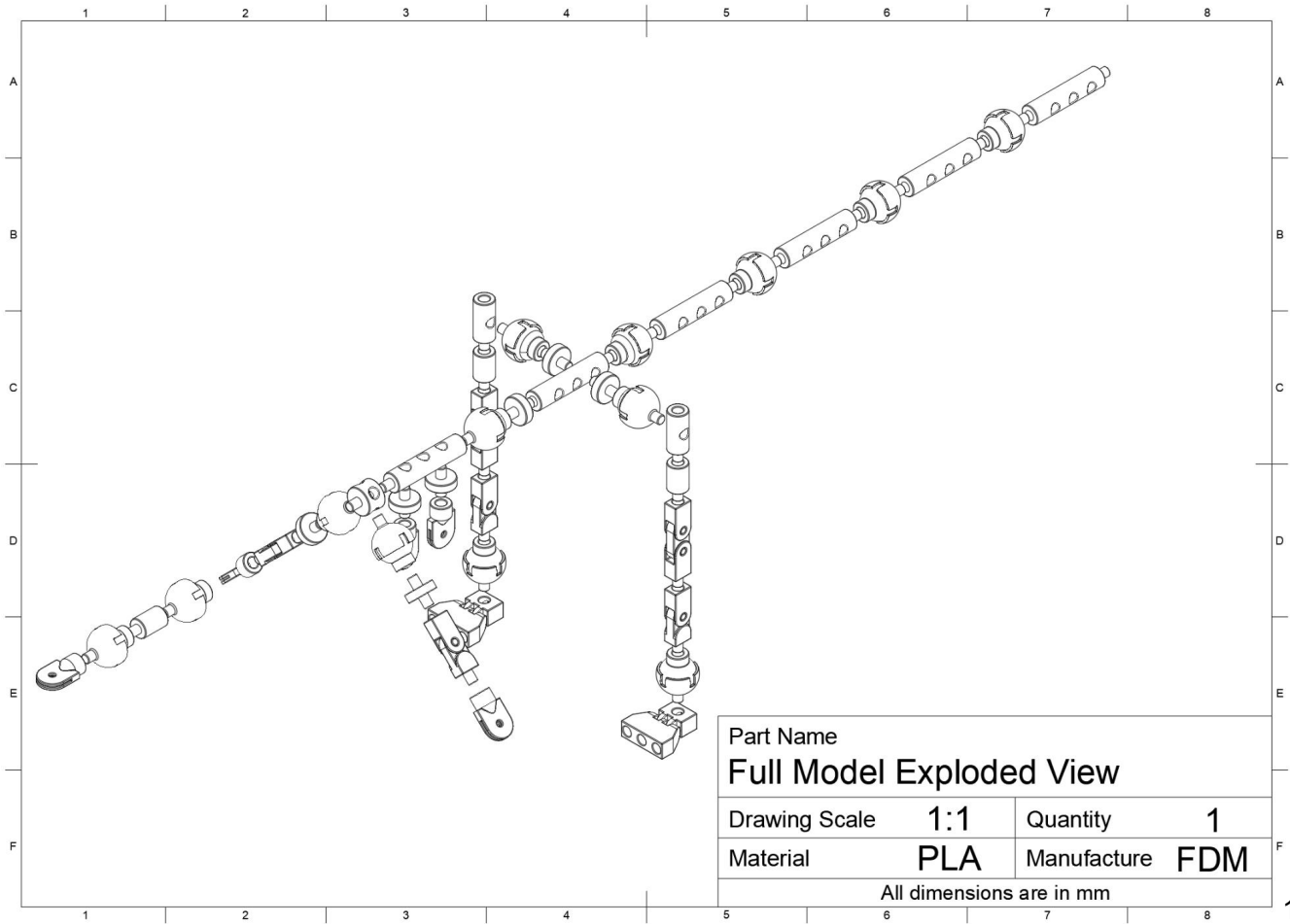
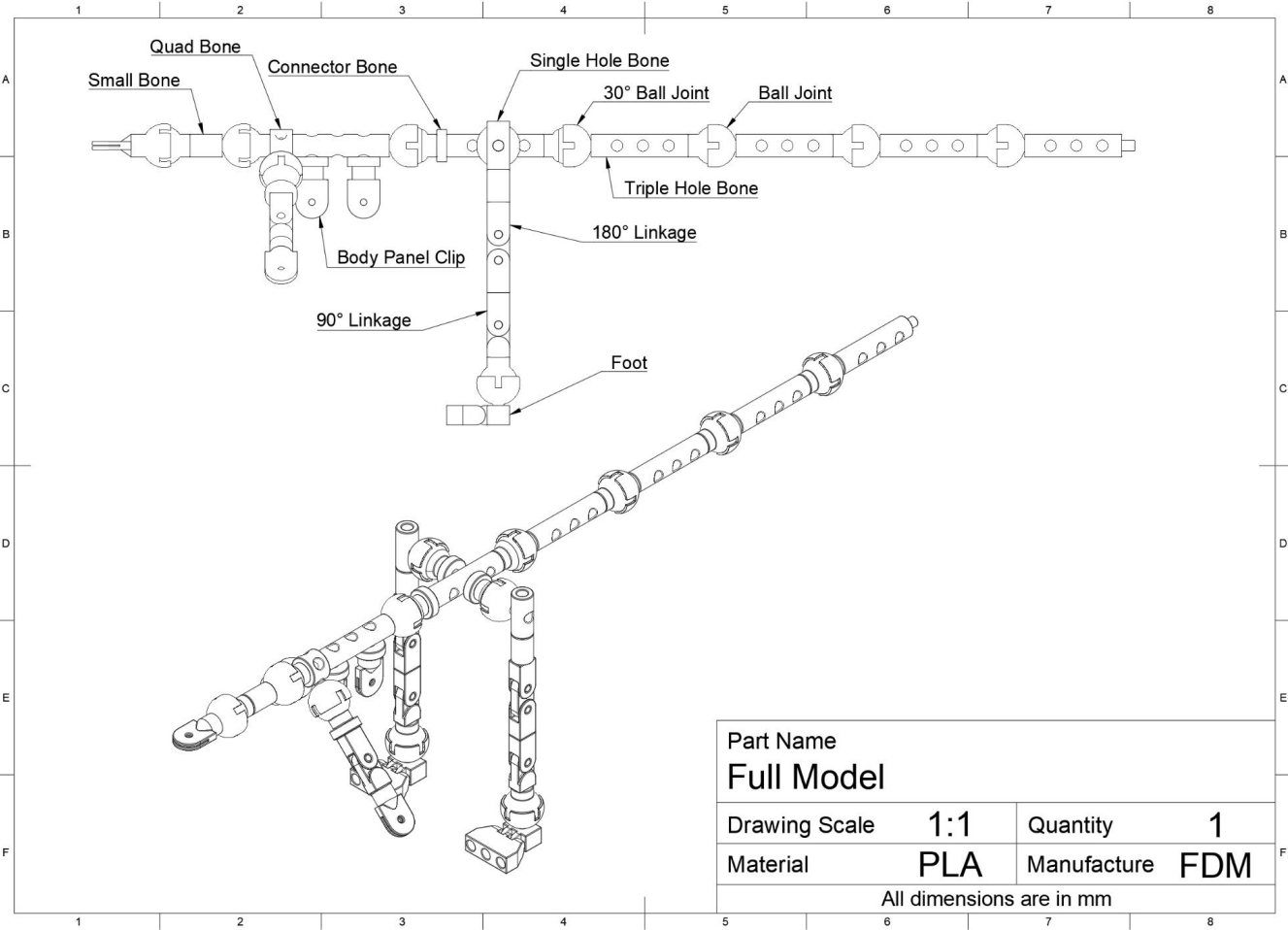
Brass

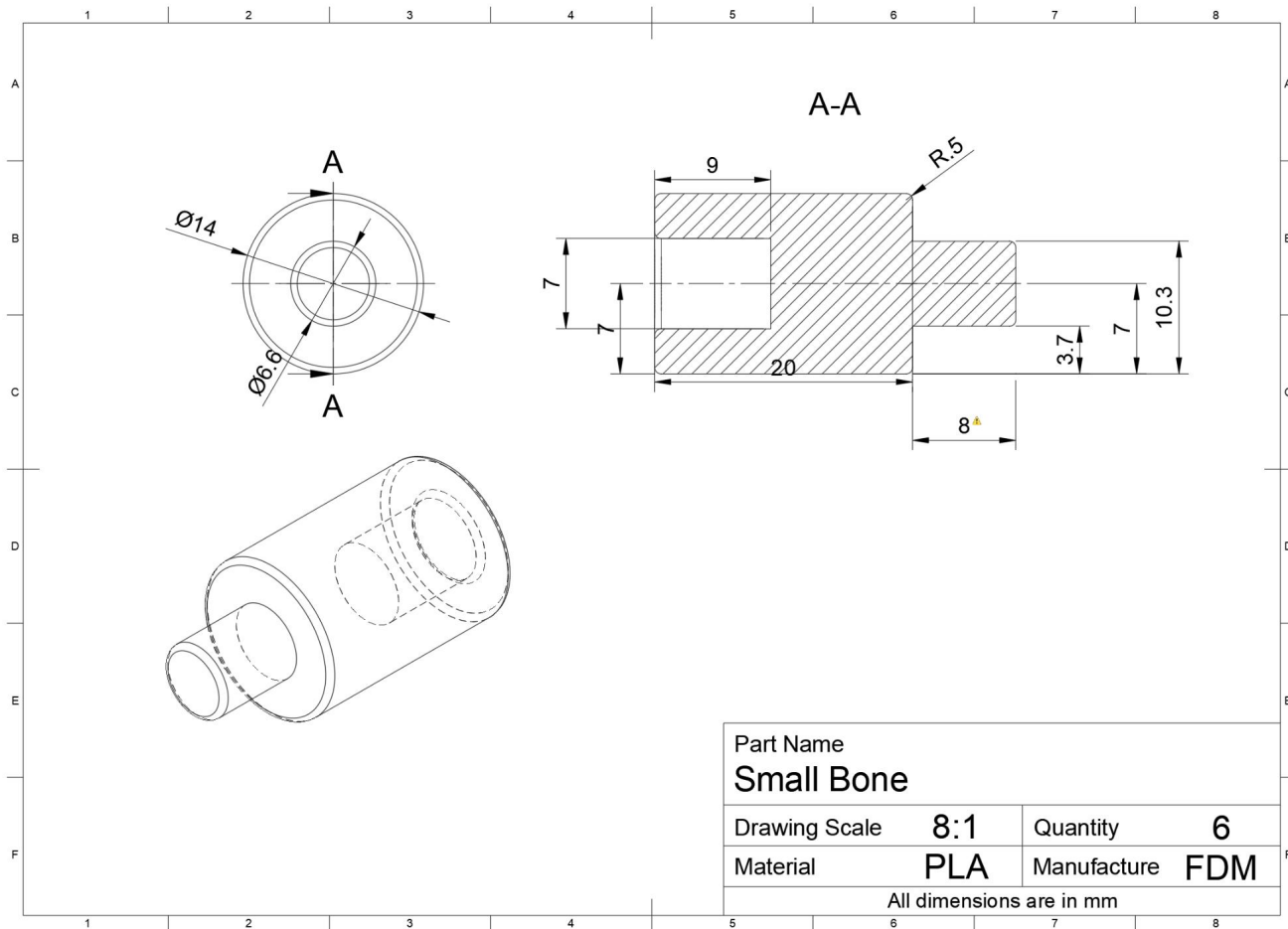
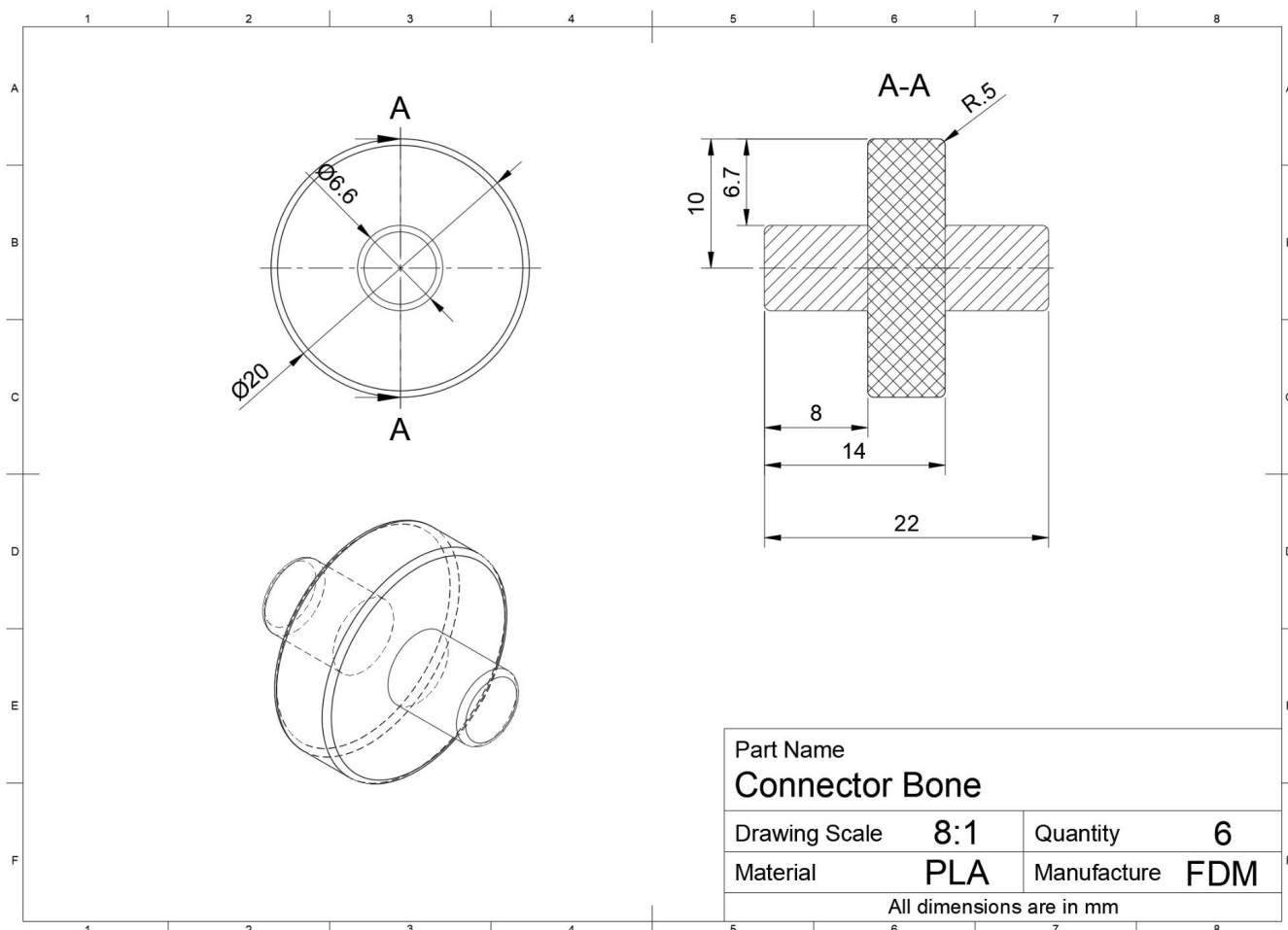
Brass is used for brads due to malleability (McClemenets), allowing the arms of the brad to bend without breaking. Brass has an elasticity modulus of about 100MPa and the thin arms made it easily bend into shape.

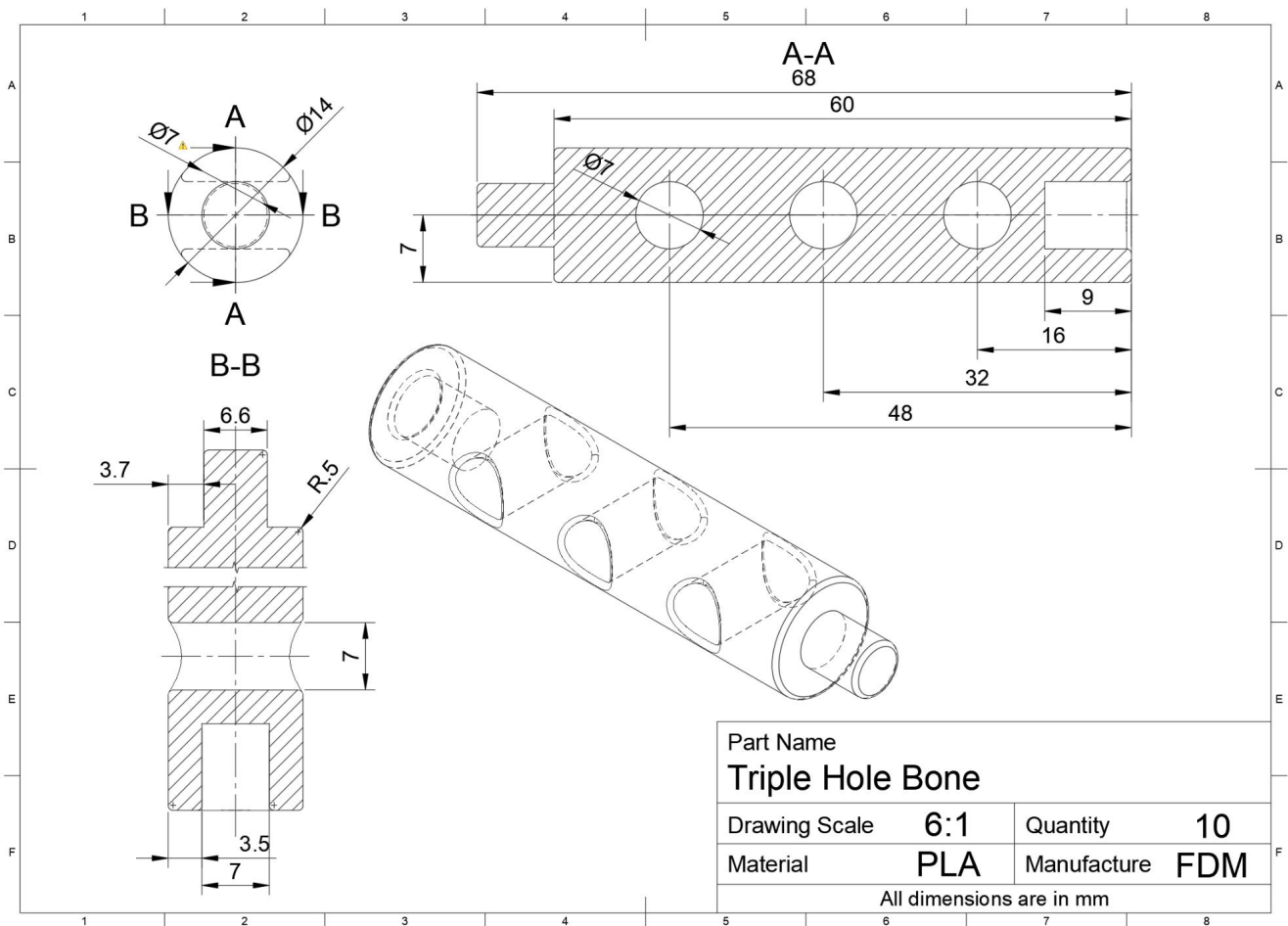
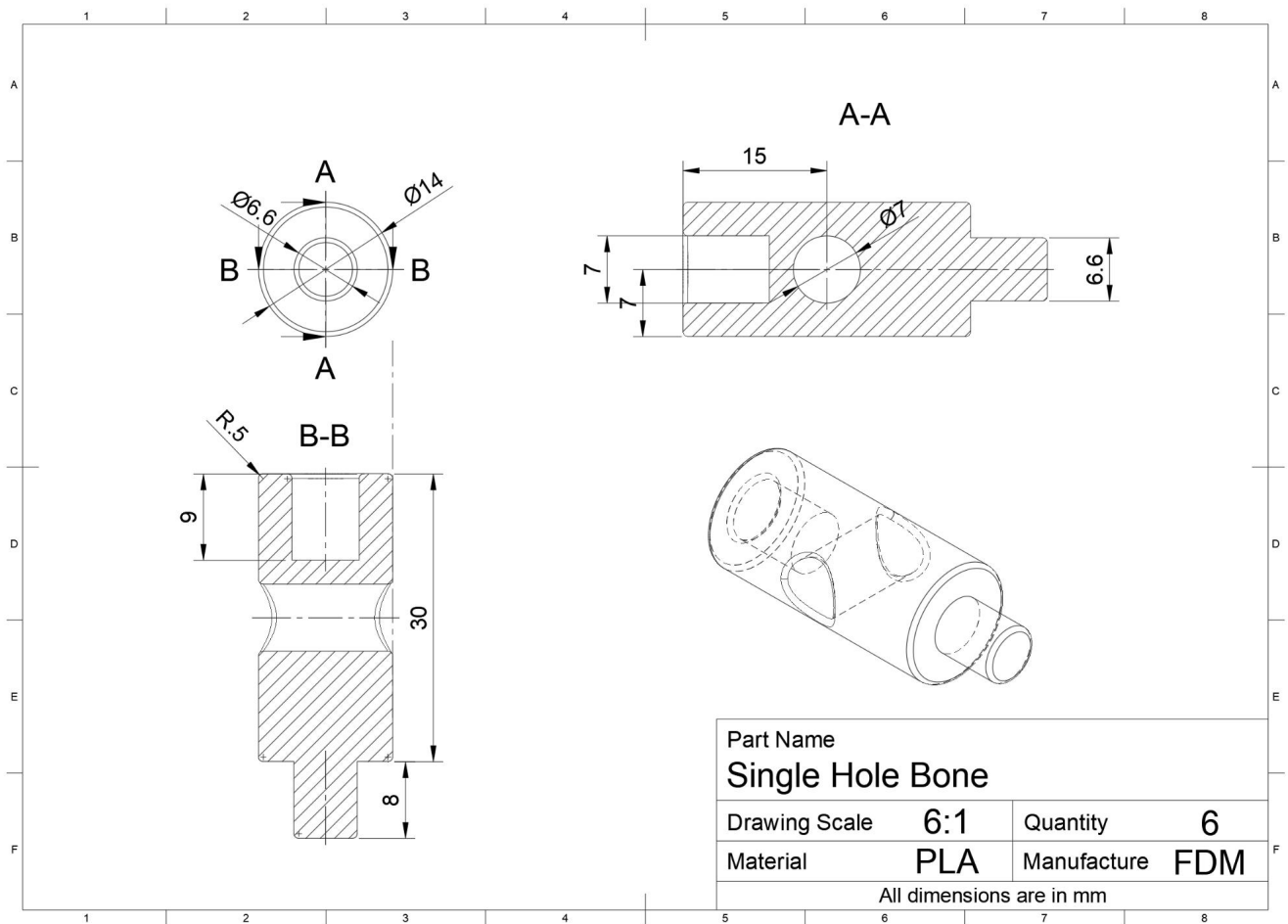
Untreated Steel

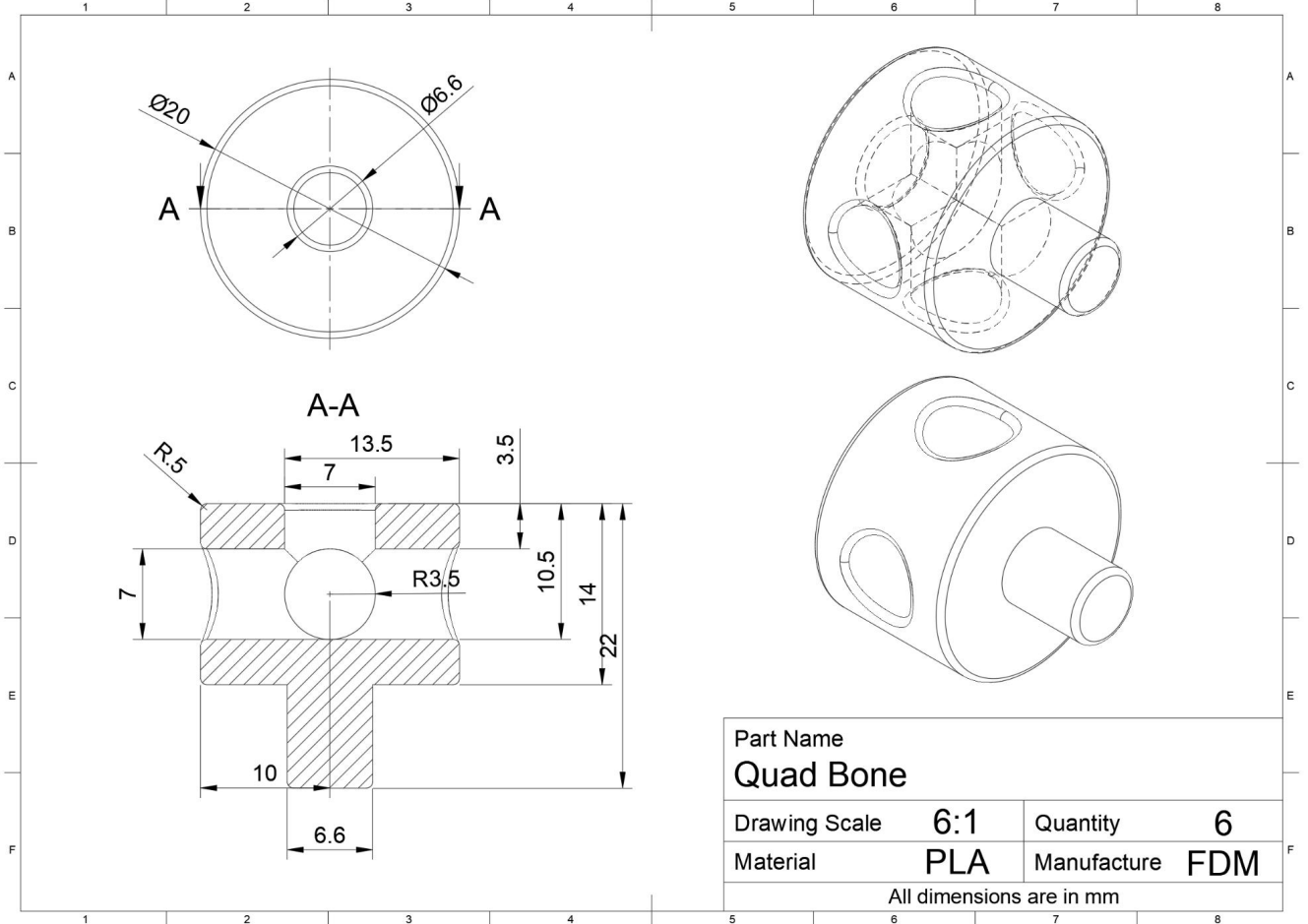
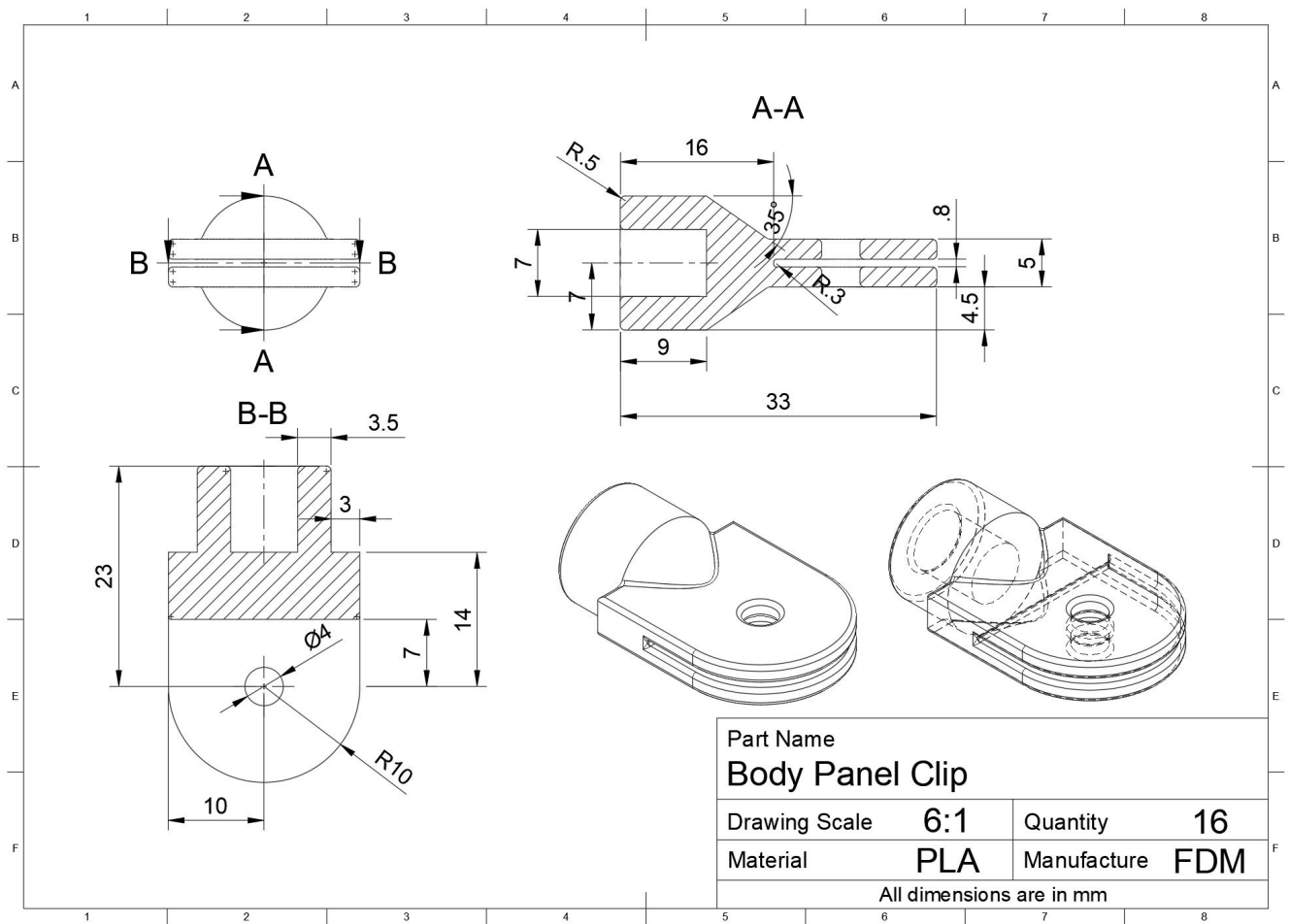
Untreated steel is used due to its ferromagnetism. Alloyed steels such as stainless steel tend to be less magnetic (Eclipse Magnetics). Carbon steel has a density of 7.81g/cm³, which is greater than metals such as copper, and similar to other types of steel (Engineers Edge), allowing it to be heavy enough to support the mannequin.

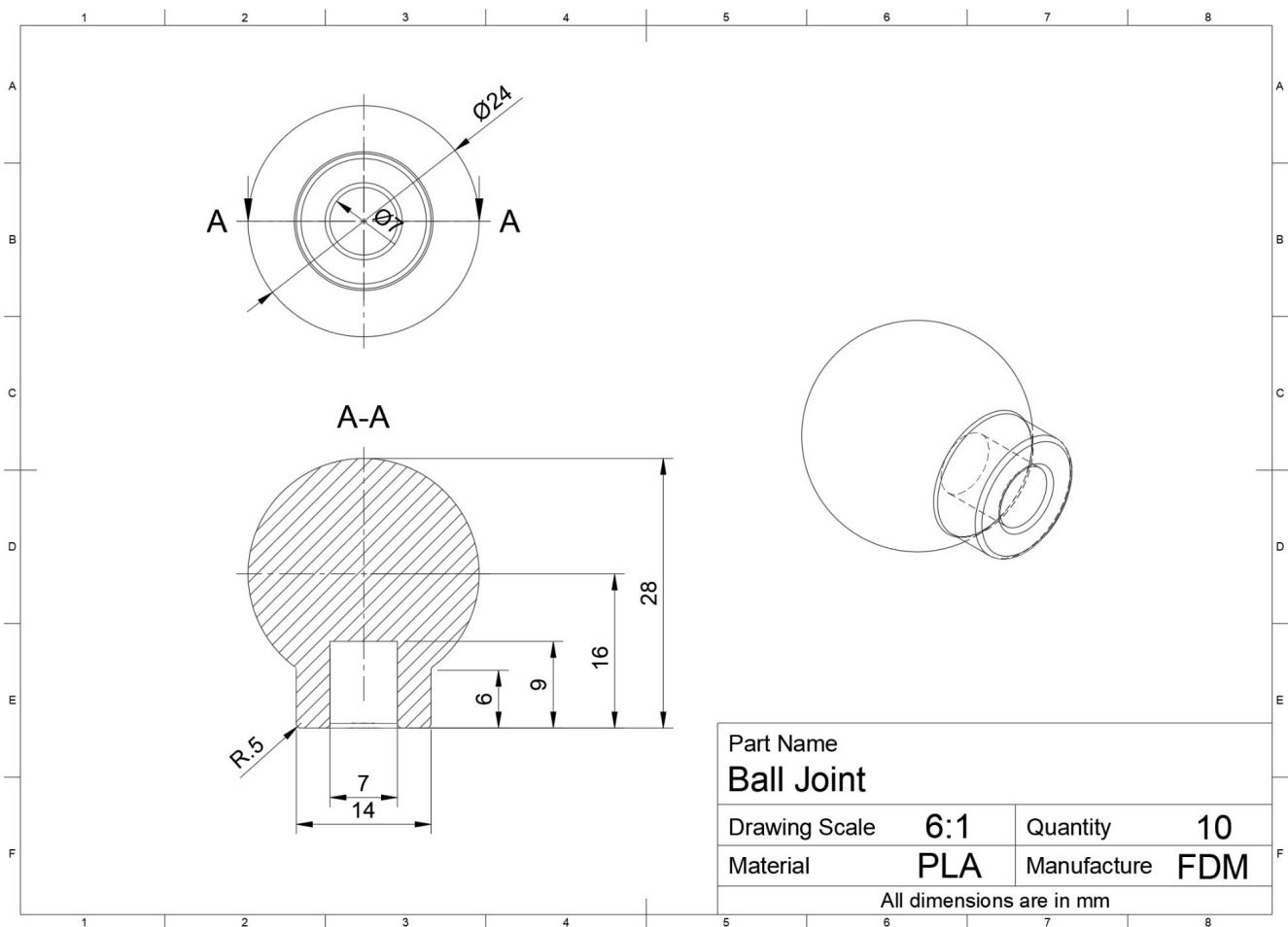
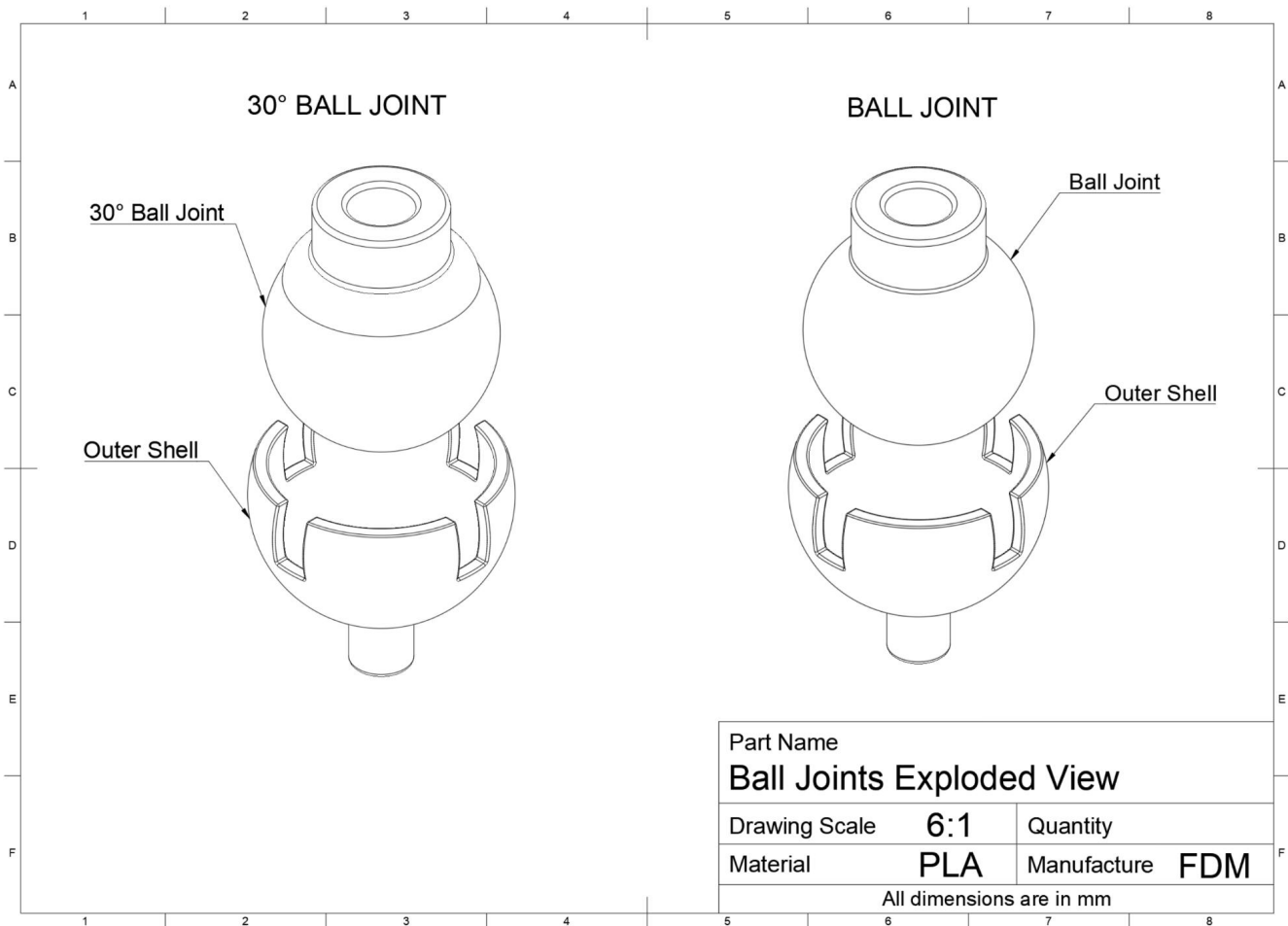
Design Proposal

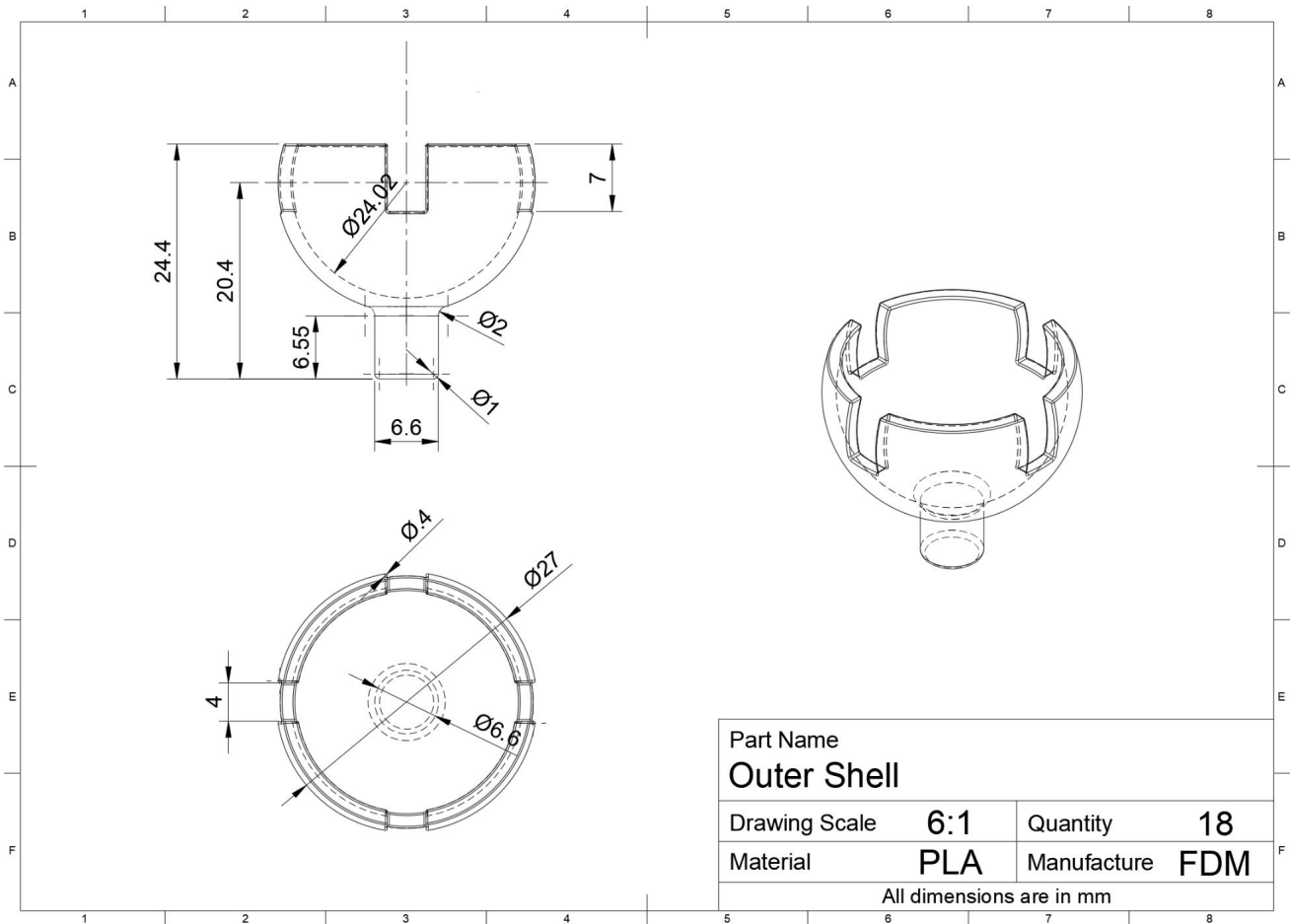
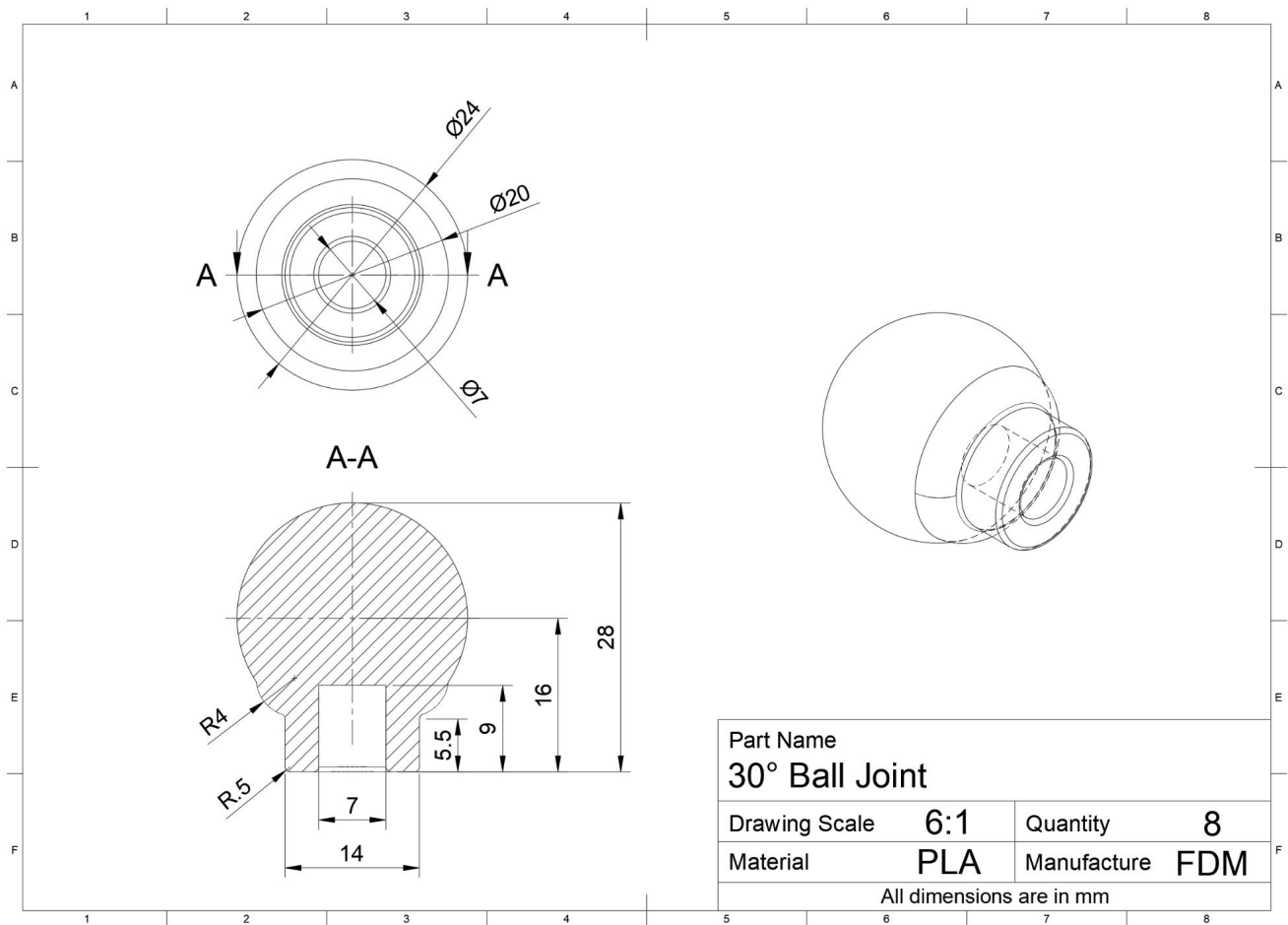


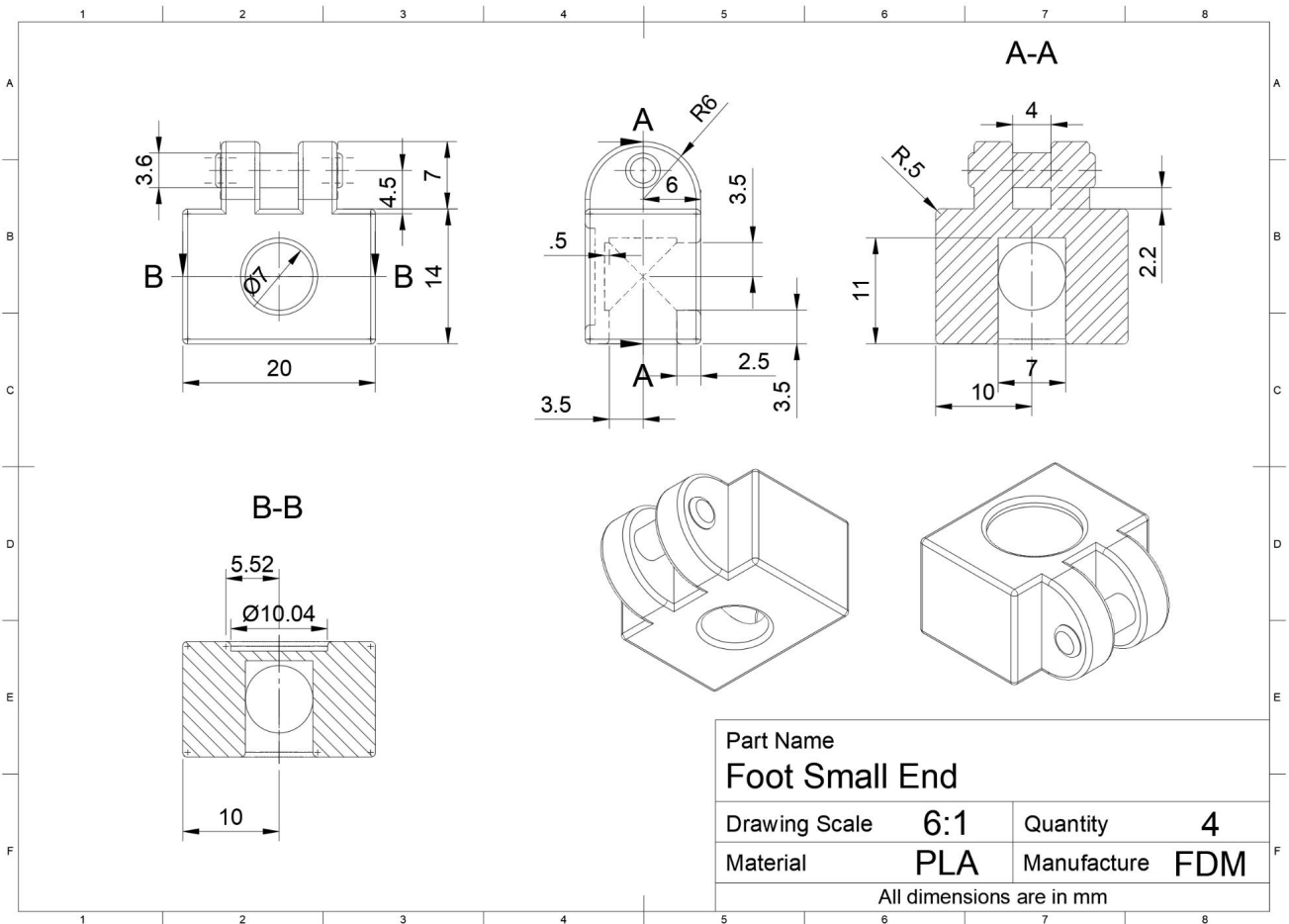
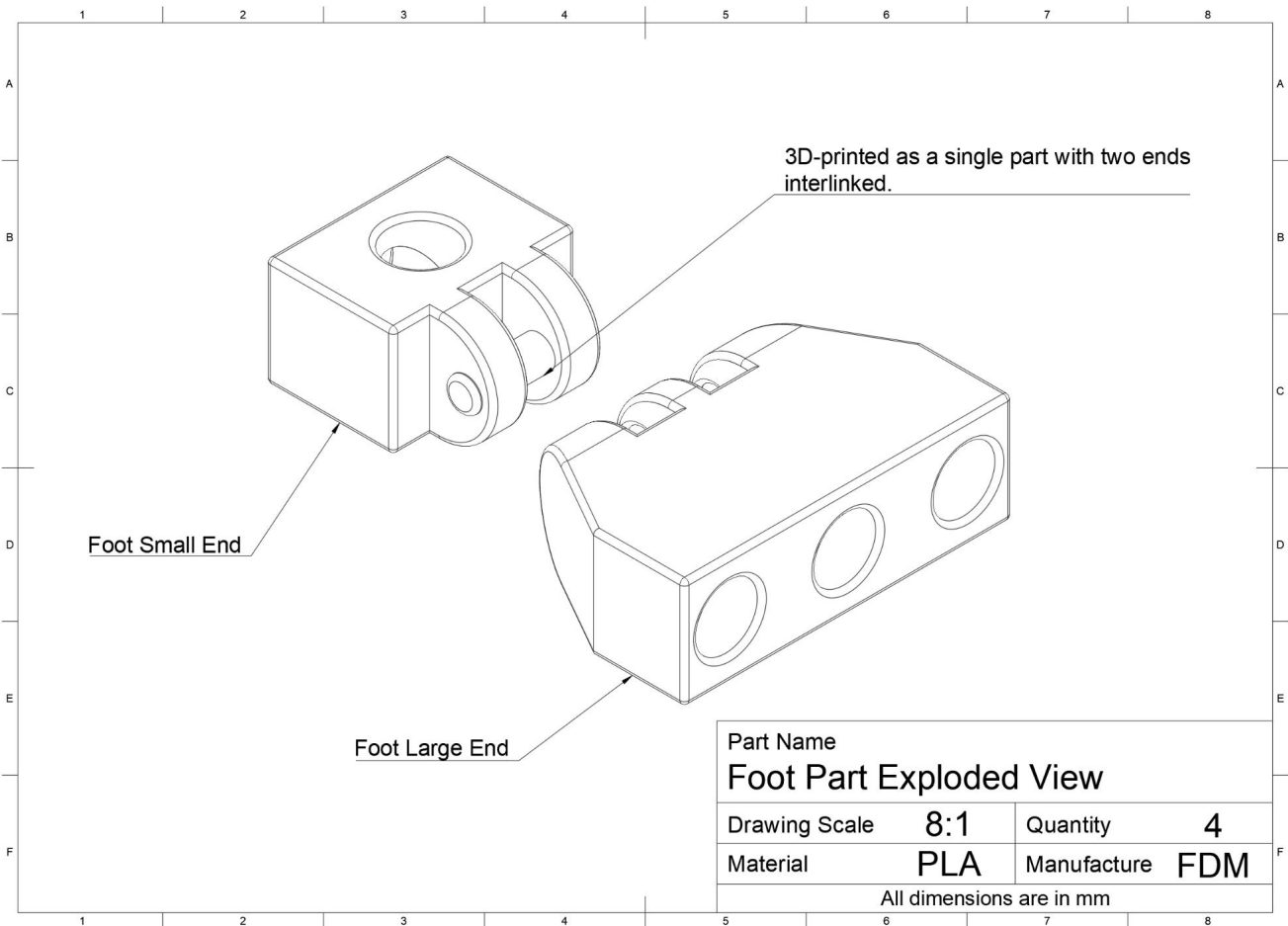


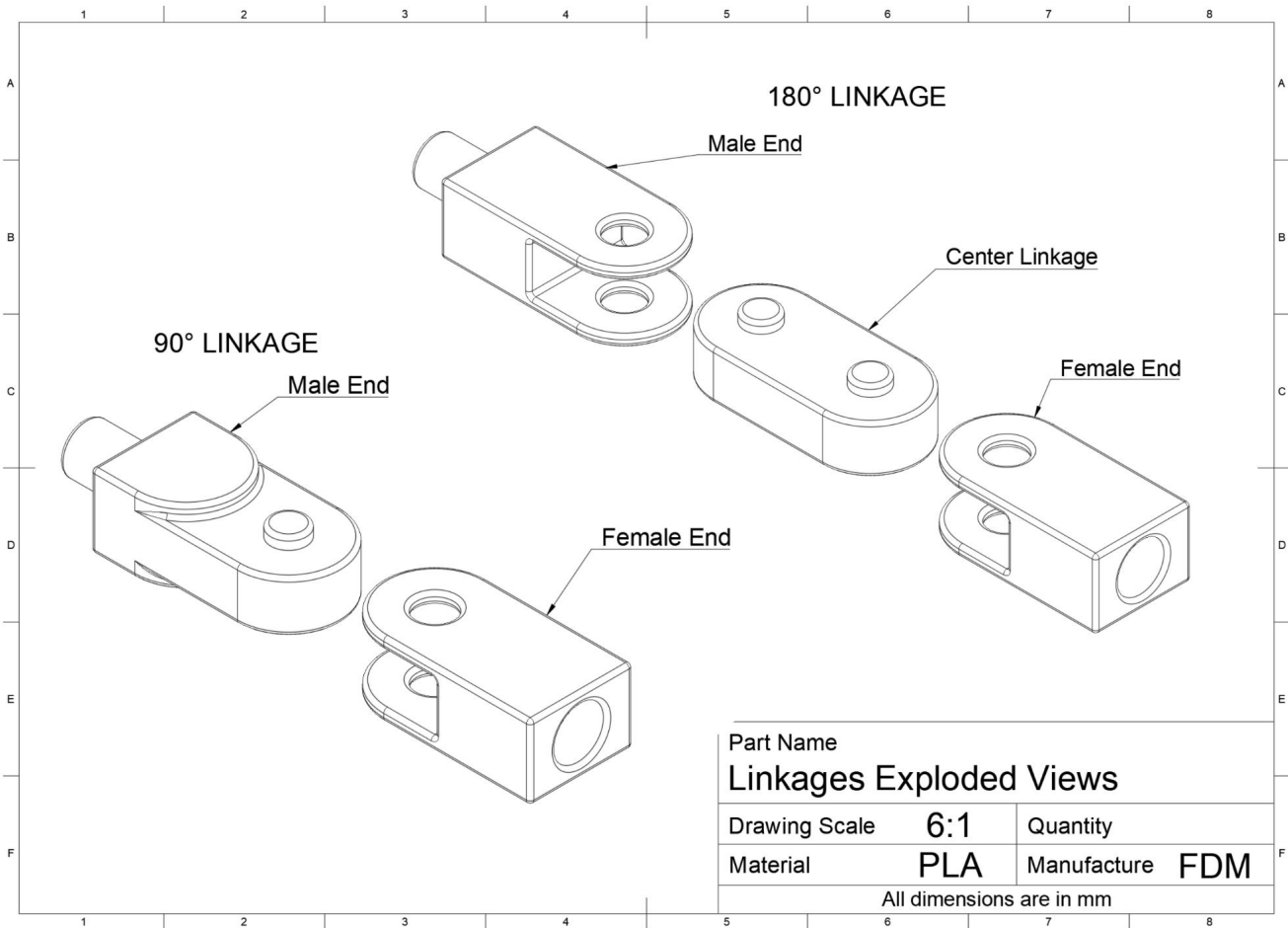
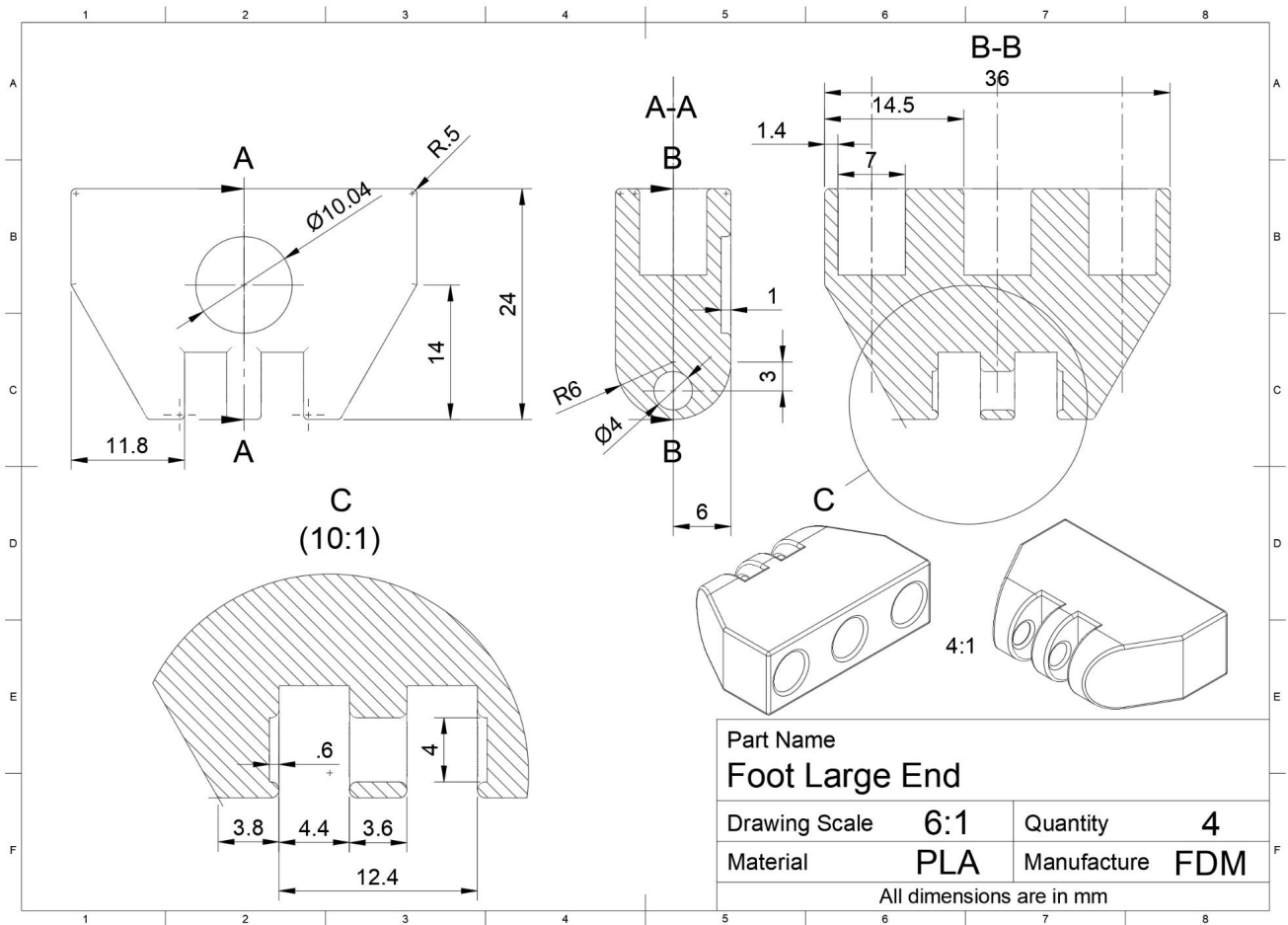


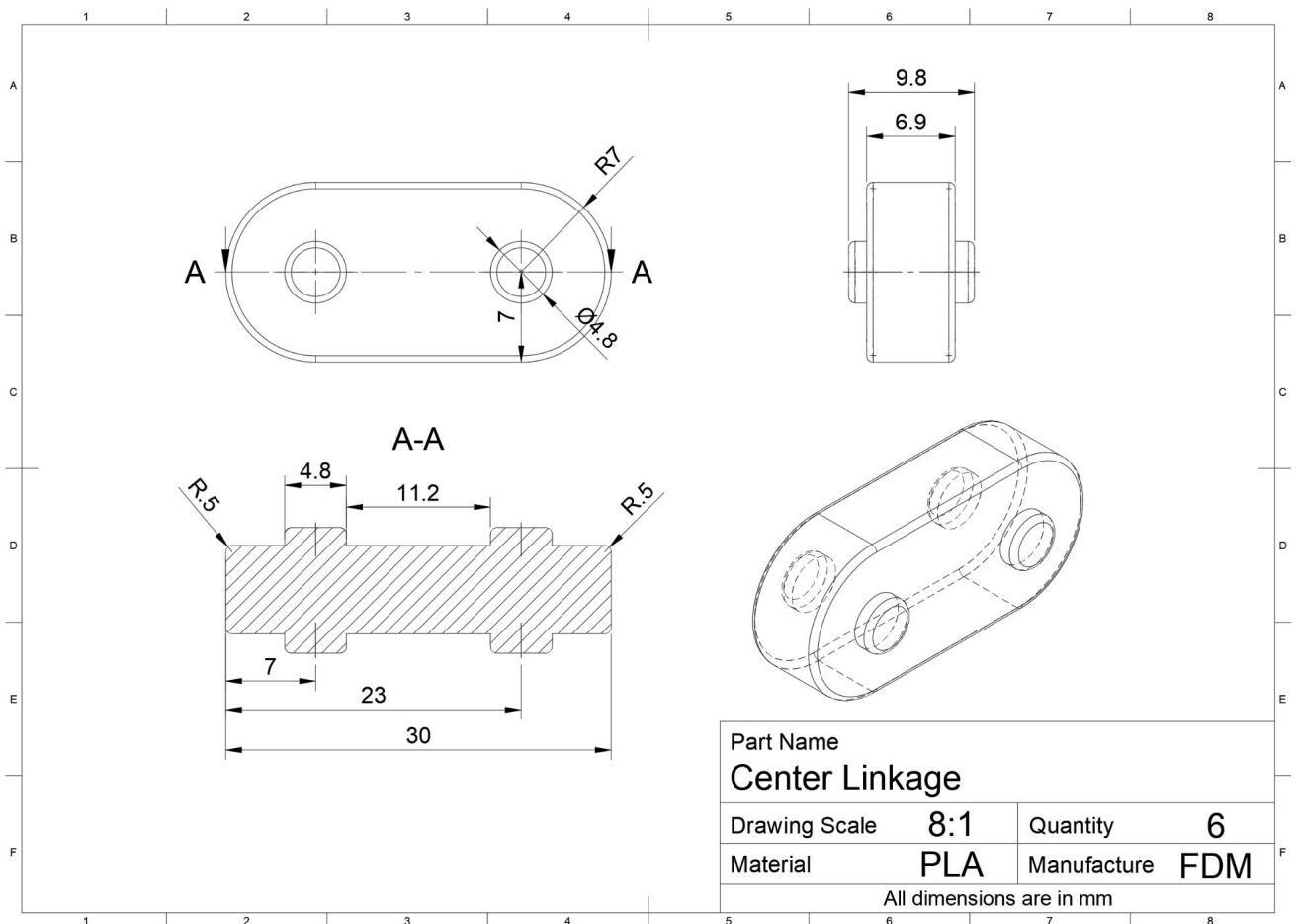
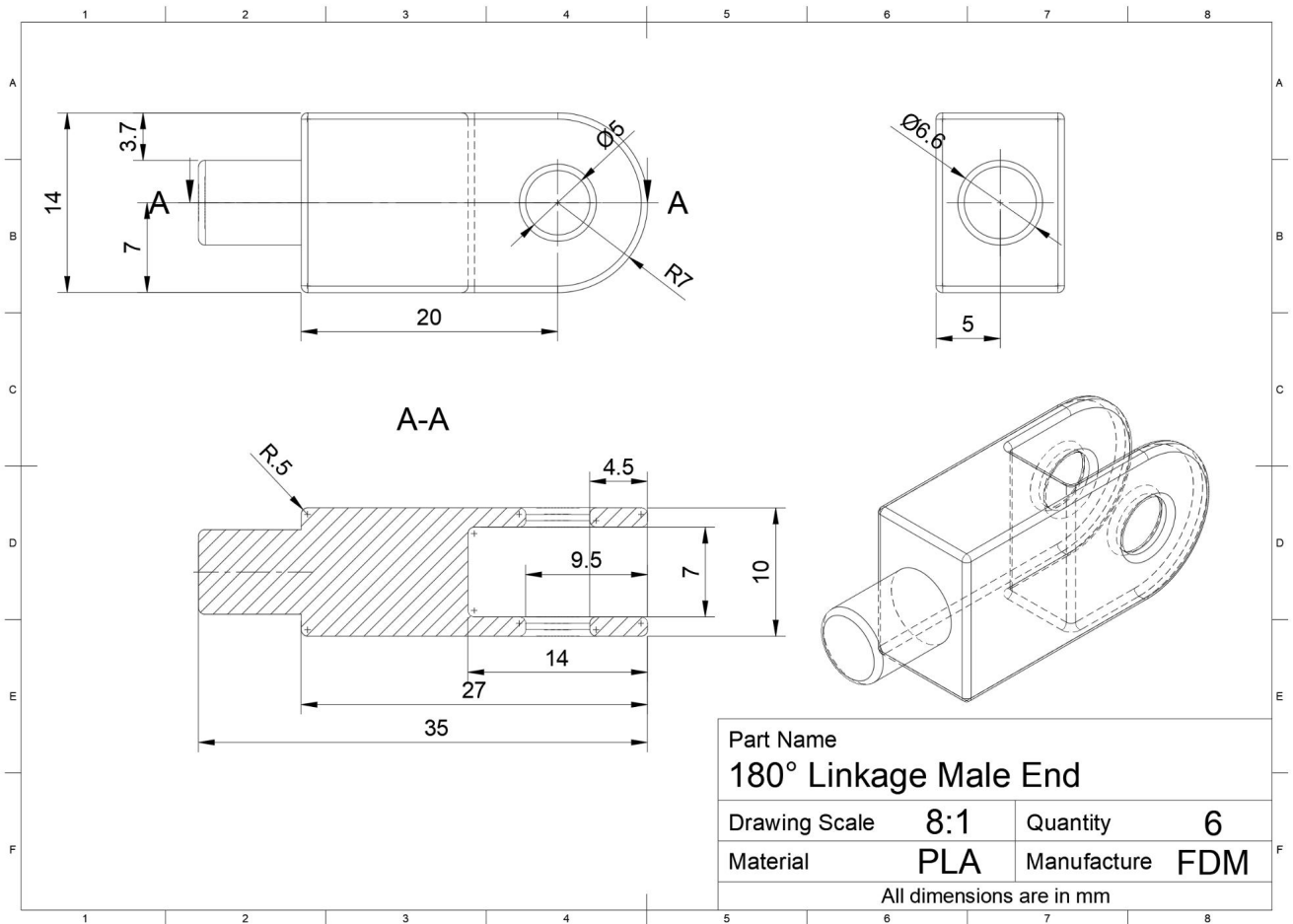


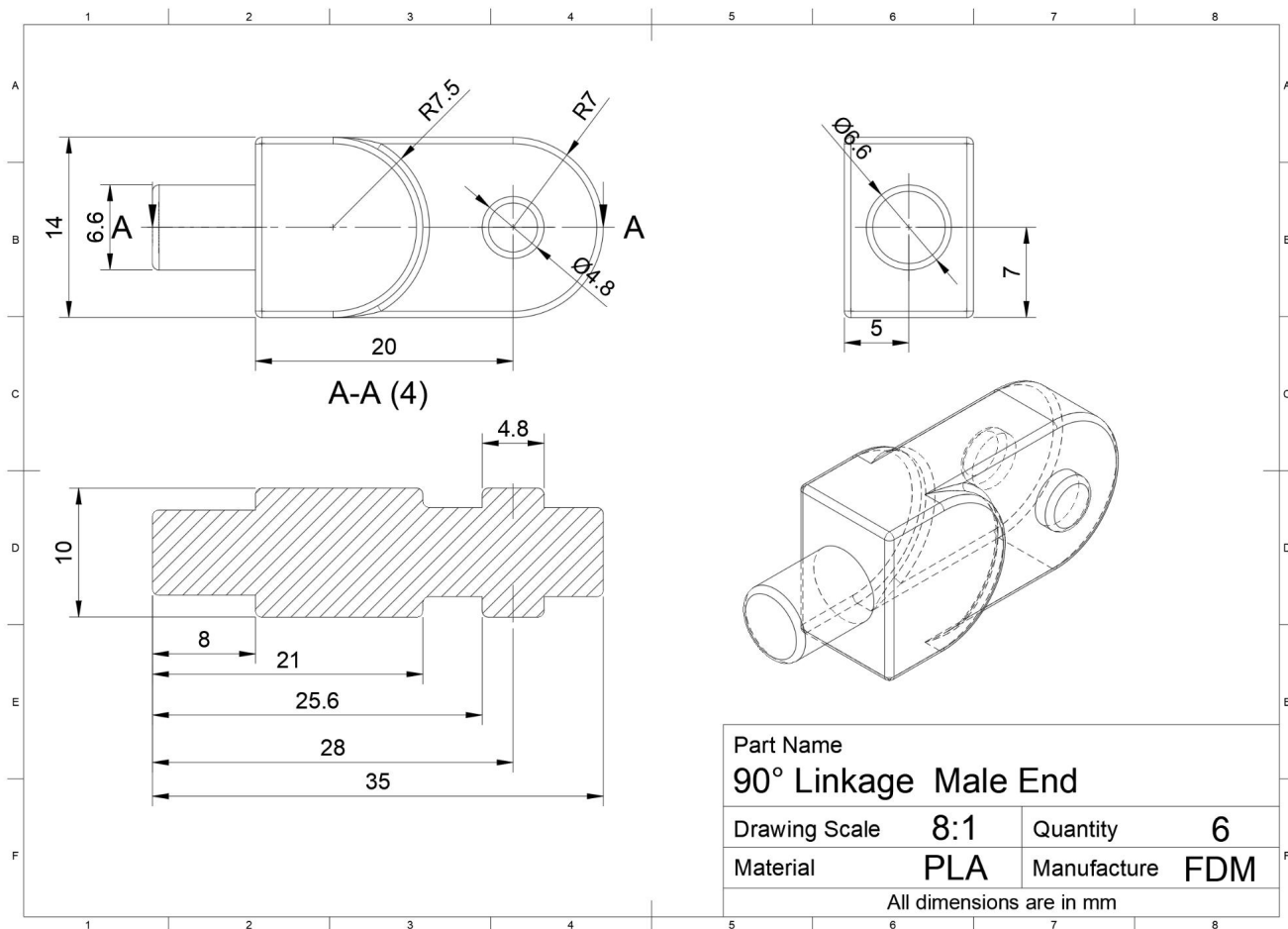
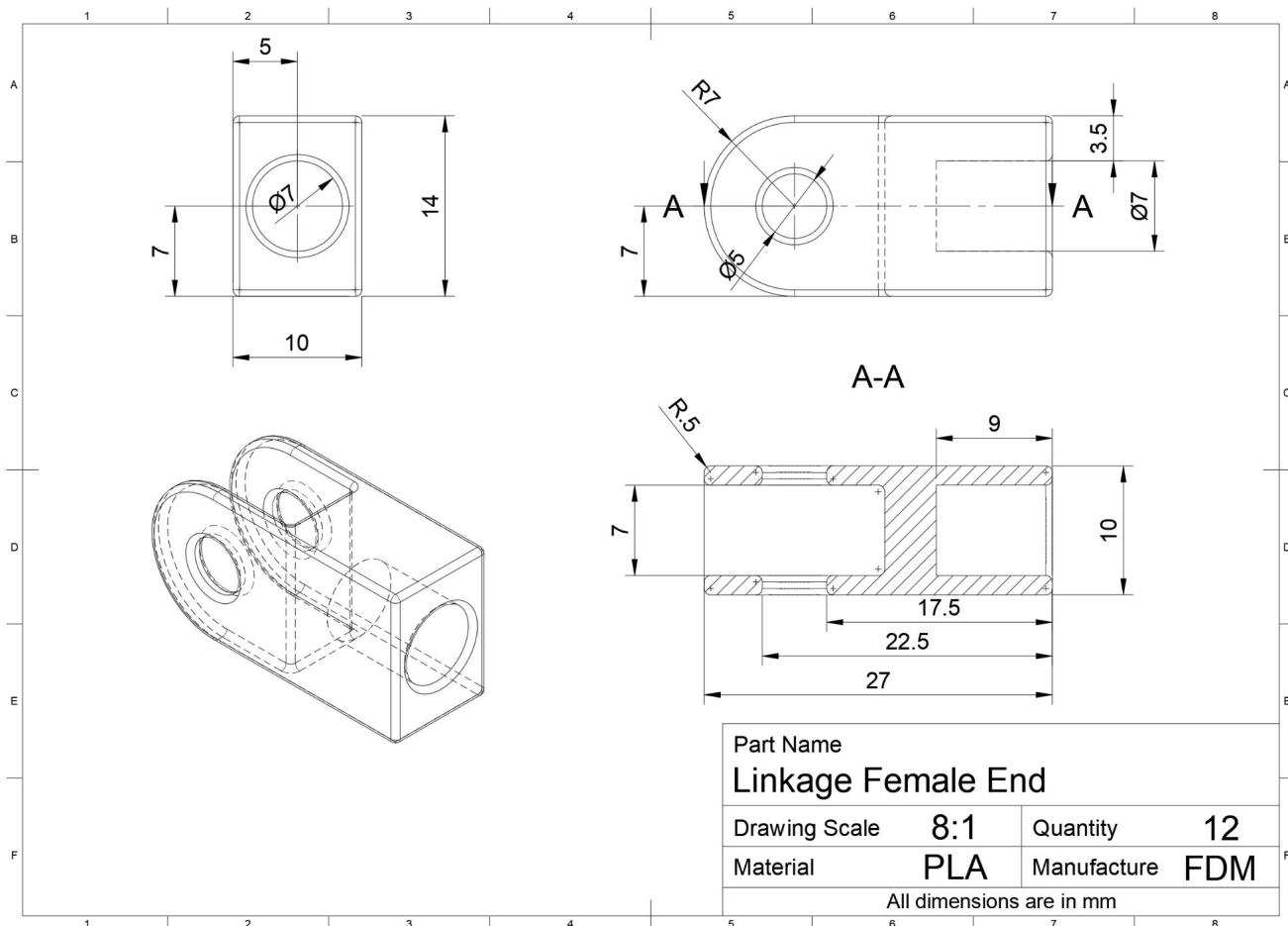








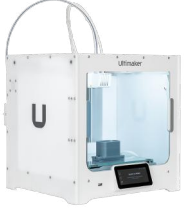




Bill of Materials

Part Name	Quantity (Units)	Dimensions, lengthxwidthxheight (mm)	Unit Cost (Euro, €) (Appendix 6)	Total Cost (Euro, €)
Small Bone	6	28x14x14	0.007	0.043
Connector Bone	10	20x20x20	0.006	0.057
Single-hole bone	6	38x14x14	0.09	0.056
Triple-hole bone	10	68x14x14	0.018	0.208
Quad Bone	6	22x20x20	0.007	0.053
Stand (Bought)	1	165x165x6	8.95 (Stedaparts)	8.95
180° Linkage	6	64x14x10	0.017	0.101
Male End	1 per	35x14x10	0.006	0.042
Linkage	1 per	30x14x9.8	0.006	0.044
Female End	1 per	27x14x10	0.005	0.031
90° Linkage	6	48x14x10	0.012	0.073
Male End	1 per	35x14x10	0.008	0.054
Female End	1 per	27x14x10	0.005	0.031
Ball Joint	10	27x27x36.4	0.023	0.229
Ball Joint	1 per	24x24x28	0.018	0.180
Outer Shell	1 per	27x27x24.4	0.005	0.049
30° Ball Joint	8	27x27x36.4	0.023	0.188
30° Ball Joint	1 per	24x24x28	0.019	0.149
Outer Shell	1 per	27x27x24.4	0.005	0.039
Body Panel Clip	16	33x20x14	0.47	1.317
Body	1 per	33x20x14	0.007	0.117
Brad (Bought)	1 per	20x8x8	0.040 (Amazon)	1.200
Foot	4	39x36x12	0.223	2.489
Small End	1 per	21x20x12	0.008	0.030
Large End	1 per	24x36x12	0.016	0.065
Magnets (Bought)	2 per	10x10x1	0.200(Amazon)	2.394
Final Prototype	€12.474			

Plan of Manufacture

Process	Scheduling	Required Equipment	Quality Control	Precautions	Safety
70% Infill Printing (Cura's Triangles) All of the parts are laid out on the 3D printing bed and printed in 2 separate sessions.	3400 mins	Ultimaker S3 FDM 3D Printer, PLA filament 	Ensuring proper infill and print speed, orientation optimized to reduce supports Slow print speed, at recommended 40mm/s to prevent defects (lemai)	Checking for enough filament before printing. Checking whether printer bed is clean	Prevent interaction with the printer while the nozzle is hot
Removing Main Support Material	60 mins	Side cutters, Needle nose pliers (Red Box Tools) 	Feeling edges of parts and using visuals to determine smoothness.	Applying pressure slowly so supports aren't flung when cut off.	Use tools carefully to prevent injury.
Cleaning Female ends and bottom of parts from support material.	90 mins	Mastertools seam scraper (Helms) 	Test-fitting male and female connections to ensure interference fits. Testing movement to ensure sliding fit between joints. Iterative printing with different infills and tolerances to ensure optimum fit.	Use tools carefully to prevent injury, use minimal force to prevent breakage of parts.	Scraper pointed away from hands to prevent injury.
Removing burr and finer support material from individual parts.	120 mins	180 grit sandpaper, Sanding mask, goggles (Lowes) 	Test-fitting parts, re-sanding where necessary	Sanding in intervals to not overheat and melt parts	Mask to prevent inhalation of dust. Cleaning up dust afterwards.
Using glue to attach magnets to indent of foot part	25 mins	Loctite Super glue (Loctite) 	Testing bond strength by using magnets. Checking for excess glue	Using paper tissues underneath working area to prevent glue drippage	Well-ventilated area for gluing. Gloves prevent skin contact with glue

Testing Strategies for Product Evaluation

Specification	Testing Strategy	Justification	Data Type
A1, A2, F2, F3, F4, F6, D1, S1, S2	<u>Expert Appraisal</u> Gathering feedback from an art teacher at my school.	An art teacher could have insights into how students learn and knowledge on art fundamentals, providing new perspectives on potential issues in using the mannequin as a referencing tool.	Qualitative feedback
A1, A2, D1, F3, F5, F6, D1	<u>User Testing Session</u> A session with art students. A T.rex is drawn from memory, and then based on the mannequin to compare the results. They can give feedback on the experience by answering a questionnaire.	Amateur international art students are the target audience for this product. Direct qualitative feedback and analysis of the drawings shows effectiveness of the mannequin as drawing-reference.	Qualitative feedback and direct observation
S1, S2, F2, F3, F4, F5, F6, M1, M2	<u>Performance Testing</u> I remake animals from different groups to test how well the model can capture animals. Comparisons made using the area of a lateral silhouette of the mannequin and the actual animal.	Determines how effectively the mannequin functions when being used. The tested specifications are not based on opinion or perception, so it can be done by a single person without biased results. The built models can be used in other tests as well. The test will yield qualitative data. Allows determining stability of joints and overall size.	Qualitative data from construction Quantitative form silhouette comparison
M3	<u>Natural Environment Testing</u> Spraying the model with 2 liters over 15 minutes.	Recreates moderate rainfall (Quiqoo), 5-9mm/hr (NASA). Might be experienced if used outside.	Qualitative observations
M1, F3	<u>Destructive Testing</u> Testing the durability of a complete model by pushing it off a workbench 86cm off from the ground 5 times. After each fall, damaged parts are recorded and replaced.	Used to find joints and parts most prone to breaking.	Quantitative, quantity of parts separated or broken
M1	<u>Tolerance Testing</u> Pulling attached parts with a spring, determining force for separation.	Shows the range of force needed to separate parts, which should be similar to the force needed to join parts too. Allows testing of the strength of different joints.	Quantitative force in Newtons
F3, M2	<u>Weight Testing</u> Weighing the largest of the models from performance testing.	Weight can be compared to estimated maximum comfortable mass, 2.75kg (Appendix 3).	Quantitative weight comparison

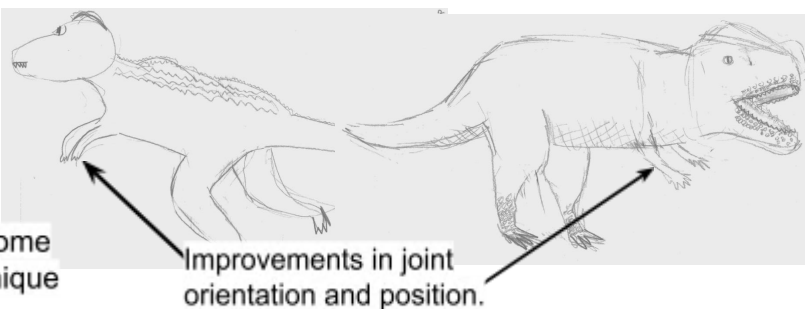
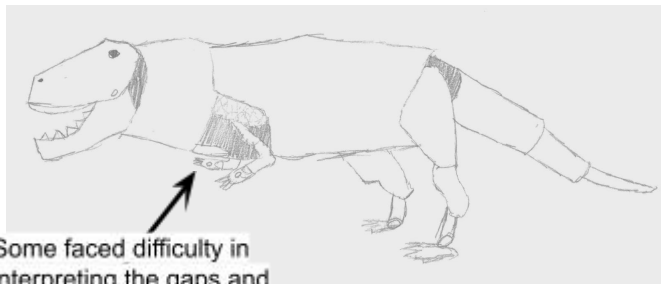
Evaluation of the Prototype

Expert Appraisal

The teacher got to see my model up-close and gave opinions on its effectiveness as a learning and reference tool for both personal and school use (Appendix 7). They stated that the color was appropriate and the ability to use different materials for the shells gave more freedom, such as being able to draw on them for more detail [A1, A2]. The possibility and shape of the model [F4, F6, D1] was found to be quite accurate and useful for learning, although it might not suffice as a substitute for drawing from life as the model cannot convey weight, muscle and skin as accurately. One of the limitations was the large size making it difficult to store for personal use [S2], if the model is kept intact. The size also makes the model less stable [F2, F3].

User Testing Session

The session with 20 students and their feedback revealed the mannequins capabilities as a learning tool. Many drawings showed improvement in overall anatomy (Appendix 9). According to feedback (Appendix 8) students mostly found the model a useful reference tool and weren't hindered by simplification of the shells. The size and material of the mannequin was also adequate [S1, S2, A1, A2]. A significant issue was the difficulty of balancing the model as it would frequently topple over.



Performance Testing

The models managed to match overall proportions and shapes, but were oftentimes thinner than life due to some bones not having paper shells. Some models couldn't accurately replicate joint movements. No joints wore down significantly during construction [F5], although some ball joints struggled to hold up weight.

Animal Model (Appendix 10)	Lateral silhouette area compared to desired area
Torvosaurus tanneri	77%
Prestosuchus chiniquensis	72%
Hatzegopteryx thambema	87%
Grus grus	107%
Tyrannosaurus rex	91%
Average	85%

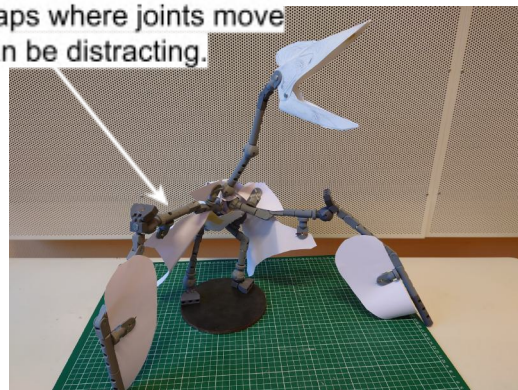
Conveys larger shapes and proportions, but struggles with smaller ones. [F6]



Specific parts such as feet and hands are simplified.



Gaps where joints move can be distracting.



Sometimes it can be difficult to fold paper shells to fit form. [F6]



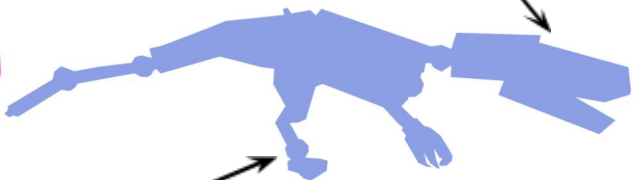
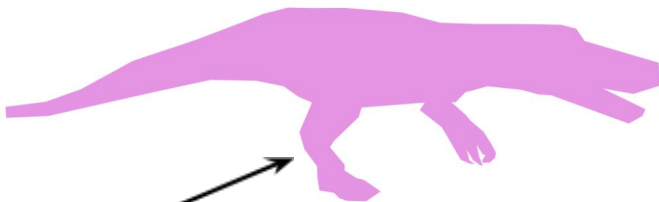
Reliance on paper shells means some parts might be inaccurate. [F6]



Struggles with high joint movement such as in folding wings.

Some figures struggle to balance due to weak foot joint. [F2]

Some parts are less rounded and smooth than life. [F6]



Comparison of silhouettes reveals limitations of the mannequin.

Model is overall thinner than life. [D1]

Natural Environment Testing

After being sprayed with 2 liters over 10 minutes, the model paper had absorbed most of the water. The shells were very soft and fragile, and the model was weighed down. The model was recorded every 2 minutes during spraying (Appendix 11). Beyond 2 minutes, the model had become unusable.



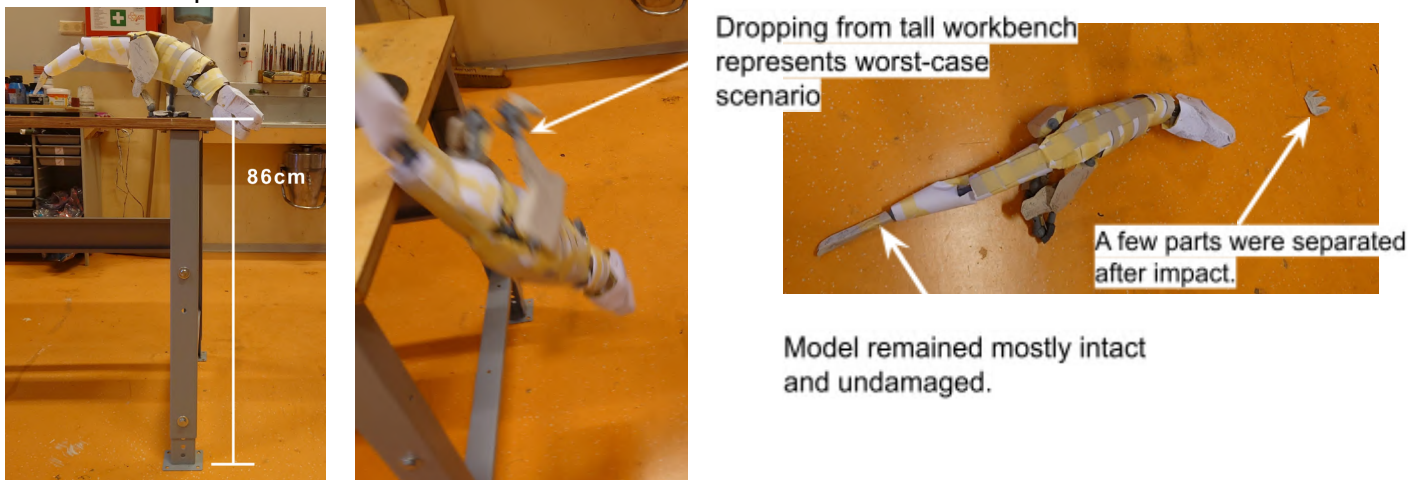
Resists light spraying. [M3]



Shells deform after absorbing water. [M3]

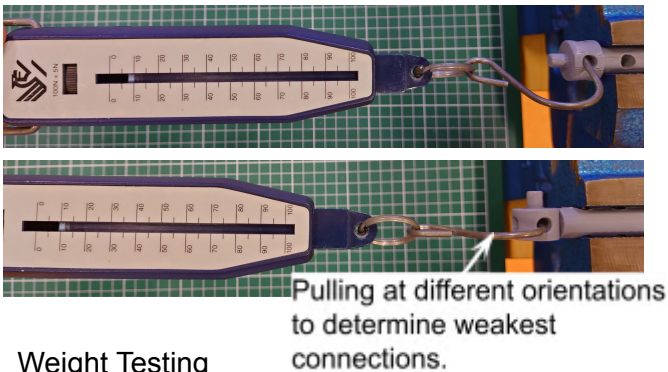
Destructive Testing

The model was more resistant to impacts than expected. In total 8 peg joints and 3 paper shells were separated. Only 1 paper shell was damaged (Appendix 12).The paper shells were flexible and cushioned much of the impact.



Tolerance Testing

The average force required is less than the lowest range of female pulling force on a horizontal bar, 189,75Nm (Roymech). Although the very high ranges means that some connections might be difficult to separate or join (Appendix 13) [F1]. The high ranges make construction and posing frustrating due to unpredictability and abnormally loose or tight connections [F1, F2].



Weight Testing

The model was much lighter than anticipated, with the largest mannequin weighing only 380.5g. That is only about 14% of the maximum comfortable weight of 2.75kg (Appendix 3). This allows models to be large yet still posable and easy to carry [F3, M2]. The 989.5g plate is heavy enough to keep the model in place.



Connections	Force to Separate (N)
Paper shell to clip	10
Male to female parallel	
Average	59
Range	90
Male to female perpendicular	
Average	86
Range	40
Female to male parallel	
Average	26
Range	50
Female to male perpendicular	
Average	34
Range	75
Subassemblies	
Average	63
Range	80

Paper shells and light PLA bones allow model to be lightweight. [M3]

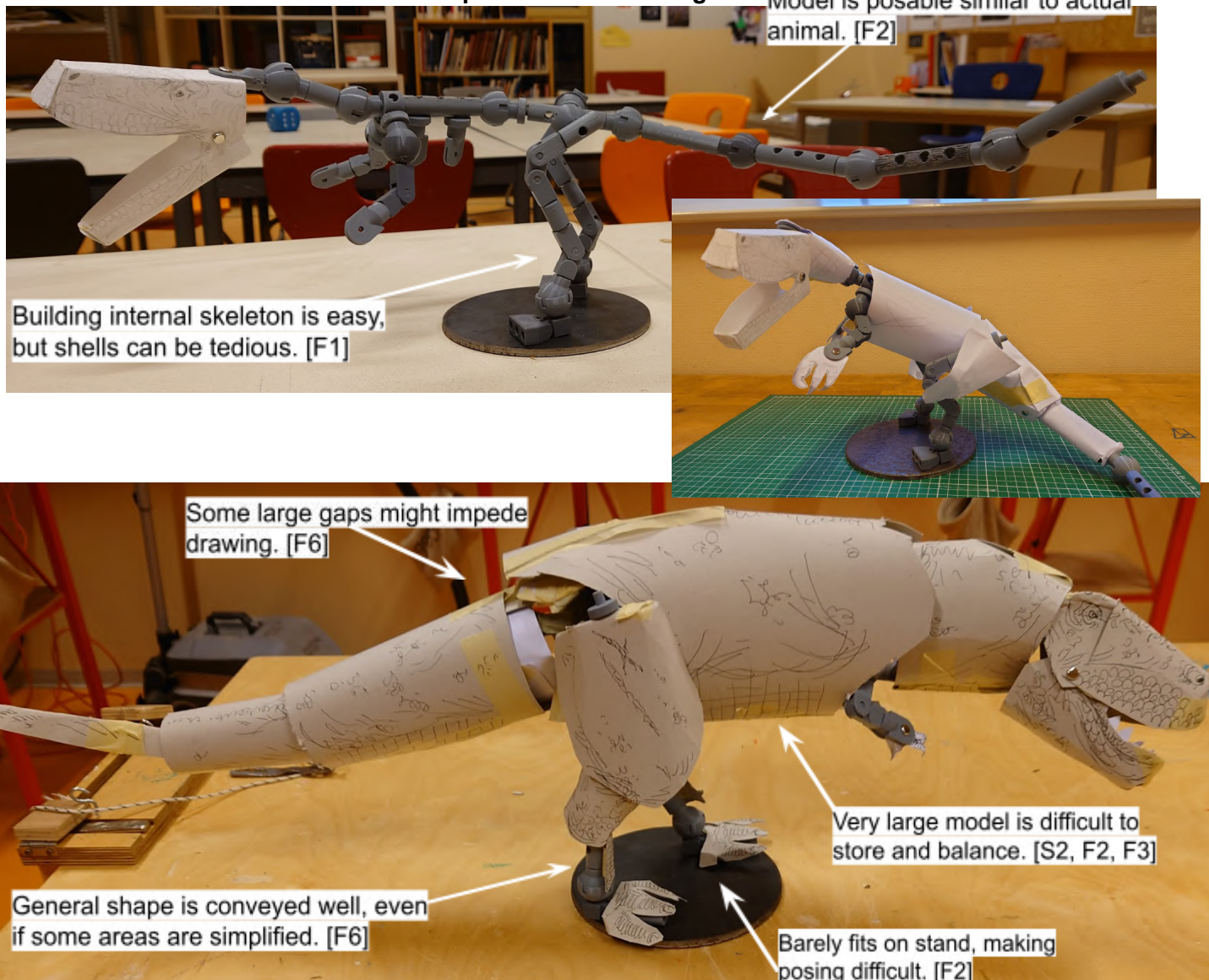
Overall Impact

The model has potential to function as an educational tool for personal and school use for learning artists. The parts allow the creation of mostly accurate animals, although at larger sizes there are issues with stability [F3, F6]. The magnetic plate and joints allow for some posing [F2, F4], although weak foot joints make balance difficult. The parts proved durable and lightweight [M1, M2] although the paper shells were susceptible to moisture if used outdoors [M3]. PLA joints also meant that they didn't wear down during use [F5]. The paper shells allowed for drawing on additional details and were easily bent into shape, but sometimes difficult to insert into the clips [F1]. Other materials such as cardstock could be used for different textures [A1, A2], but are hard to insert brads through.

The model could sometimes be too large [S2], due to the space needed for the clips and having to keep parts in proportion [D1]. Even smaller models were easily observable [S1].

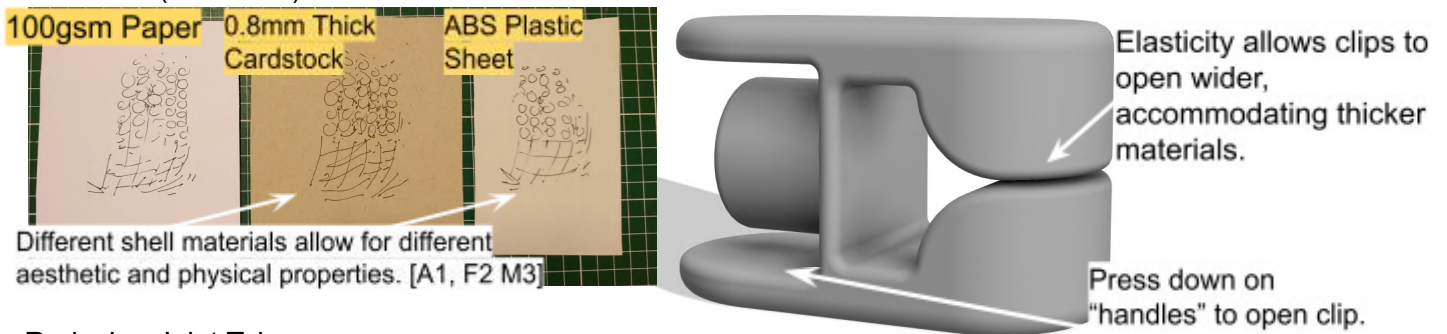
Specification	Evaluation
A1, A2	Met
F1, F2, F3	Not met
F4	Partially met
F5	Met
F6	Met
M1, M2	Exceeded
M3	Not met
S1	Exceeded
S2	Partially met
D1	Met

Improvements to Design



Flexible Clip Joint

Being able to use different materials is an advantage [A1,A2], but is limited as it is difficult to insert the soft brads into materials thicker than paper. Materials such as ABS plastic are also water-resistant (Roger) [M3]. More flexible clips made of SLS-compatible TPU, which has an elasticity modulus of only 40.5 MPa (Protolabs) should allow for easier insertion of varied materials.



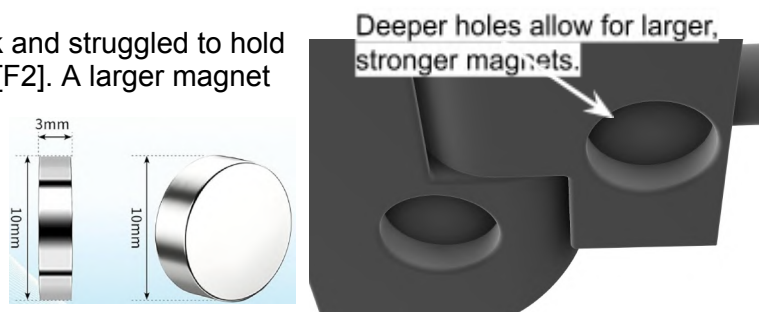
Reducing Joint Tolerance

Due to the manufacturing method used, there was large variance in the tolerance of the joints, which made some fits very tight, and others too flexible. This limits the enjoyability of the building experience [F1] and posability [F2, F3]. This could be accomplished by using Selective Laser Sintering, or SLS printing, instead of FDM printing. SLS, like FDM, can be used to make durable [F2, M1], complicated parts with little finishing required (Unionfab). SLS printing also doesn't require supports, reducing wasted time and material and is ideal for precise-fitting joints (Formlabs). Nylon 12 would be a suitable material alternative as it is lightweight [M2], weather resistant [M3] and durable (Formlabs).

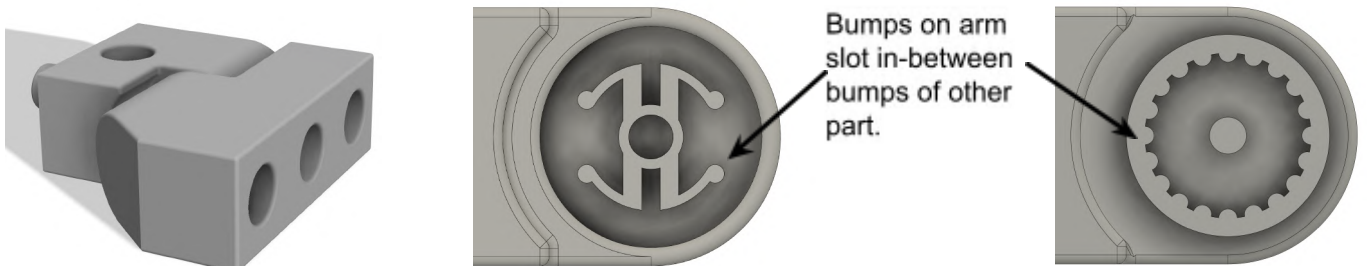
Stronger Foot Magnet

The magnets on the foot were somewhat weak and struggled to hold larger models in place, making posing difficult [F2]. A larger magnet of the same material should be strong (AEMagnets) enough to solve this issue. Neodymium magnets of 10mm in diameter and 3mm in thickness could suffice.

Figure 6.1 (Amazon)



Increasing Foot Joint Strength

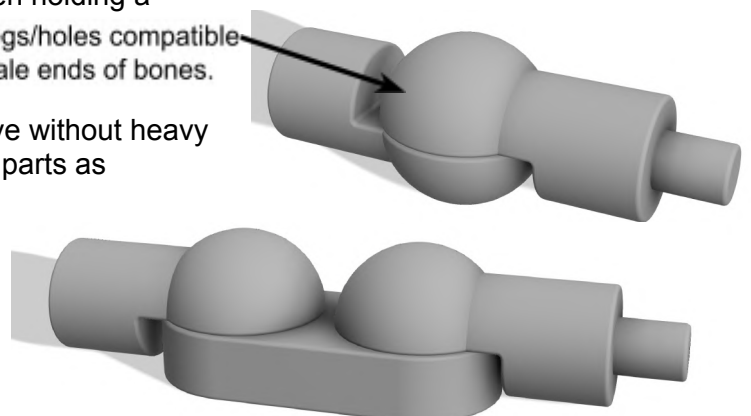


The foot joint was quite loose, making posing the model difficult as it would give way, causing the model to topple over [F2, F3]. An improvement to this design would be to increase the range of movement [F4] and make the joint harder to move, so it can bear the entire weight of the model. An incremental hinge joint would solve this issue, without limiting posability. The joint would fit into certain positions and be harder to push out of those positions, especially when holding a pose.

Improved Linkage Joint Assembly

The linkage joints were very tight and difficult to move without heavy sanding. The assembly process risked breaking the parts as overlapping plates had to be bent before the pegs slot into the holes forming the joint. This process makes it very difficult to separate the joint without

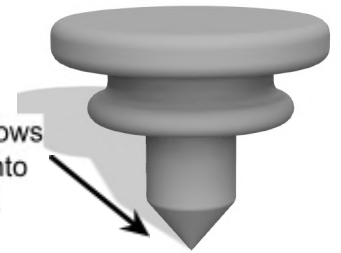
Connection pegs/holes compatible with male/female ends of bones.



breaking or bending the overlapping plates [F2]. Ball-shaped joints have increased range of motion [F4] and are more natural thanks to their rounded shapes [F6]. The join connection is the same as other peg joints, allowing for more unique connections.

Body Panel Pin

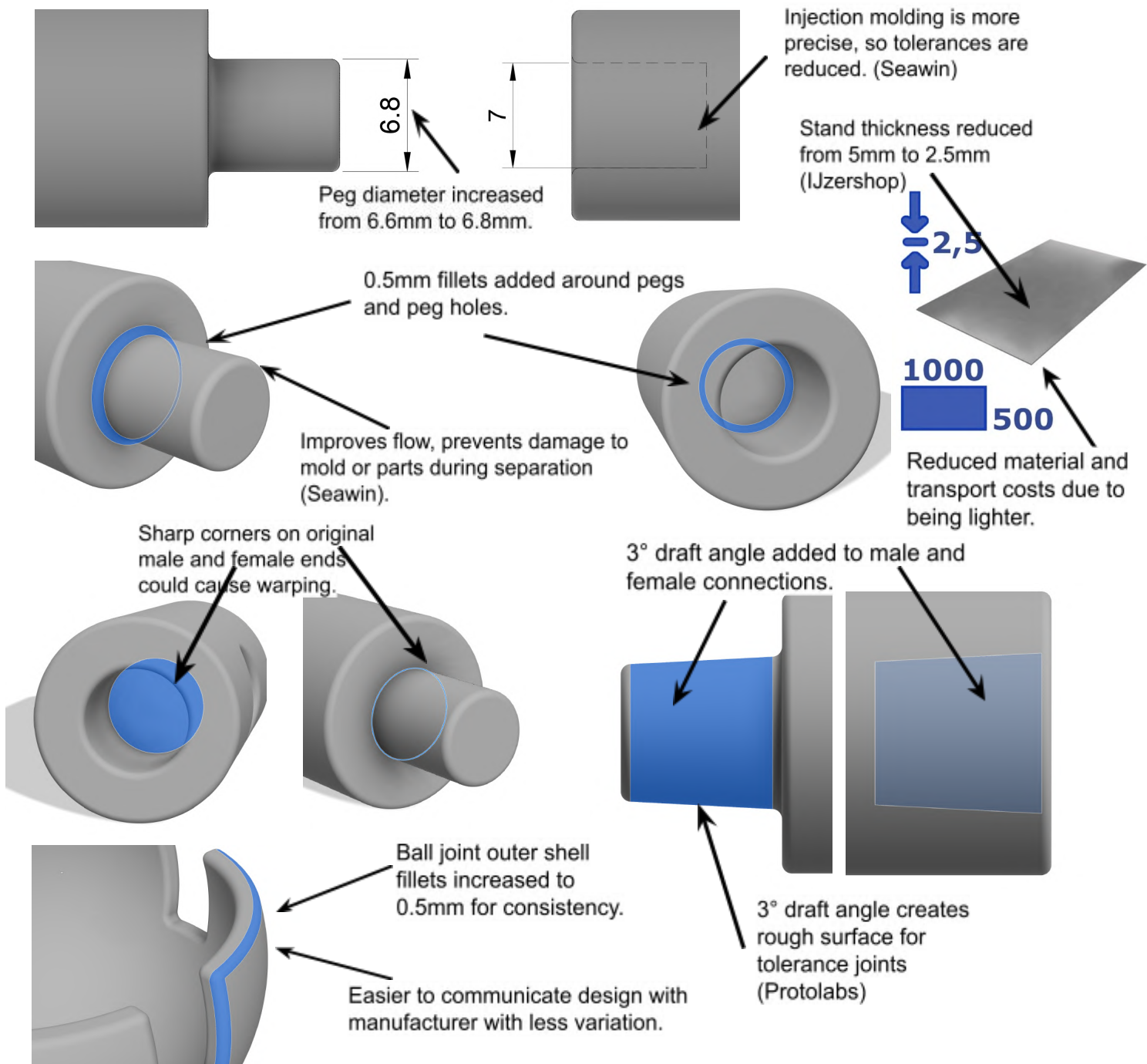
Sometimes it was difficult to attach the paper shells to the clips, especially in ways that kept the desired shapes [F1, F6]. This new pin part can be attached to the holes in bones to keep paper parts in place. Reducing reliance on the larger clips should allow for size reductions in models [S2].

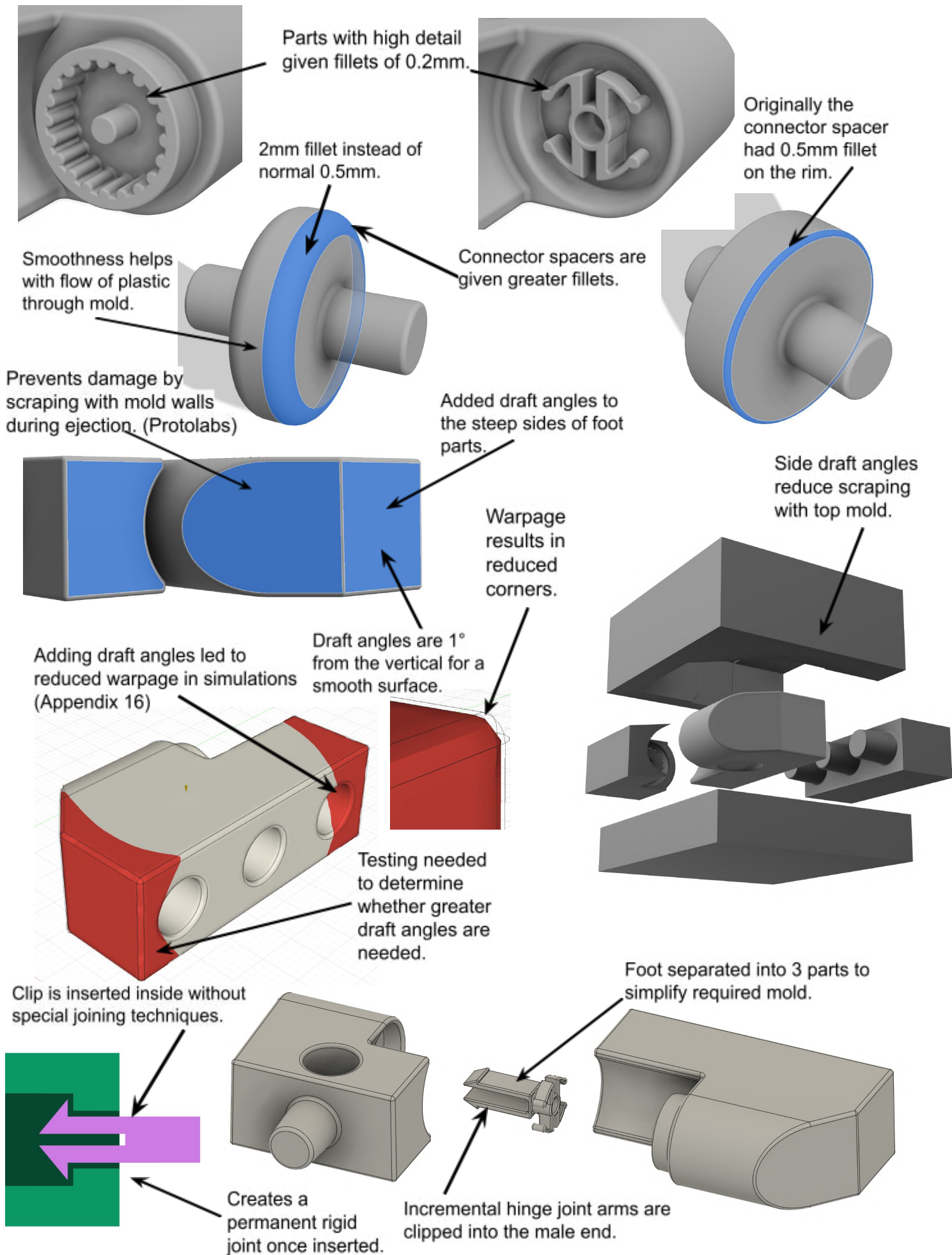


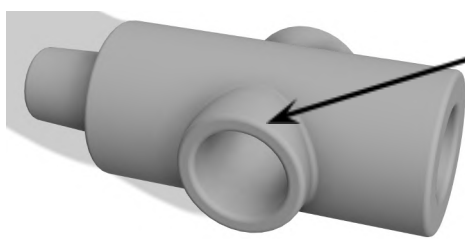
Larger Stand

For larger models or those with a wider gait, fitting onto the stand was difficult. A larger stand with a diameter of 200mm instead of 165mm should solve this issue. The stand will also be made thinner to reduce its weight.

Development of the Design for Manufacture

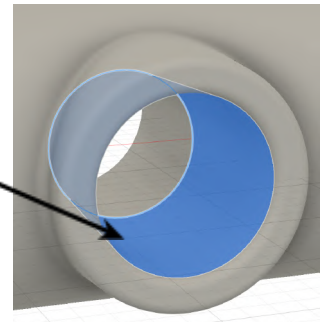






Side connections are extended to accommodate for draft angles.

Allows connections from both sides despite draft angles.



Extensions mean draft angles don't impede connections from both sides.

Original Design

Adjusted for Draft Angles

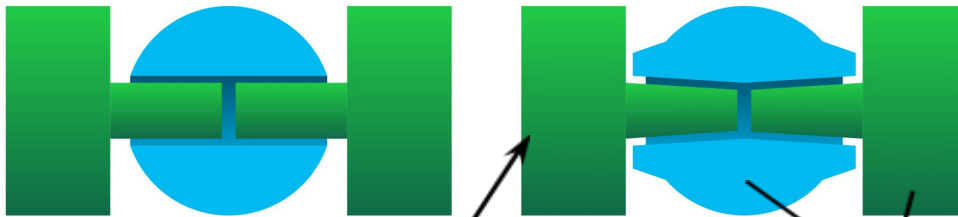
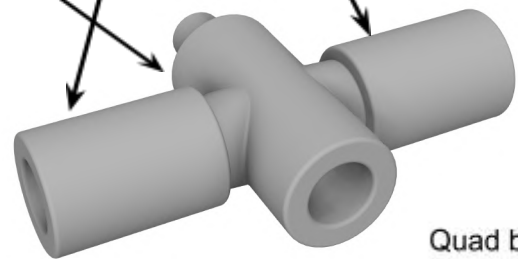
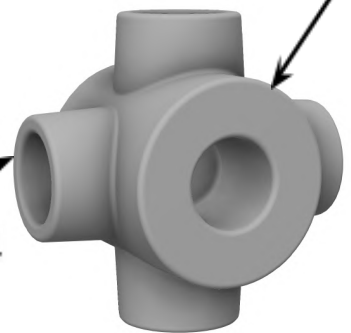


Diagram shows the change from a cut-section view.



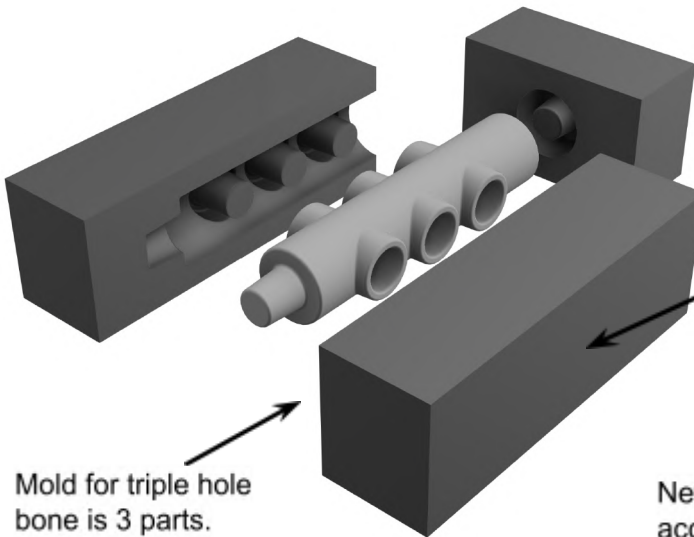
Quad bone simplified for easier manufacture.



New design also accommodates draft angles.

Clip part ends rounded to improve flow and ejection.

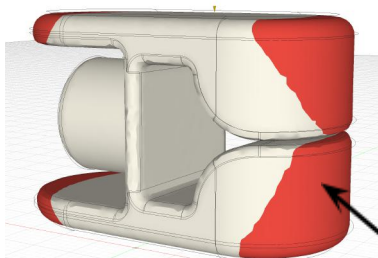
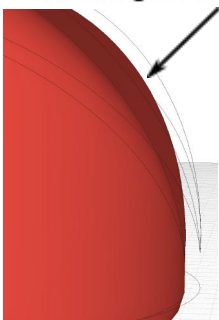
Mold for triple hole bone is 3 parts.



Mold demonstrates the importance of draft angles.

Most parts will use a single injection point.

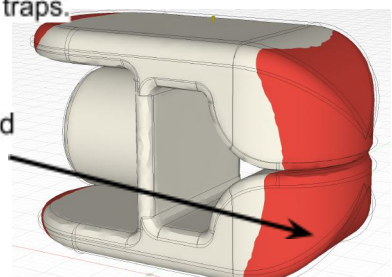
Warpage causes shrinking at corners



Single injection point has greater quality prediction and reduced air traps. (Appendix 16)

Rounded clip has reduced warpage. (Appendix 16)

Original design used unnecessary extra material.



Final Product

All male and female ends are given fillets.

Side connections simplified and adjusted for draft angles.

Prevents sharp corners to improve flow during molding.

3° draft angle added to male and female connections.

Sharp corners rounded off to improve flow and mold ejection.

Detailed parts are made smoother with fillets of 0.2mm.

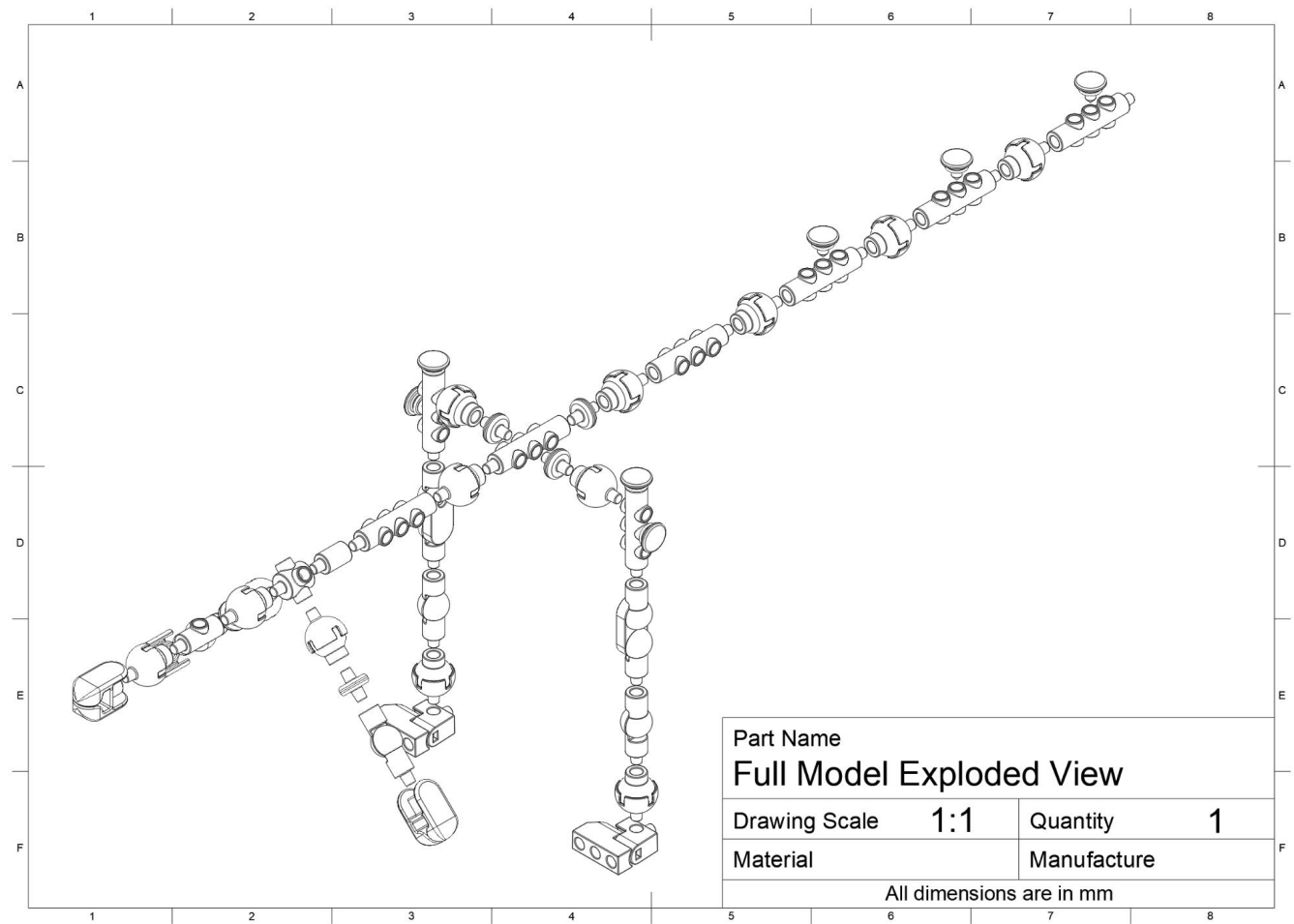
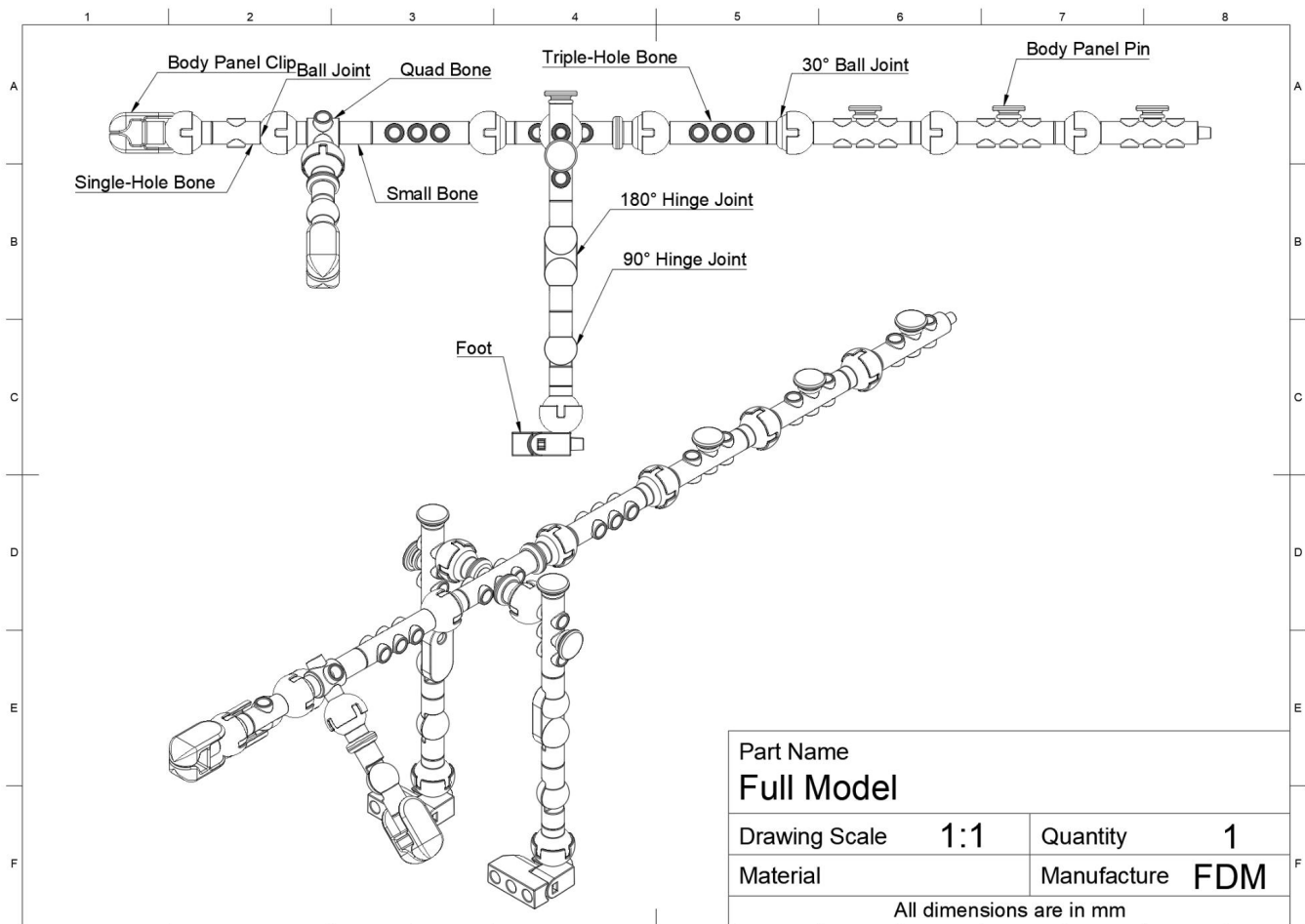
Draft angles of 1° added to sides of foot part.

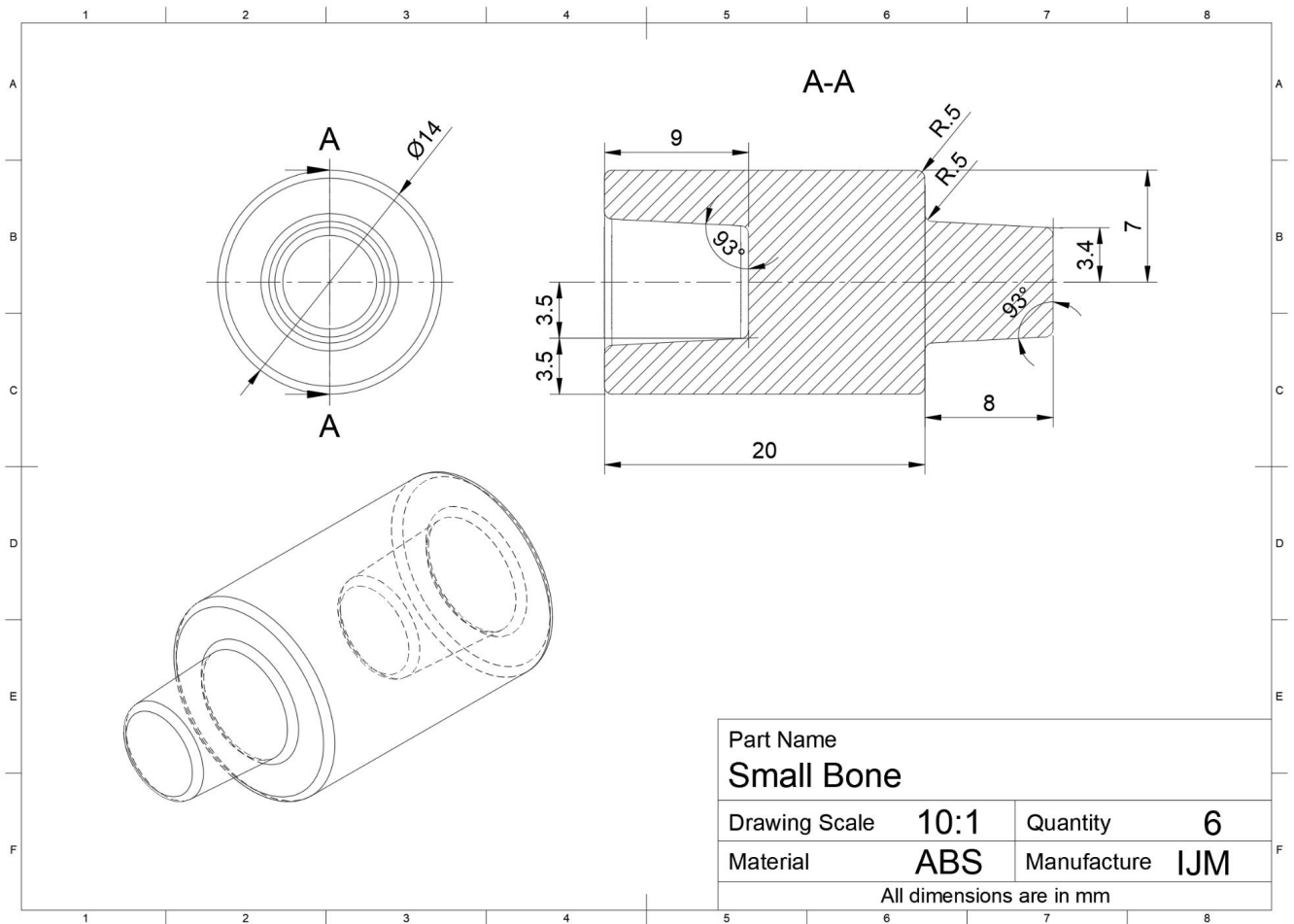
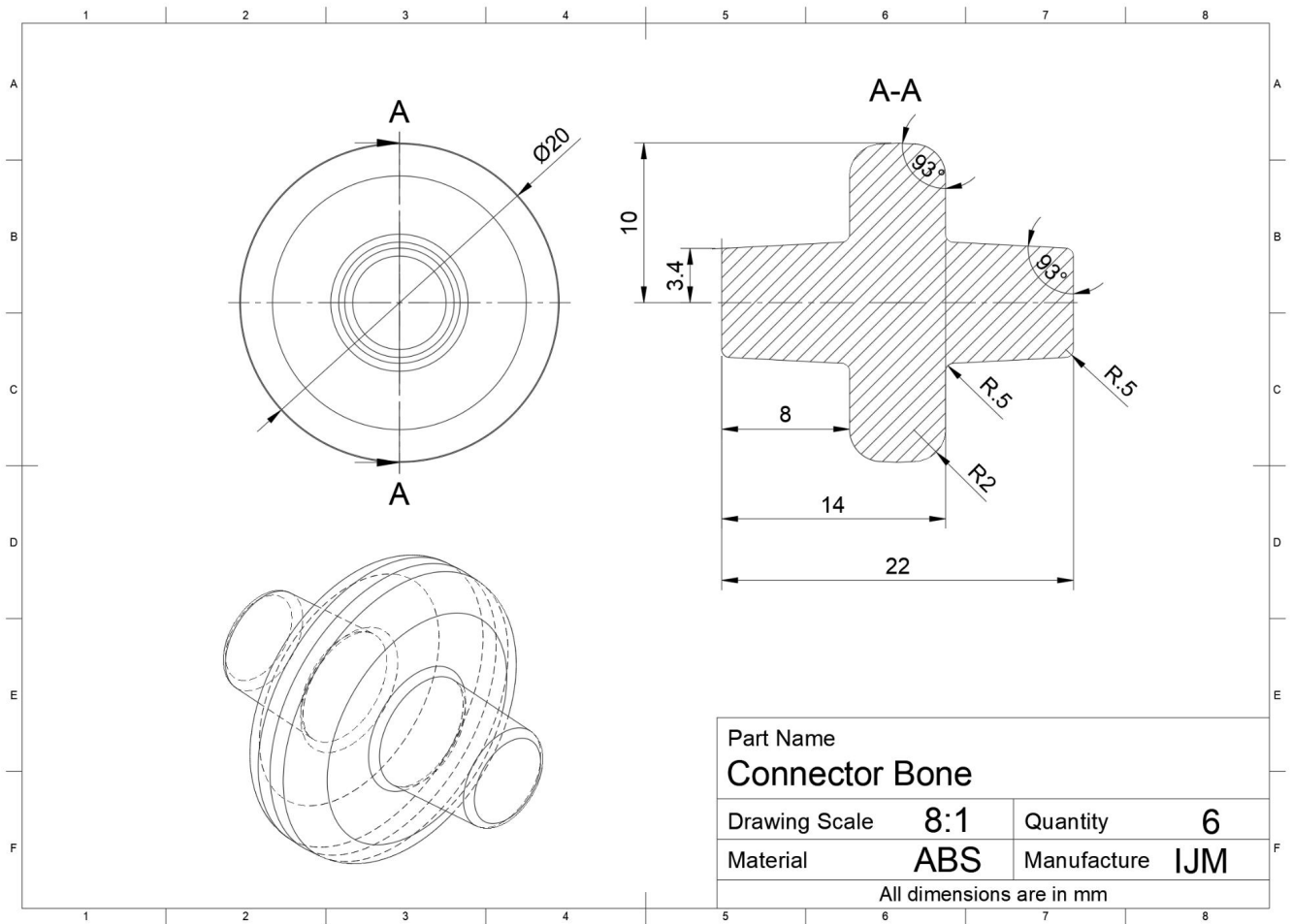
Reduces scraping during ejection from mold and warping.

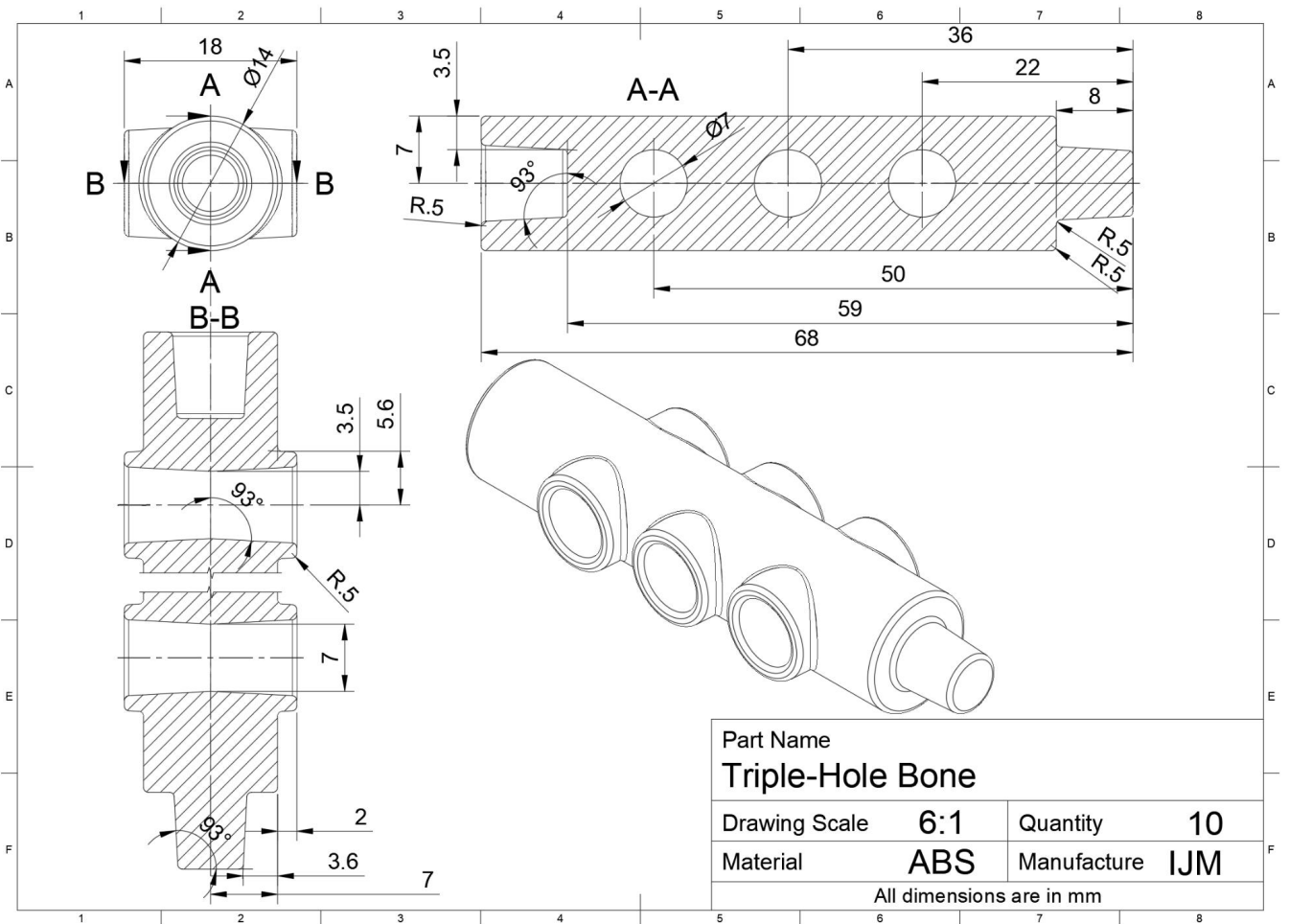
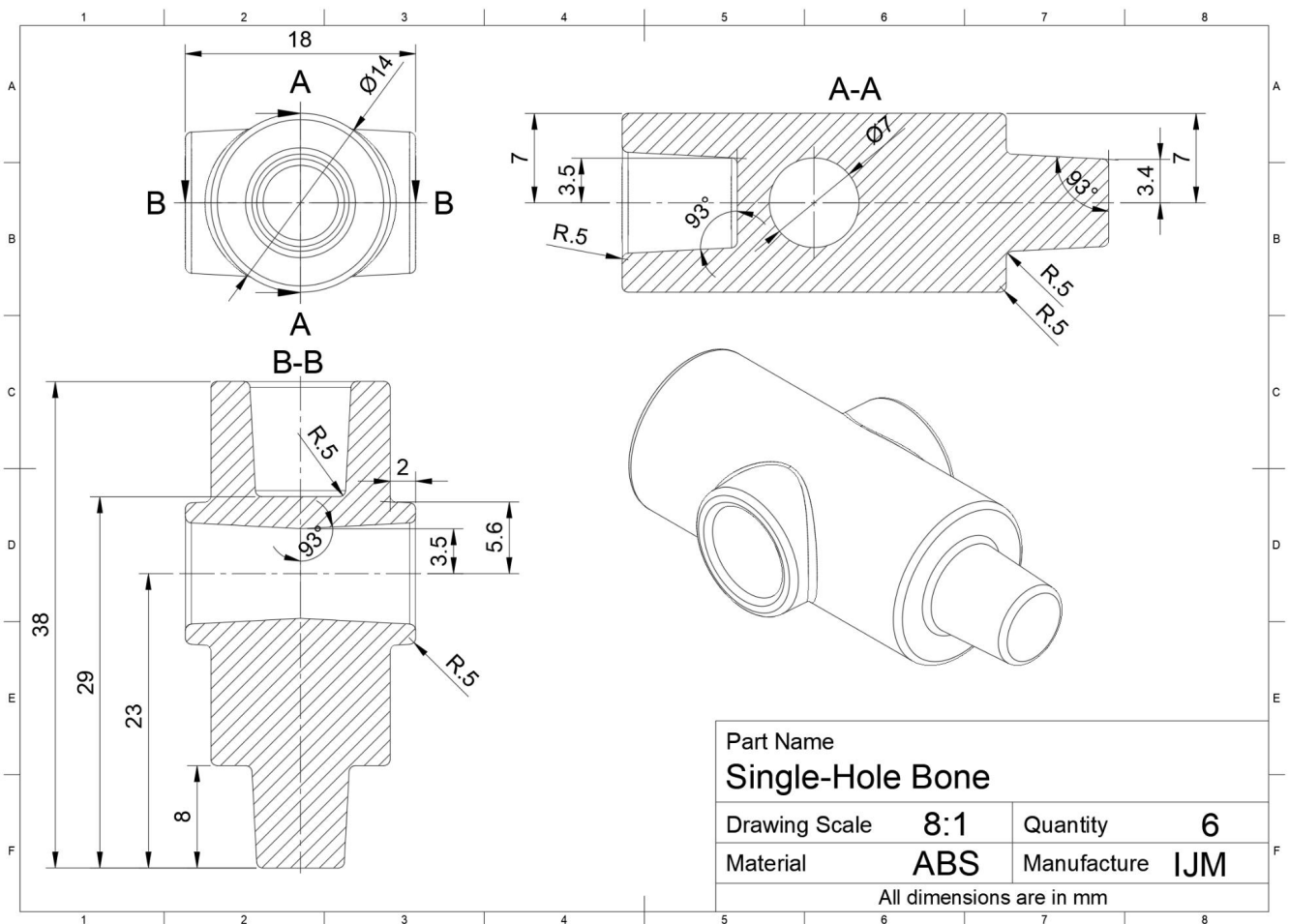
Foot female end separated into 2 parts for easier molding.

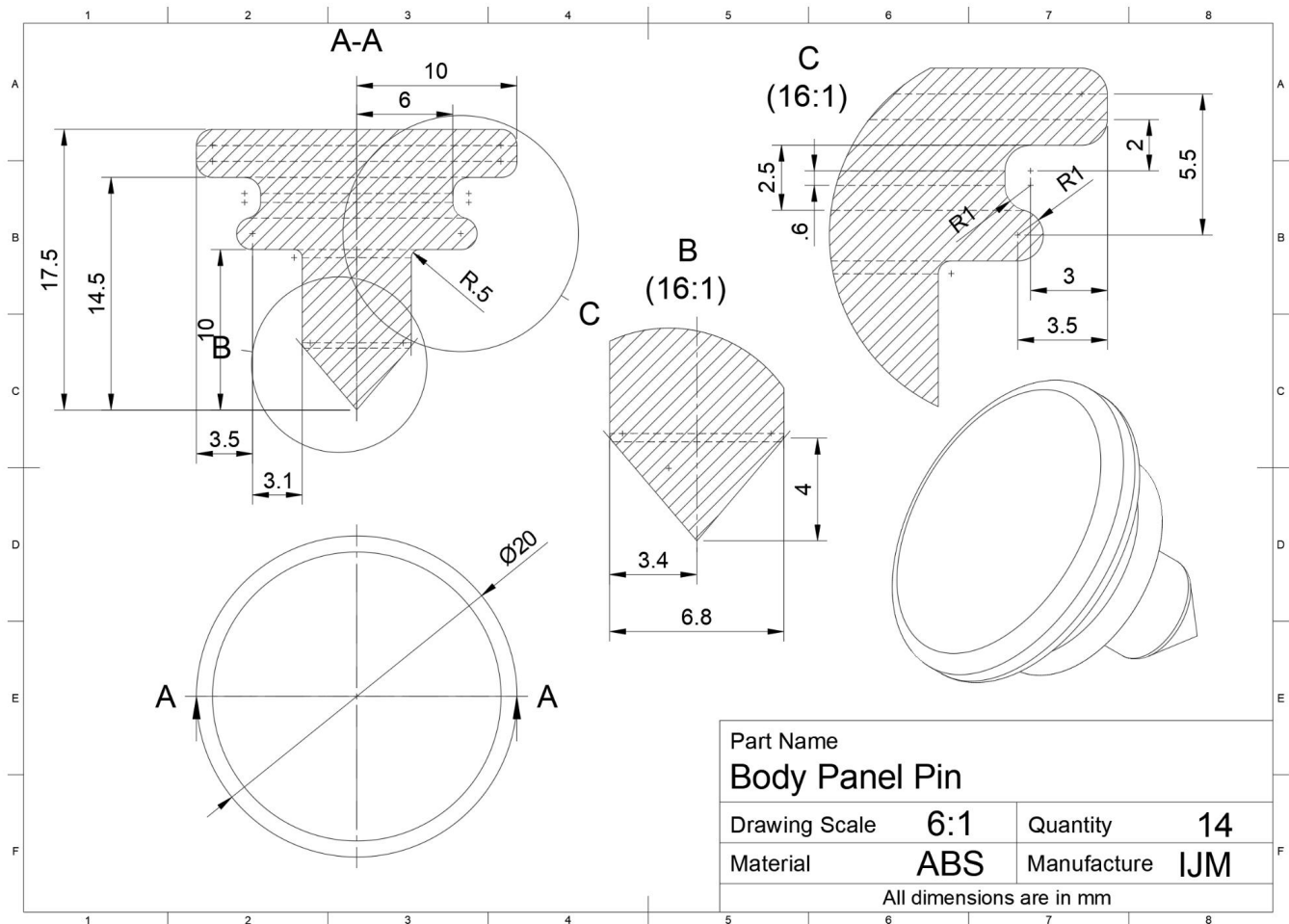
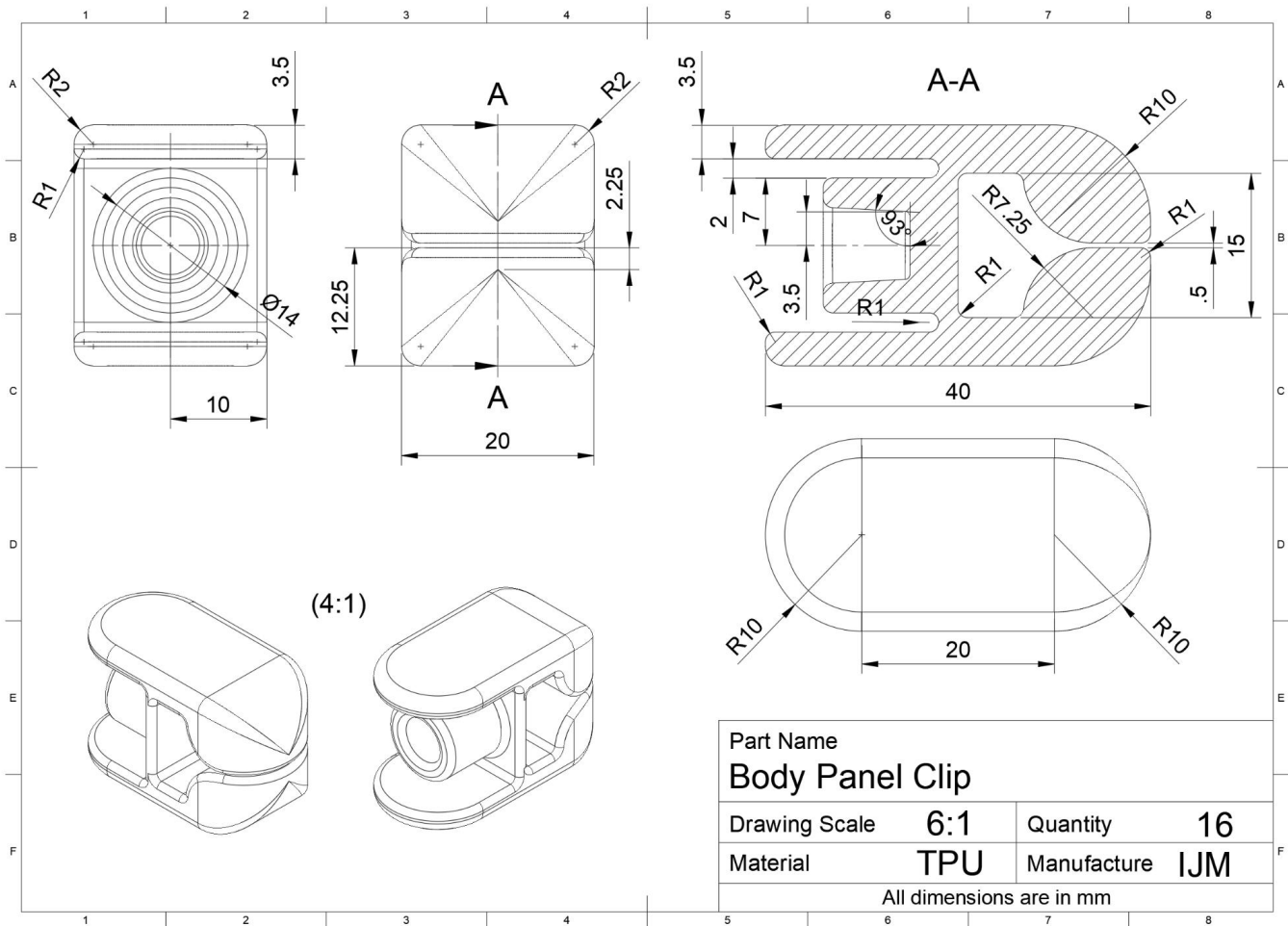
Final Design Proposal

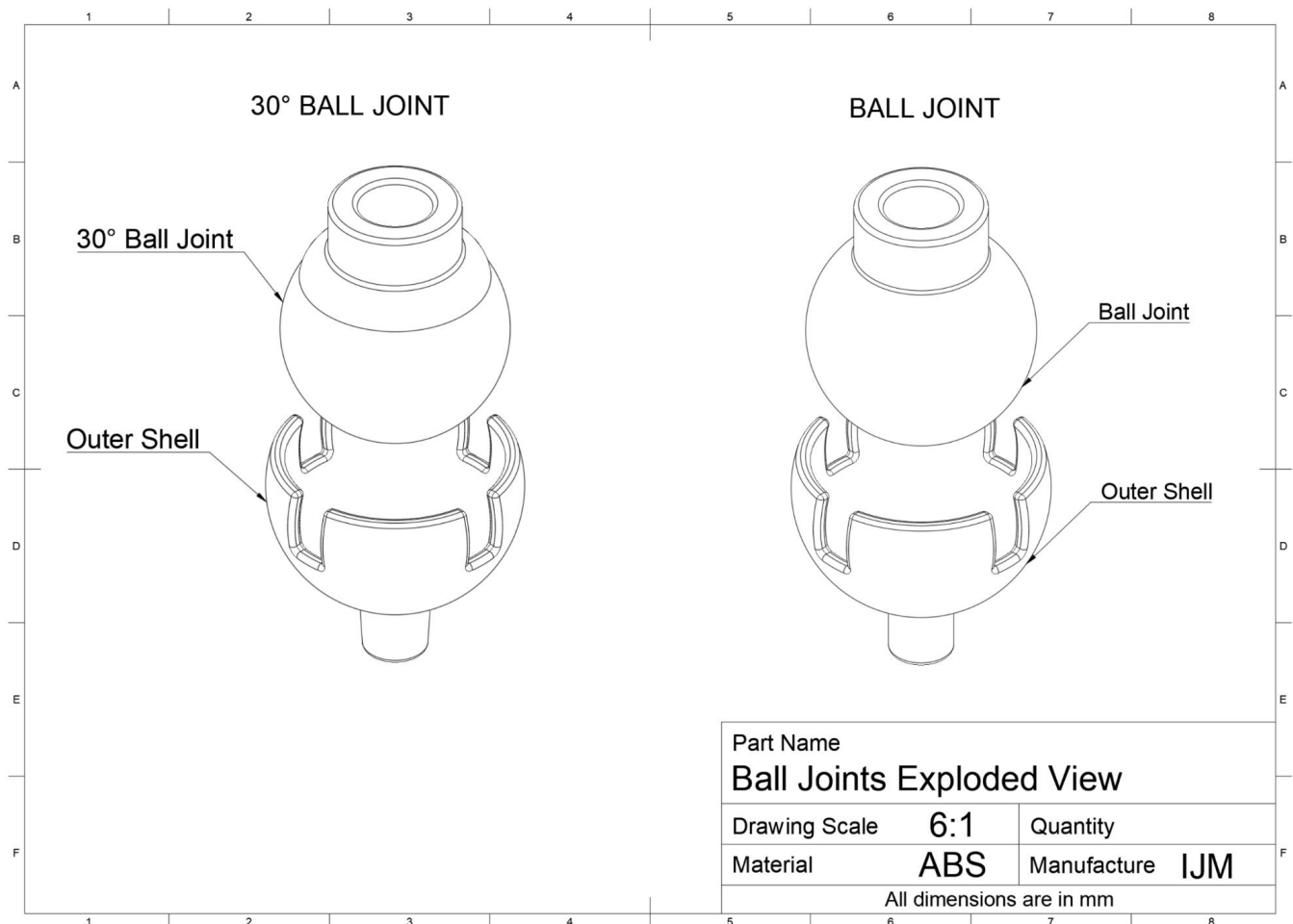
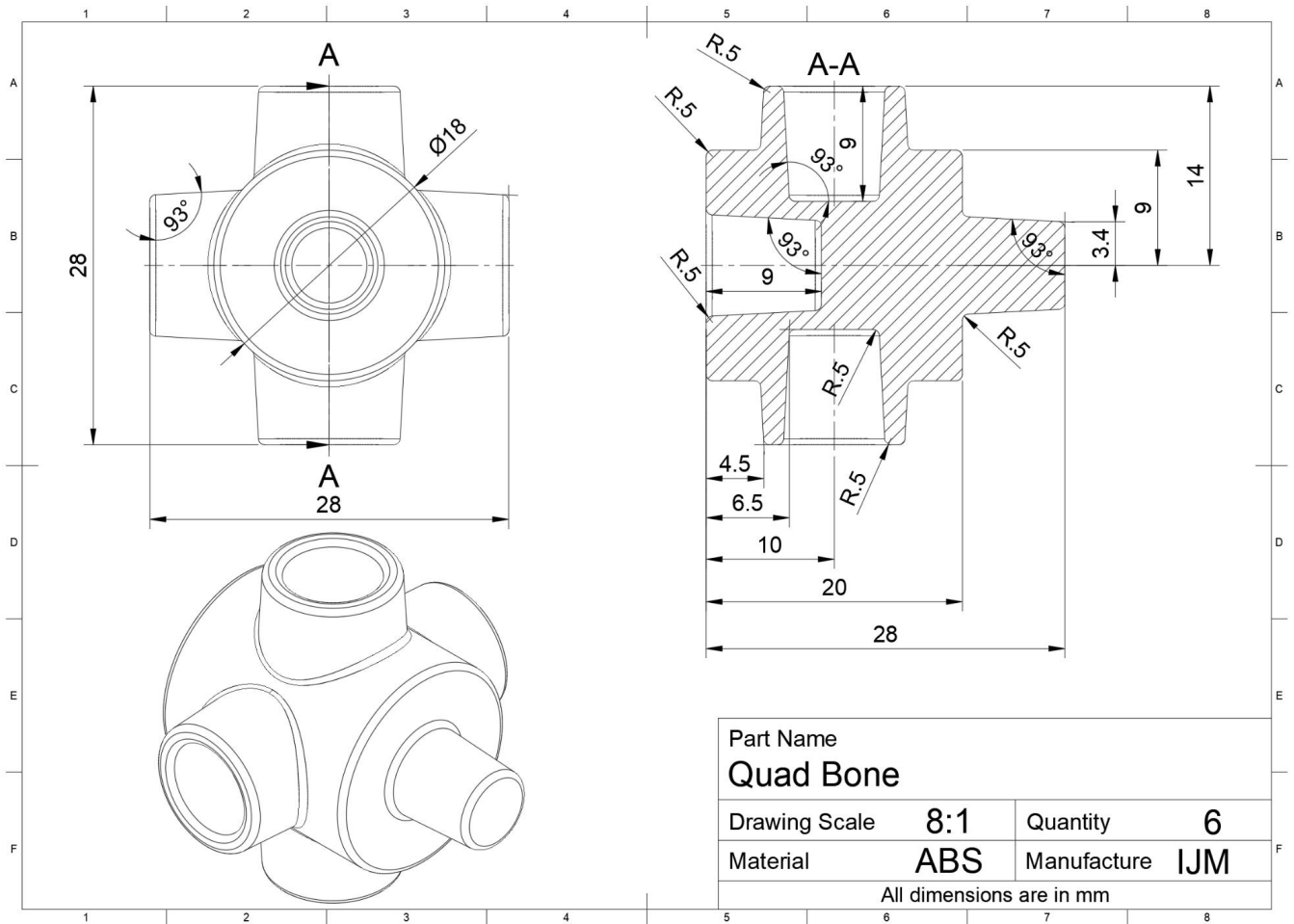
Note: IJM stands for injection molding

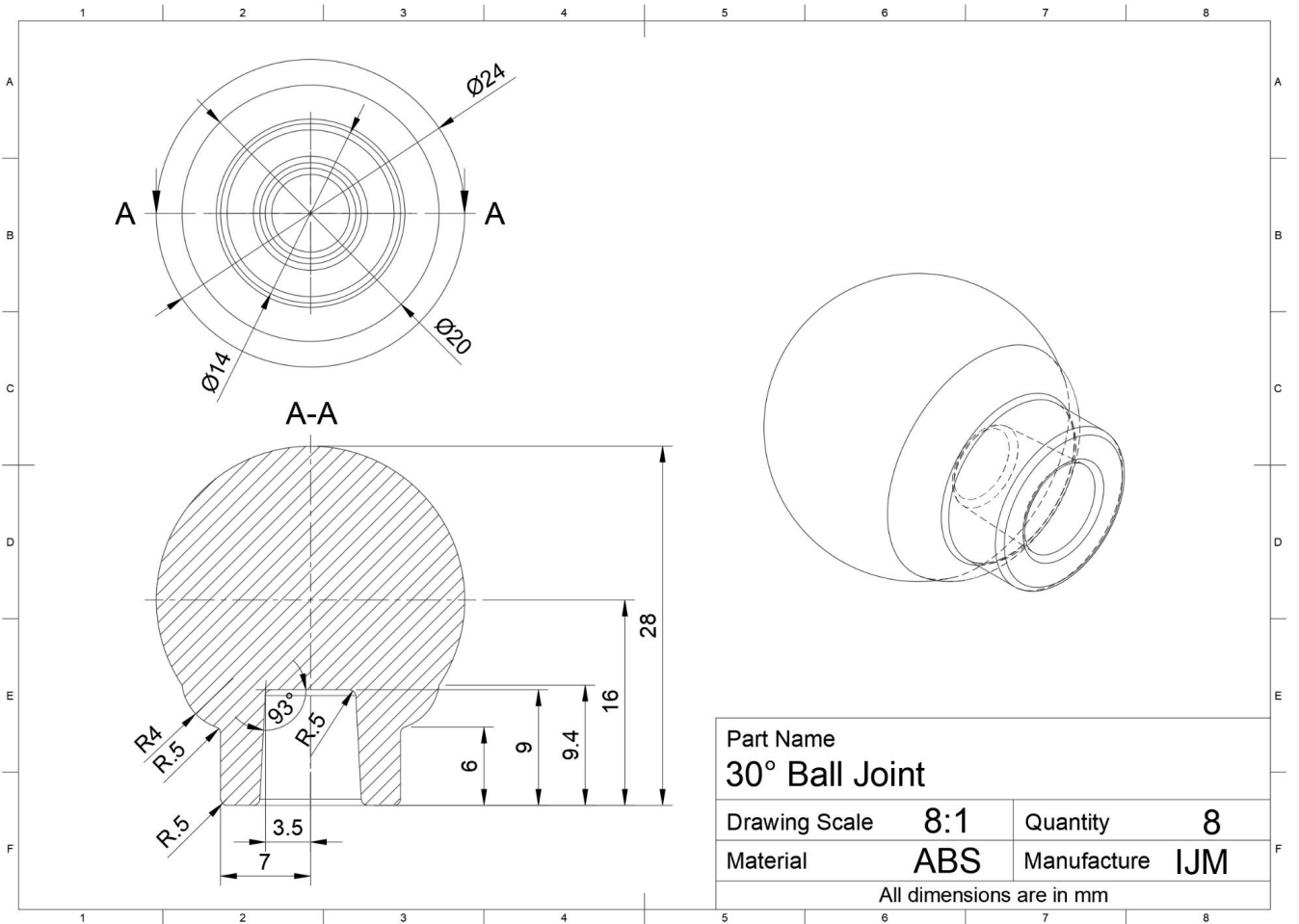
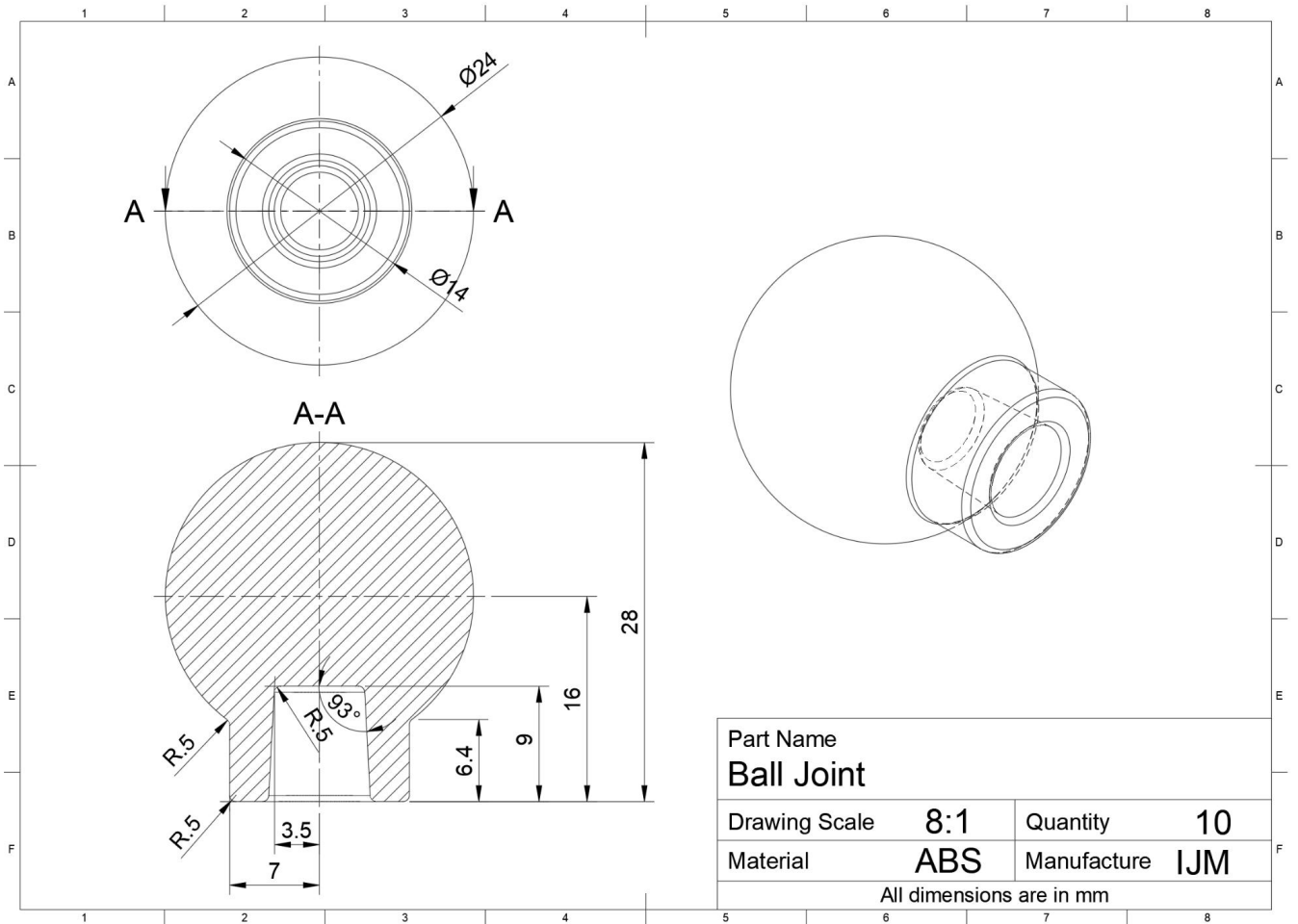


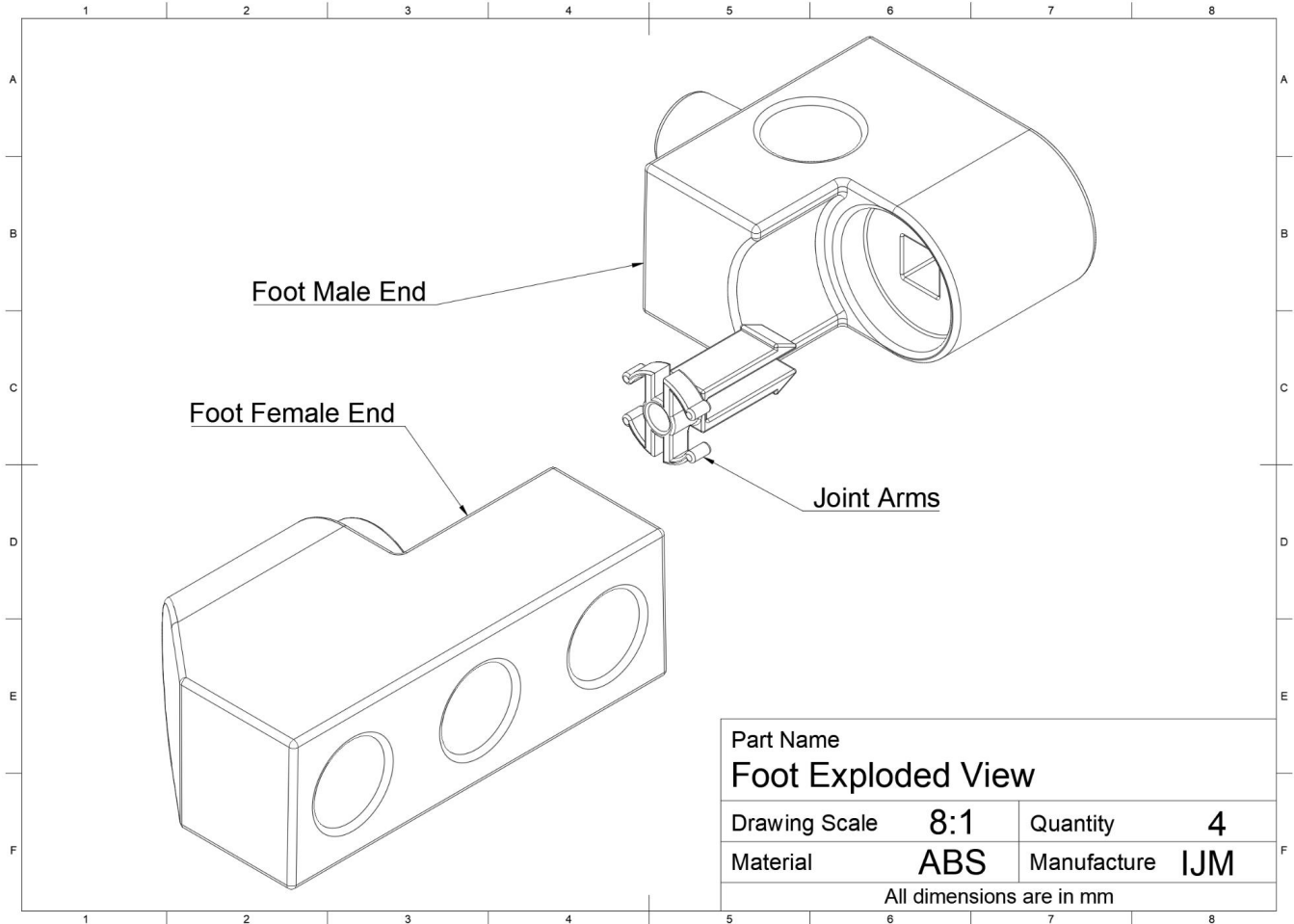
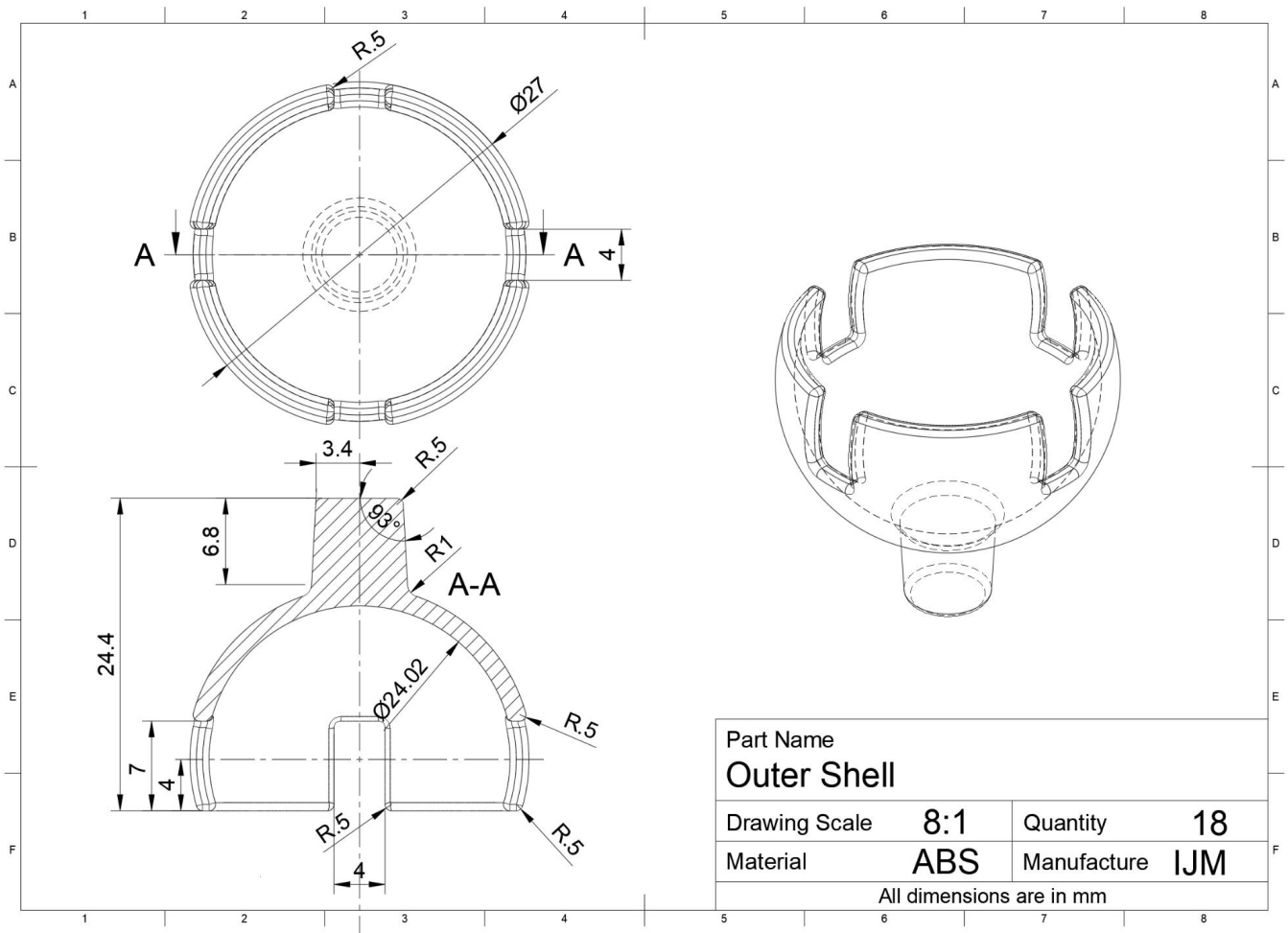


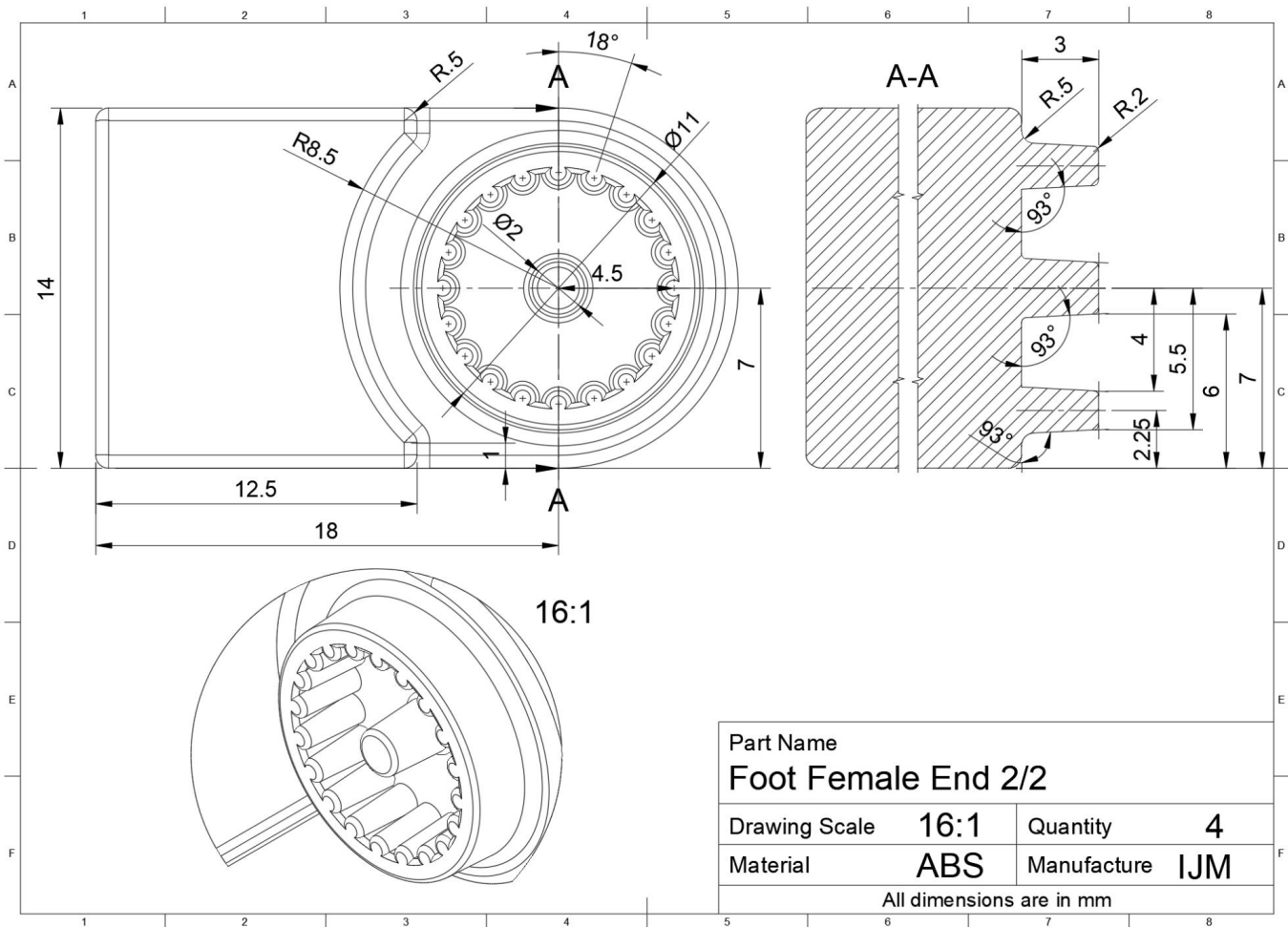
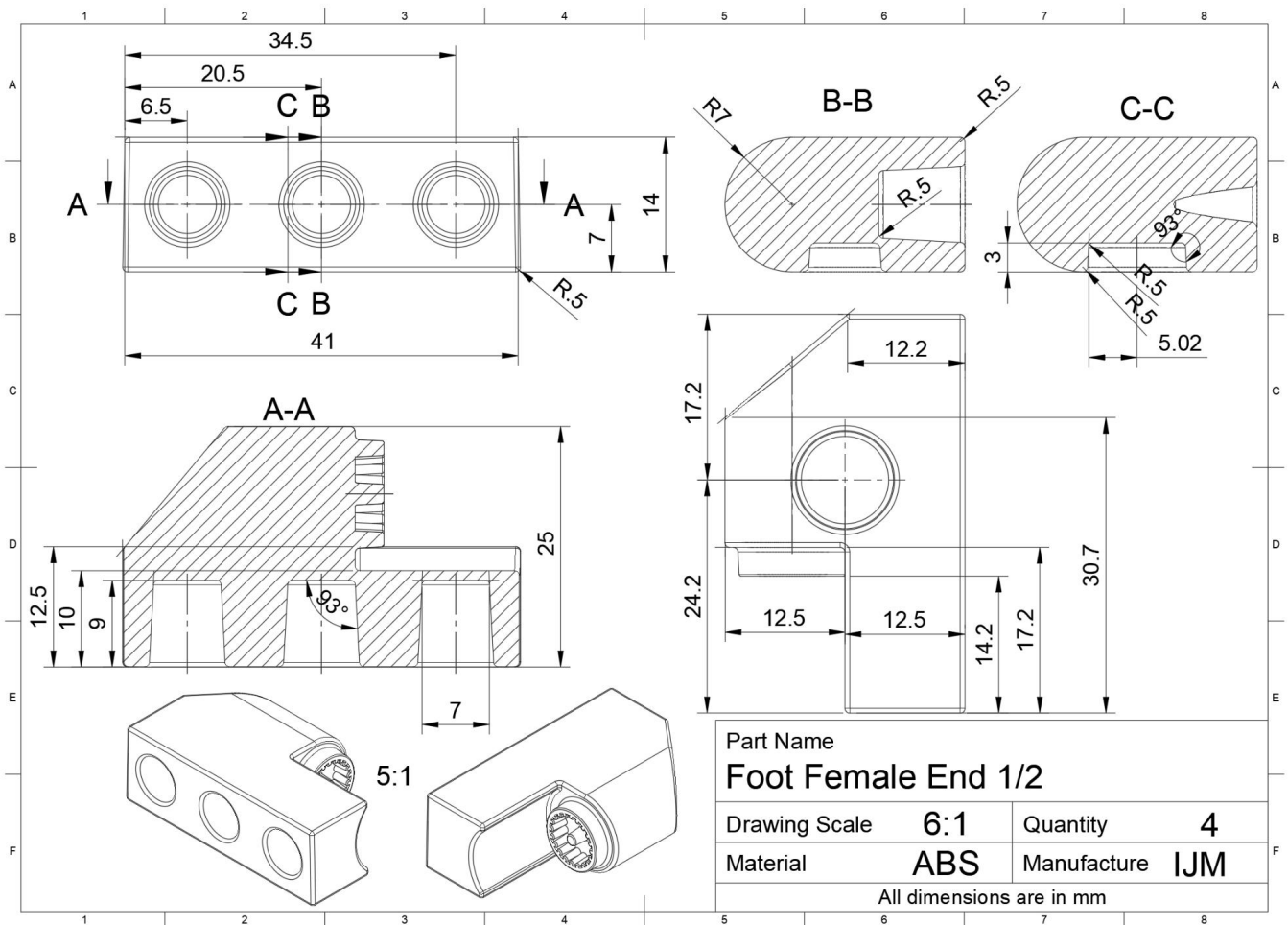


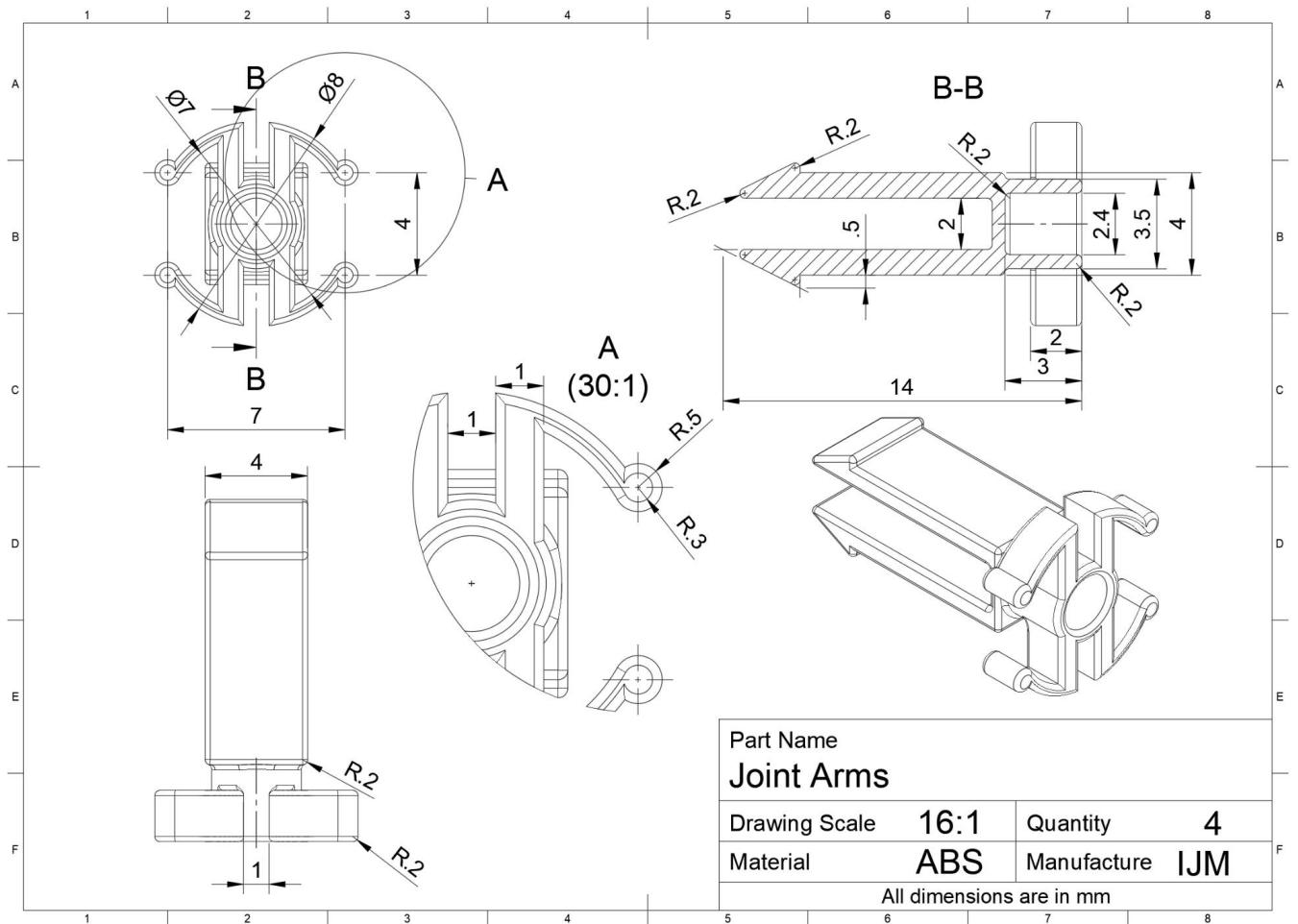
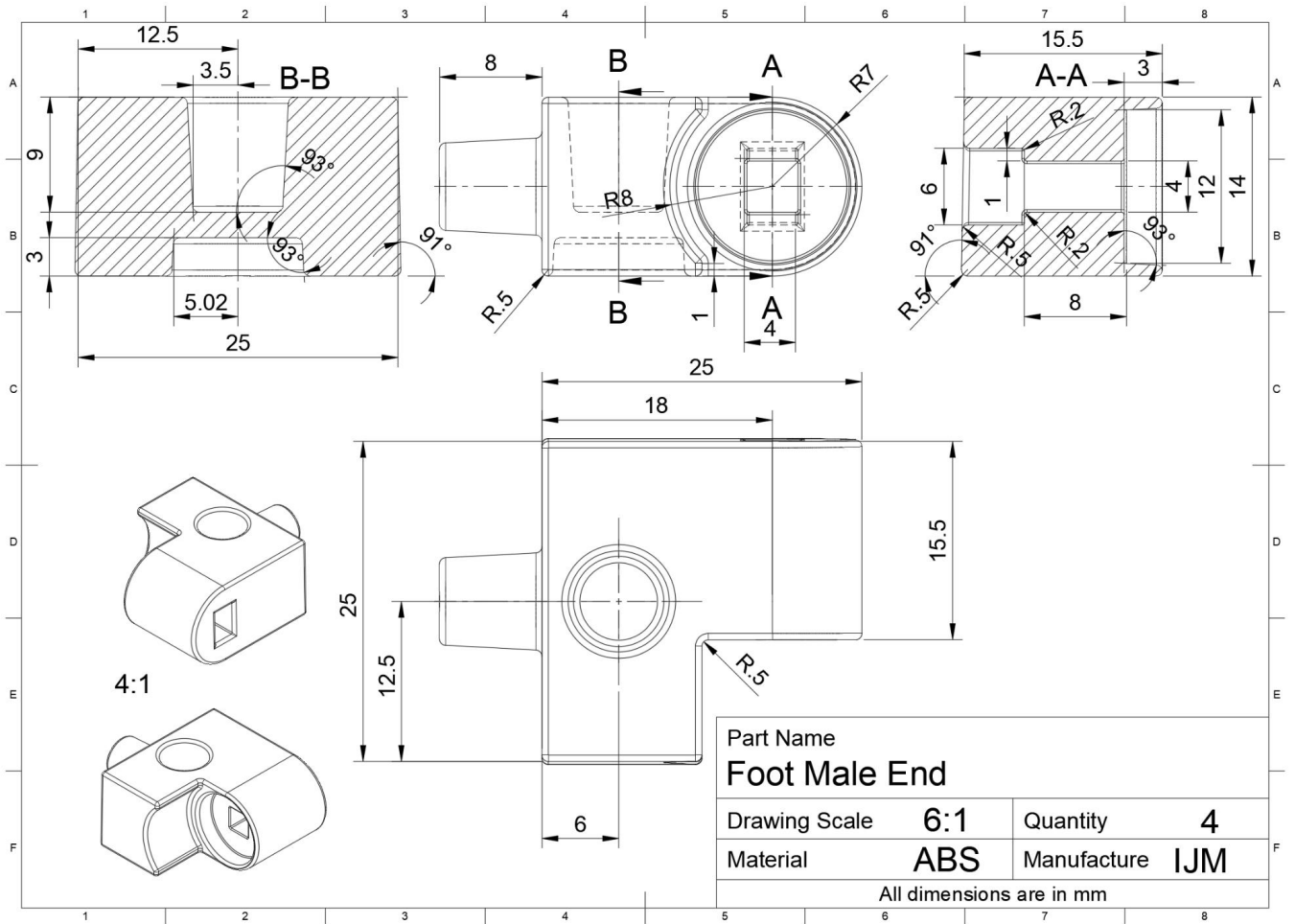


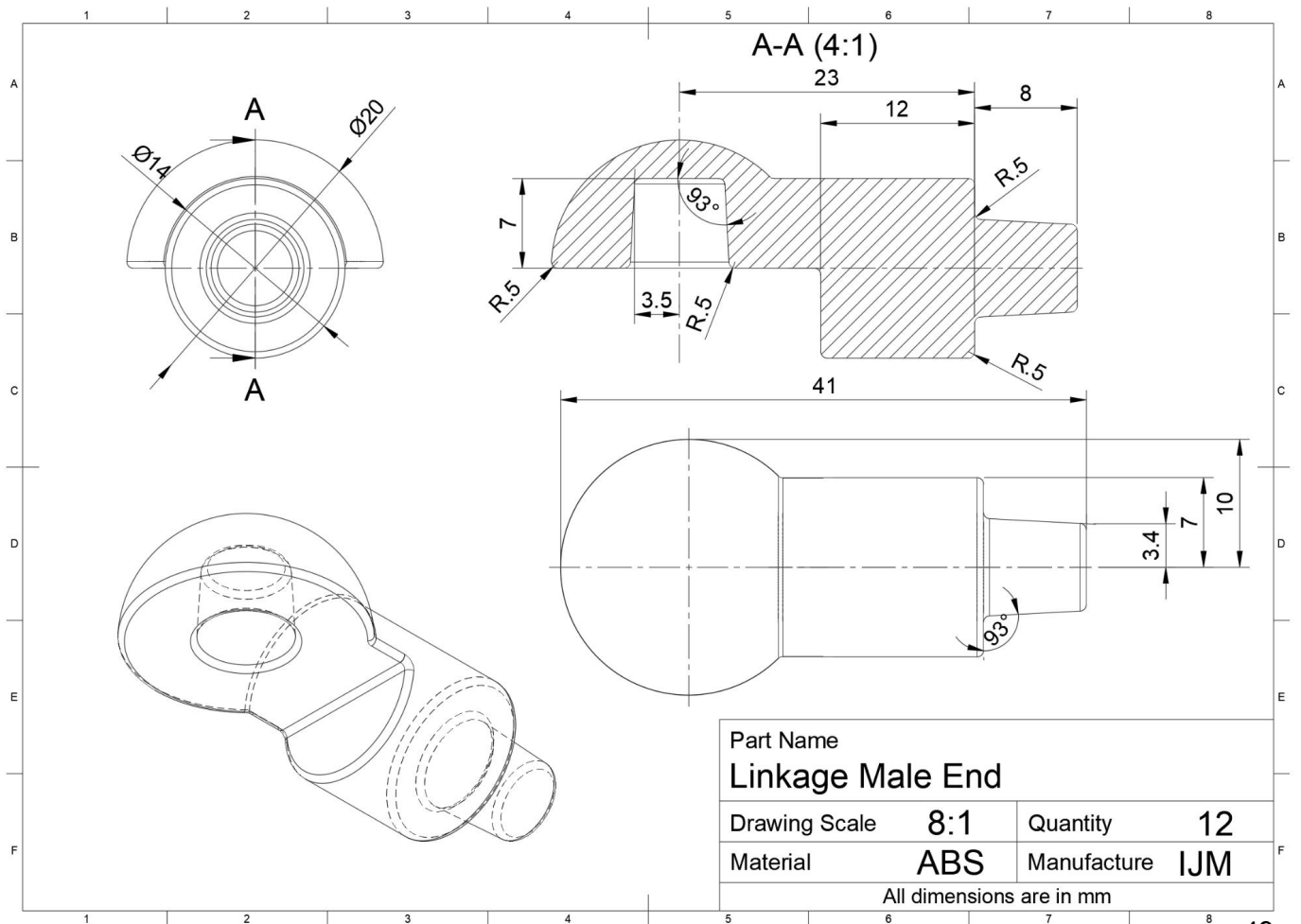
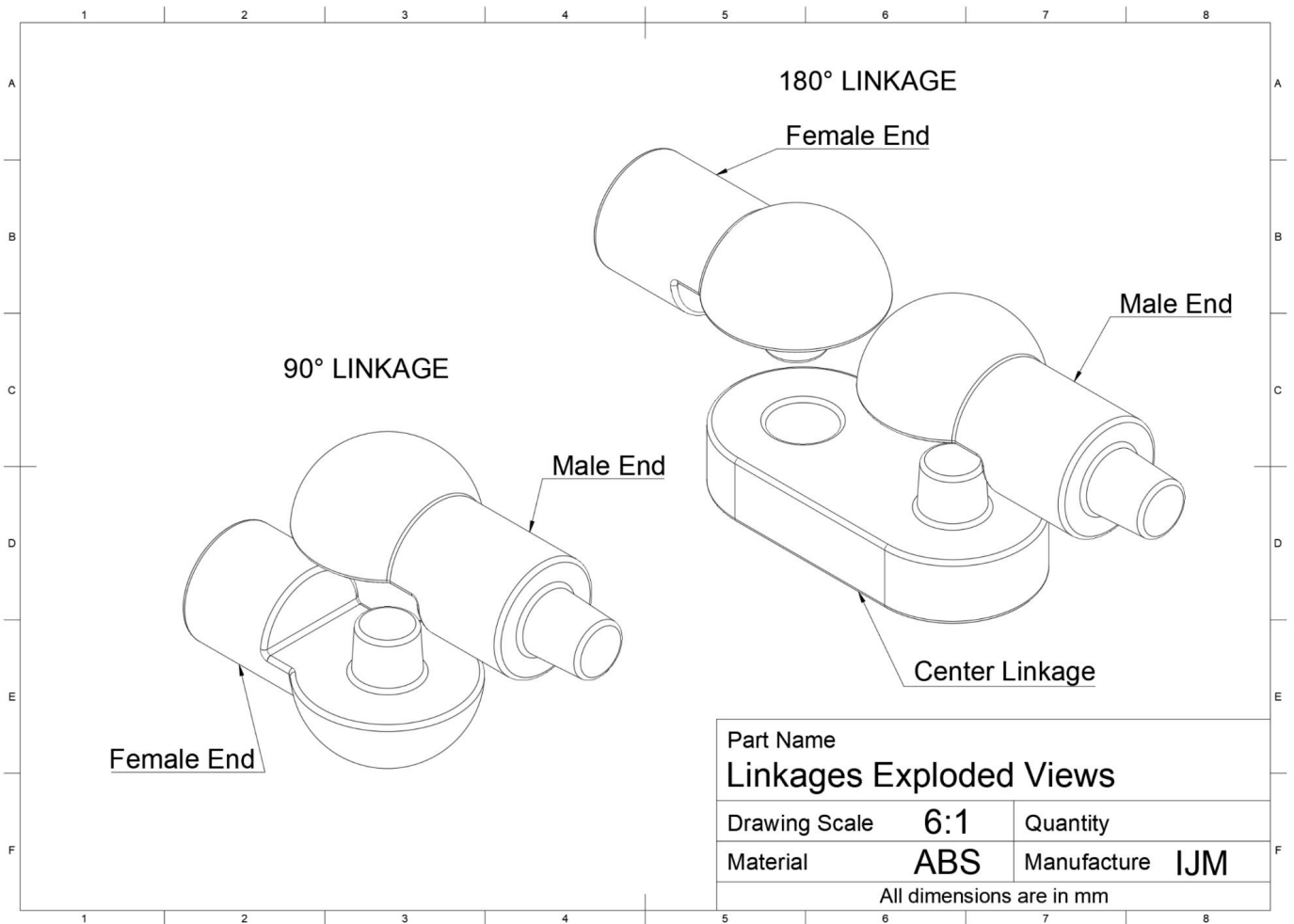


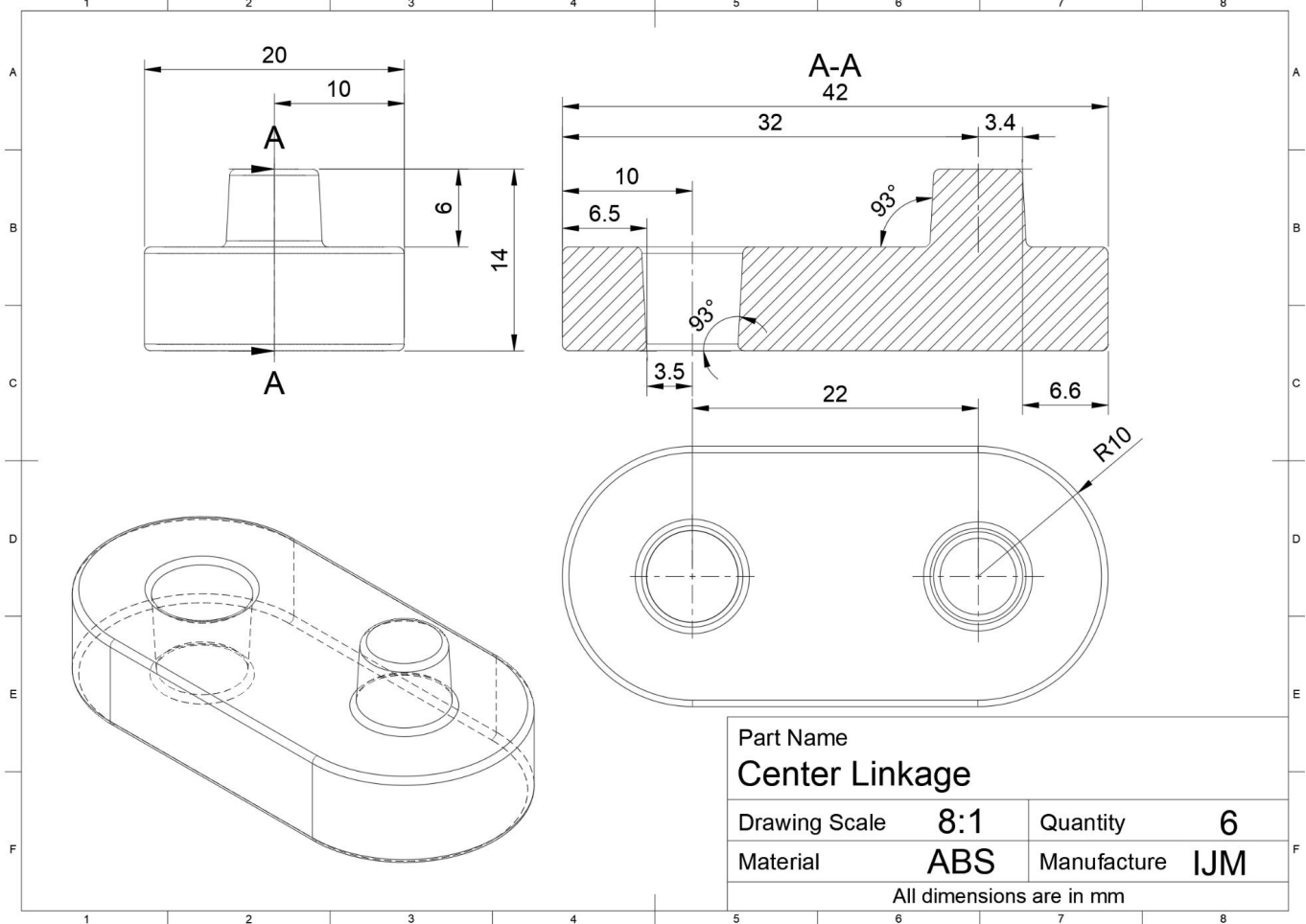
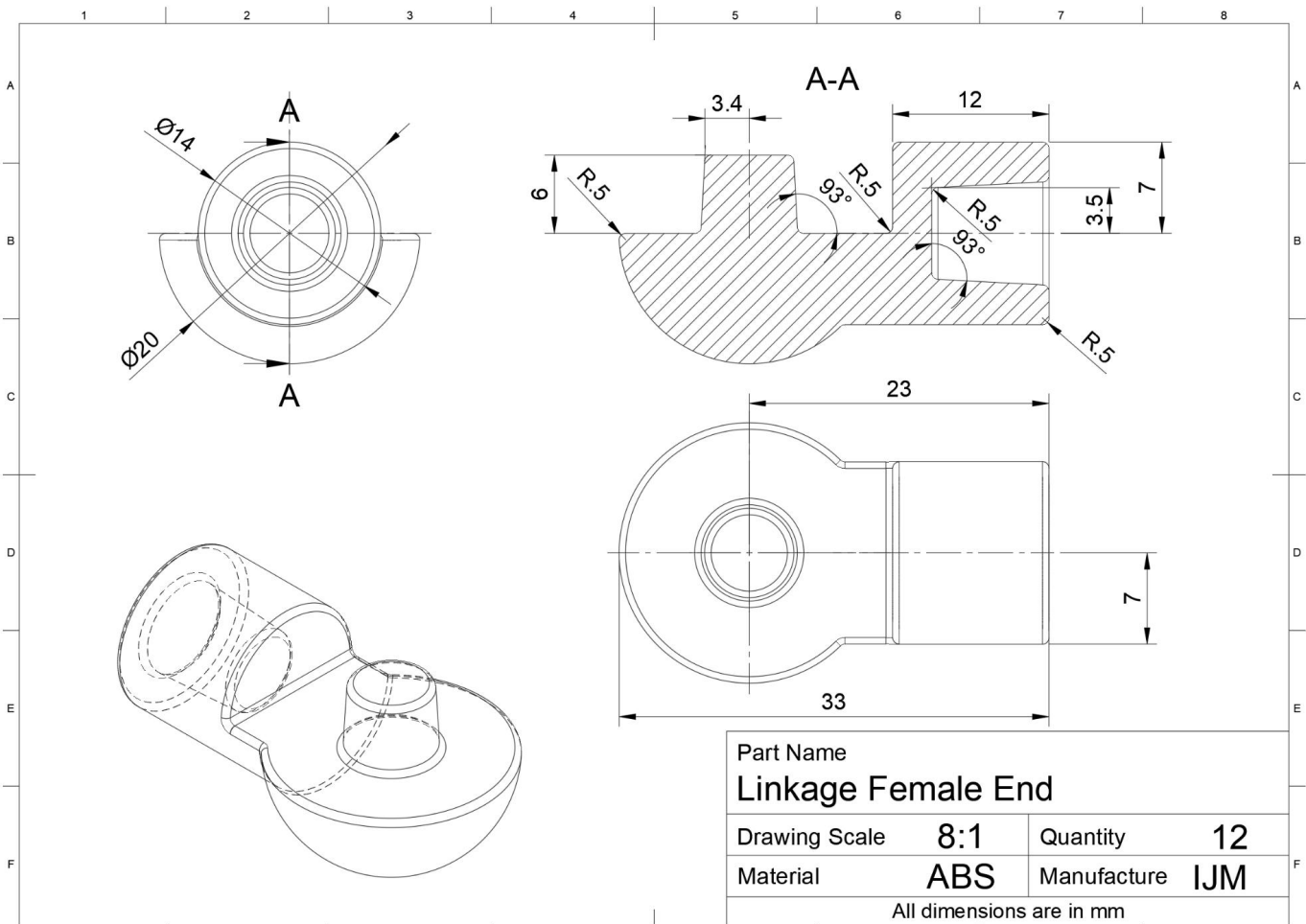


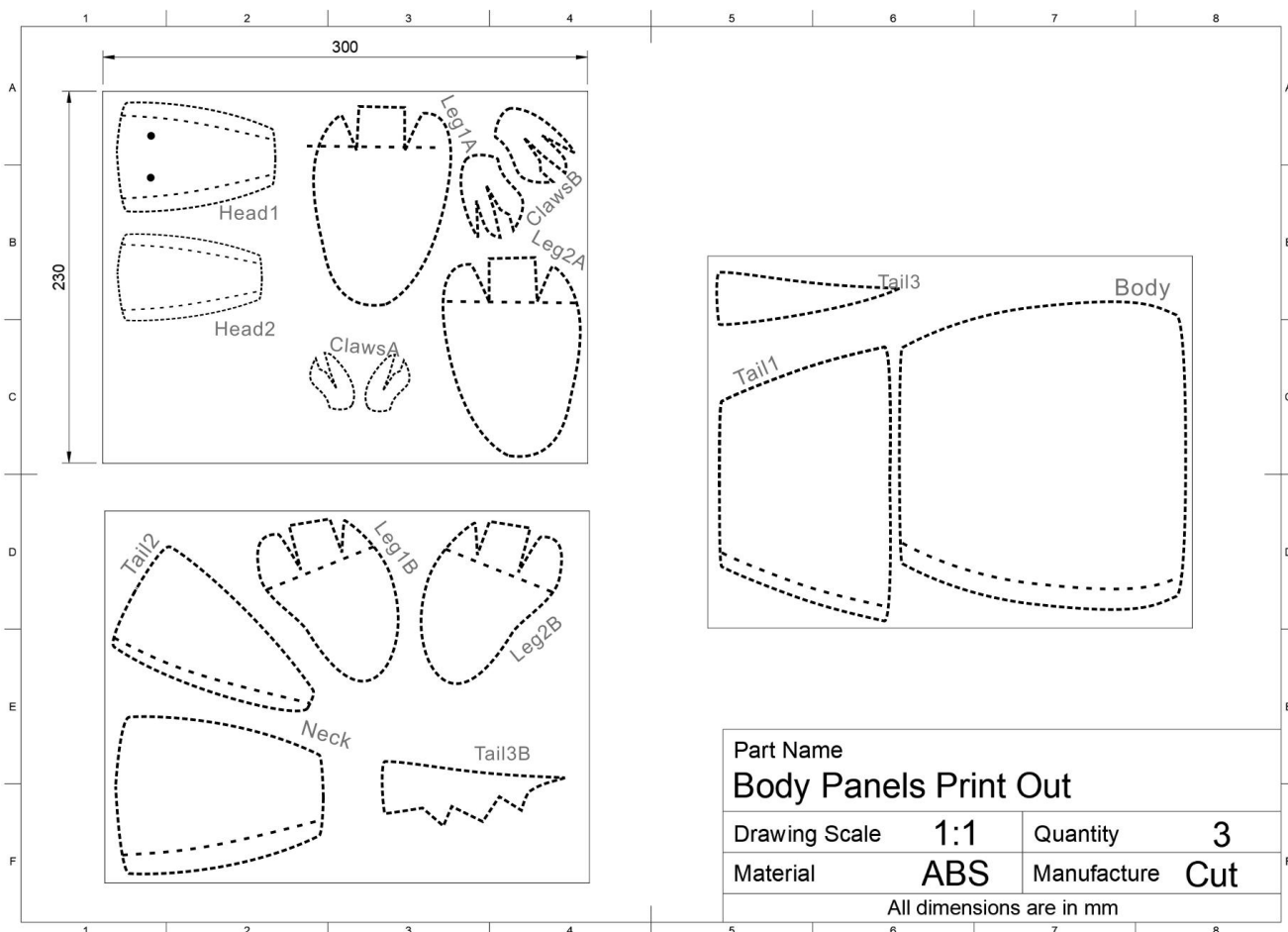
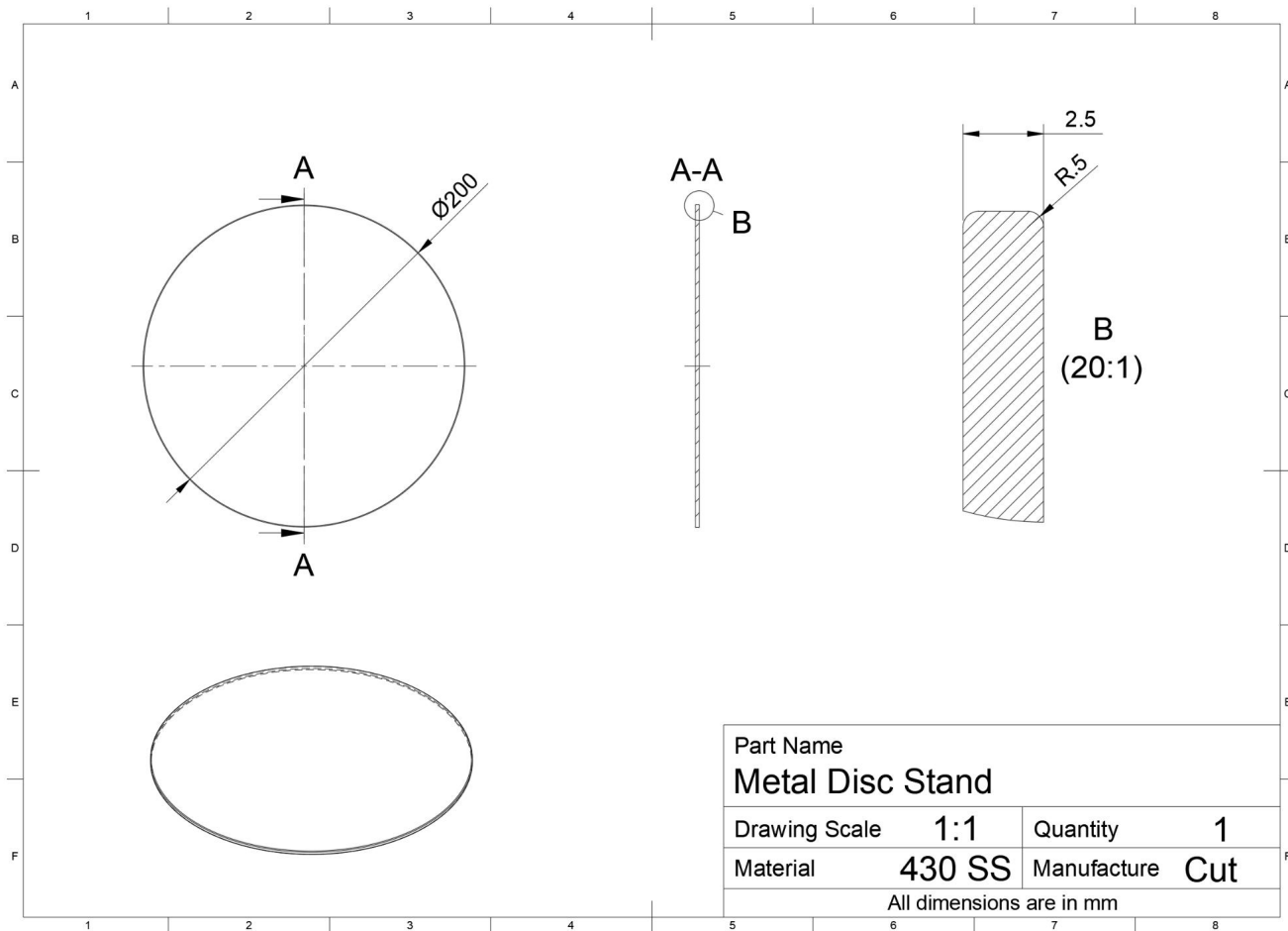








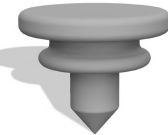
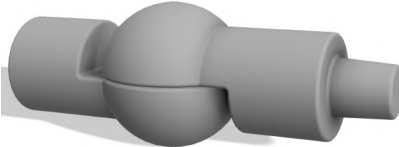
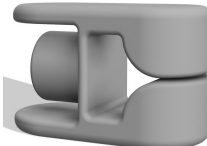




Bill of Materials

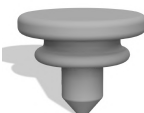
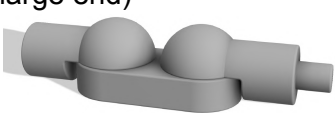
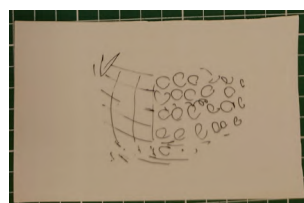
Part Name	Quantity (Units)	Dimensions, lengthxwidthxheight (mm)	Unit Cost (Euro, €) (Appendix 14)	Total Cost (Euro, €)
Small Bone	6	28x14x14	0.0051	0.0304
Connector Bone	10	20x20x20	0.0040	0.0405
Single-hole bone	6	38x14x14	0.0067	0.0402
Triple-hole bone	10	68x14x14	0.0127	0.1272
Quad Bone	6	28x28x28	0.0095	0.0570
Body Panel Pin	14	20x20x17.5	0.0030	0.0421
Stand (Bought)	1	200x200x8	2.5133 (Appendix 17)	2.5133
Body Panel Clip	16	40x20x25	0.0147	0.2351
Body Panel Sheets	3	230x300x0.5	1.1878	3.5635
180° Linkage	6	76.5x20x18.1	0.0234	0.1404
Male End	1 per	41x20x17	0.0066	0.0398
Center Linkage	1 per	42x20x14	0.0099	0.0593
Female End	1 per	33.5x20x17	0.0069	0.0413
90° Linkage	6	54.5x20x20	0.0135	0.0811
Male End	1 per	41x20x17	0.0066	0.0398
Female End	1 per	33.5x20x17	0.0069	0.0413
Ball Joint	10	27x27x36.4	0.0163	0.16386
Ball Joint	1 per	24x24x28	0.0128	0.1282
Outer Shell	1 per	27x27x24.4	0.0035	0.03466
30° Ball Joint	8	27x27x36.4	0.0167	0.13352
30° Ball Joint	1 per	24x24x28	0.0132	0.1058
Outer Shell	1 per	27x27x24.4	0.0035	0.02772
Foot	4	44x41x14	0.1494	1.0976
Male End	1 per	33x25x14	0.0100	0.0399
Female End	1 per	25x41x14	0.0144	0.0577
Joint Arms	1 per	8x8x13	0.0002	0.0009
Magnets (Bought)	2 per	10x10x3	0.125 (Amazon)	1.00
Final Product	€8.2658			

Material Choice for Final Production

Part Name	Material Name and Description	Justification
Singlar Parts Small bone, Connector bone, Single-hole bone, Triple-hole bone, Quad Bone, Body Panel Pin 	<u>ABS Plastic</u> Acrylonitrile Butadiene Styrene (SpecialChem), is widely-used for injection molding (Manufyn). It is cost-effective, with high mechanical strength and appealing aesthetic properties (DSW)	ABS, has mechanical and physical properties on-par with or better than those of PLA. This makes it dimensionally stable and resistant to impacts and wear [F2, F5, M1, M2]. Water absorption between 0% and 0.7% (Plastim) makes it weather-resistant [M3]. Compared to other materials suitable for injection molding, Nylon 6, Polycarbonate and Acetal (Manufyn), ABS had the second highest compressive strength and gardner impact values (Appendix 15) Flexural strength isn't very high, yet more than necessary, giving the parts some beneficial flexibility. The water absorption, 0.7% (Plastim), was higher than desirable, but is still low [M3]. While tensile strength was the lowest, it is still close to the desirable minimum. For injection molding, ABS flows smoothly, cools predictably and can fill complex geometrics (Manufyn), making it a reliable choice. Most importantly, ABS had the lowest density, 1.04g/cm³ (Matmake) [M2] and price, €0.001638/g (Mike) [P1].
Sub-Assemblies 180° Linkage (Male end, linkage, female end), 90° Linkage (Male end, female end), Ball Joint (Ball joint, outer shell), 30° Ball joint (Ball joint, outer shell), Foot (Small end, large end) 		
Body Panel Clip 	<u>TPU</u> Elastic, melt-processable plastic compatible with various molding techniques. (Hock)	TPU is chosen for greater flexibility and elasticity (Protolabs) over ABS (Appendix 16) while remaining compatible with injection molding (Ha Noi Mould). It also has a low price of €0.001092/g (Made-in-China) [P1].
Metal Disc Stand	<u>Stainless Steel 430</u> Stainless steel with relatively low carbon percentage. (Eclipse magnetics)	Ferromagnetic with decent corrosion and pitting resistance. (Eclipse magnetics), compatible with foot magnets. High density (Engineers Edge) keeps model stable [F3].
Foot Magnets	<u>Neodymium</u> Highly magnetic metal.	Highly magnetic (Stanford Materials), allows holding up the model without taking up a lot of space [F2, F3]
Body Panel Sheets	<u>ABS Plastic</u> ABS plastic is a cheap plastic (Mike) with good mechanical and physical properties (DSW).	Panels should be lightweight and bendable. Thin ABS plastic sheets are a cheap solution that are also weather-resistant (Appendix 15). Having decent but not extremely high tensile strength and flexural strength (Appendix 15) makes ABS flexible and easy to cut.

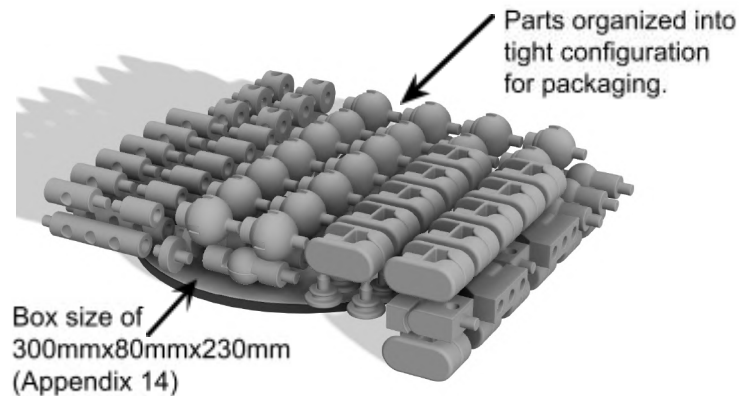
Material	Tensile Strength at Yield [M1]	Max Compressive Strength [M1]	Gardner Impact [M1]	Flexural Strength [M1]
ABS	48MPa (SpecialChem)	69MPa (Matmake)	50.8J (ACPlastics)	66.8MPa (ACPlastics)
Nylon 6 (Suitable alternative)	76MPa (GEPlastics)	39MPa (Directplastics)	36.2J (Songhan)	110.3MPa (Resin Enterprise)
Necessary Value (Appendix 15)	51.7MPa	49.5MPa	23.2J	49.5MPa

Choice of Manufacturing Techniques for Final Product

Part Name	Process Name and Description	Justification
<u>Singlar Parts</u> Small bone, Connector bone, Single-hole bone, Triple-hole bone, Quad Bone, Body Panel Pin 	<u>Thermoplastic Injection Molding</u> Uses thermoplastic polymers that can be heated up and injected into a metal mold made of 2 or more pieces (RCO Engineering). After initial investment, it is very cost-efficient and is easily scalable (RCO Engineering). It has a wide variety of compatible materials, including TPU for the clips (Jino Injection Moulding).	Injection molding allows for highly detailed and intricate parts (RCO Engineering), making it suitable for some of the more complicated parts, such as the incremental hinge joint of the foot parts. It delivers tolerances as small as $\pm 0.005\text{mm}$ (Seawin), which should suffice for the tolerance fits of the joints. While the fixed costs for the molds is very high, typically ranging from €4000 to €17000 (Seawin), they are mostly a one-time purchase. The models for the parts are quite simple, so they should be on the lower end. The long lead-time of 6-12 weeks (Seawin), shouldn't be a significant issue if products are made with batch production, where products would be made in batches of up to 5000 mannequin sets, and distributed to retailers.
<u>Sub-Assemblies</u> 180° Linkage (Male end, linkage, female end), 90° Linkage (Male end, female end), Ball Joint (Ball joint, outer shell), 30° Ball joint (Ball joint, outer shell), Foot (Small end, large end) 	The process results in minimal waste and is very widely-used, making it accessible (RCO Engineering).	Compared to other suitable processes, such as FDM or 3D printing, injection molding has a smoother finish with smaller tolerance, and can produce at much larger scales (Naoum). This makes injection molding the most suitable out of these processes.
Body Panel Clip 		
Metal Disc Stand	<u>Water Jet Cutting</u> Material is cut away using a highly-pressurized stream of water (Fractory).	Rectangular metal sheets purchased in bulk can be cut into shape by a specialized manufacturer for low cost. Highly accurate and doesn't need additional processing (Fractory).
Body Panel Sheets 	<u>Up-Cut Sheeter</u> Cuts rolls of material into uniform sizes. (Rosenthal) <u>Laser Printer</u> Uses a laser to engrave images onto materials such as plastics	Sheetters are suitable for cutting a variety of sheet-like materials into rectangular shapes (Rosenthal). The laser printer is necessary to print patterns onto the body sheets and can be done for a low cost by an external supplier (Videojet).

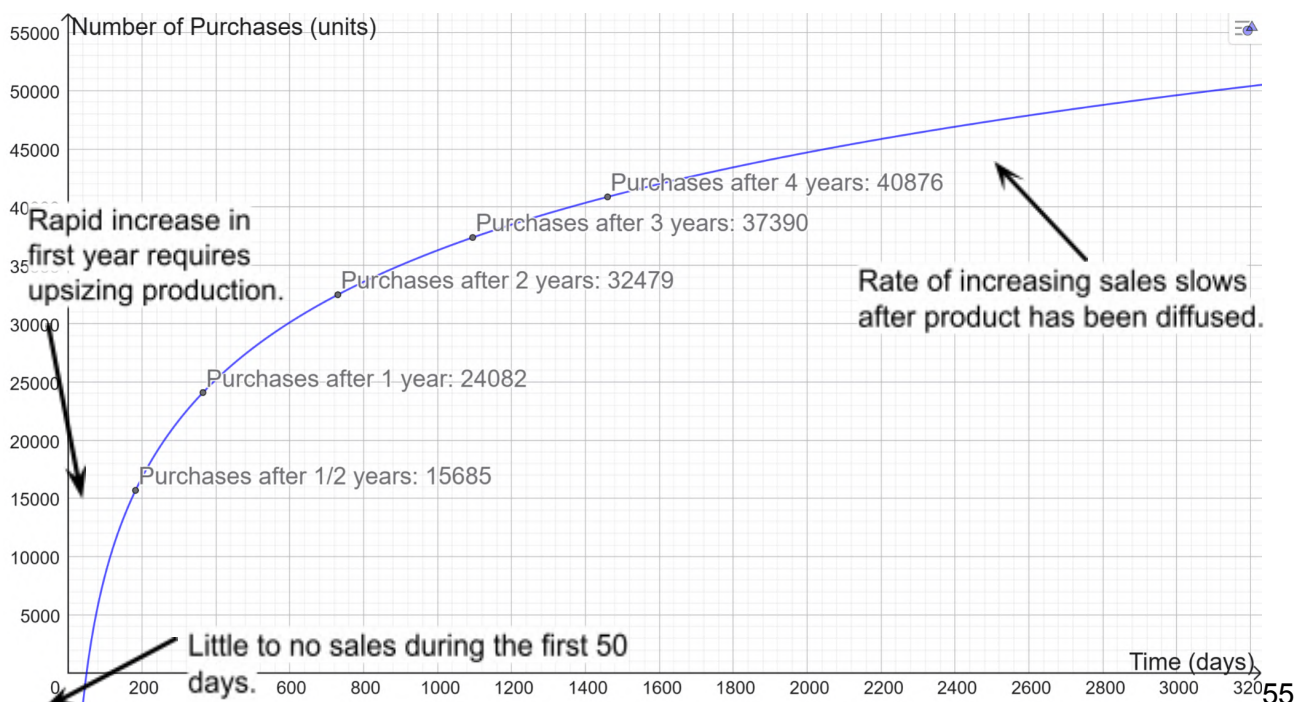
Scale and Volume of Production

The testing was done with international students in the Netherlands aged 16-18, the mannequin does not require specific language understanding. The market could be expanded to include art and design students aged 16-23, as students taking a Bachelor's degree in art and design would also benefit from the mannequin (The Best Schools). In the Netherlands, students start their bachelor's with an average age of 19.6 years (OECD), hence the upper bound for someone still in the 3-year program (Educations.com) is 23. One of the recommended requirements for the product during expert appraisal was a low price [P1] (Appendix 7). Minimum shipping costs within the Netherlands will be about €10.30, (Appendix 7) which is almost as much as the bill of materials itself. The product could undergo market development by expanding to other EU countries, where shipping costs are similar (European Commission). For consumer products, the market penetration is about 2-6% (Airfocus). Senior high school students are shown to emphasize brand and quality when purchasing products (Encellado 433), which might not be strong suits of a newly-released product. However, value is also considered by students (Encellado 434), which the mannequin might be considered to have due to being educational. A median value of 3% is thus chosen. Art students in the Netherlands are given a slightly higher value of 5%, as the locally-produced product might make the brand more appealing (Jaufenthaler), and also make the product more accessible.



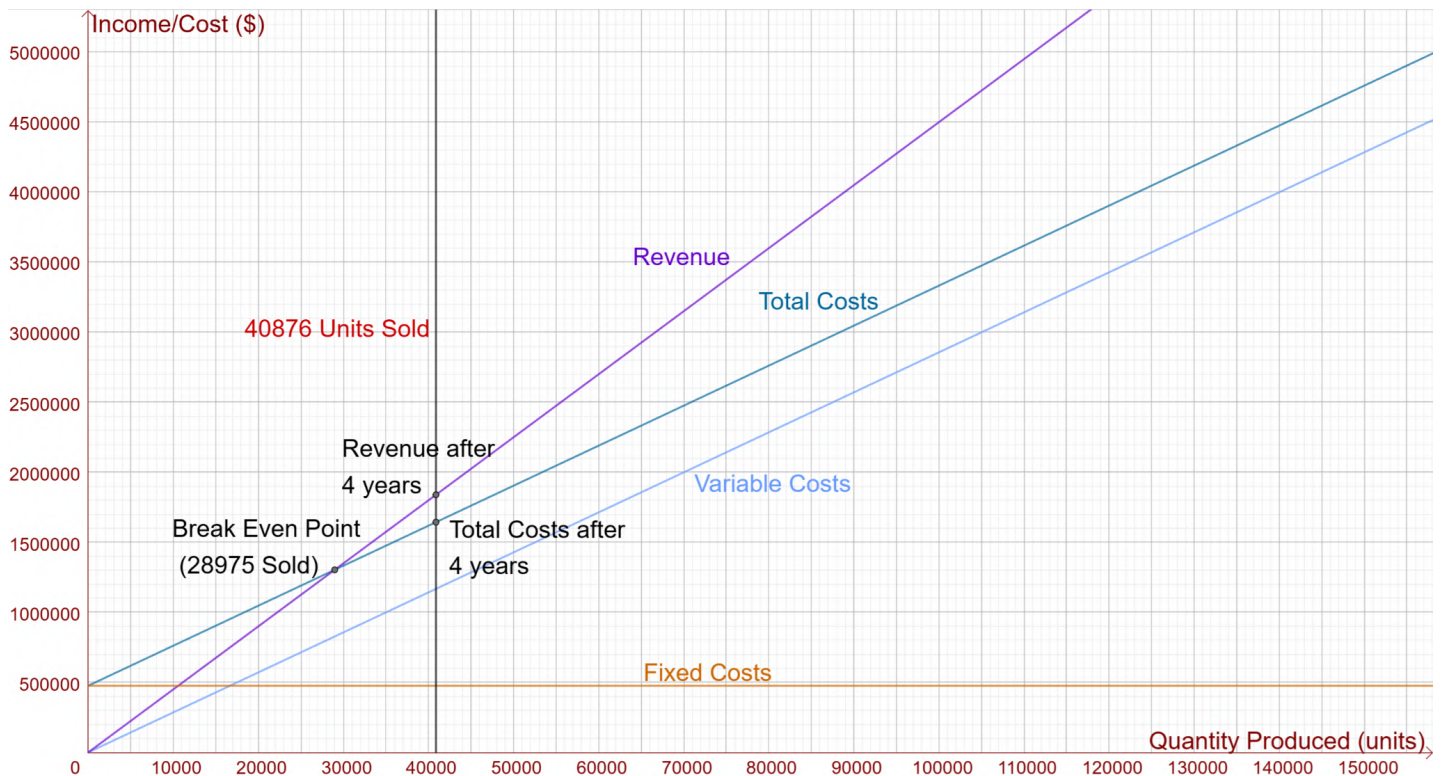
Population of Art Students in the Netherlands (Appendix 15)	Market Penetration percentage (Airfocus)	Population of Art Students in the EU Excluding Netherlands (Appendix 15)	Market Penetration percentage (Airfocus)	Expected Number of Consumers
39436	5%	1296814	3%	40876

Most start-ups see success and significant profits after 4 years of activity (Schroter), so it is assumed the initial quantity of mannequins will be diffused over this time. The sales are modelled using a logarithmic graph. The first 50 days after launch will have few sales, due to having to market and distribute the product to retailers. Sales then increase steadily, as the product is diffused. As the majority of initial sales are made, sales after 4 years are from fewer new customers or repeat customers, causing slowed but continuous growth.



From the graph it can be seen that high-scalability is an important aspect, which injection molding excels at (Naoum). Cheaper and more flexible aluminum molds can be used for initial runs, as they are suitable for smaller scale production, at less than 100,000 parts (Protolabs). The average volume of production should be 10219 products per year, which is within the capabilities of injection moulding (Naoum). Batch production should be a suitable scale of production, as once the molds are made it should be easy to adjust the amount produced based on demand. As the boxes for the mannequins are relatively small (Appendix 14), and they can be stored indefinitely, any excess supply should not be a significant issue.

The total unit cost was calculated to be €28.564 (Appendix 19). The majority of the variable costs consisted of transport, material costs, and labor. The set-up costs were quite high, at €476220 (Appendix 19), due to having to set up complicated machinery. The product's price should not exceed €50 [P1] to be appealing to art students. Likewise, it should also be cheaper than competitor products, which are around the same price range. The chosen price is €45, which gives a profit margin of about €16 per product, without taking fixed costs into account. When graphed, it is seen that the break-even point is at around 29000 units sold, so about halfway between the first and second years of beginning production. The revenue after 4 years is $€45 * 40876 = €1839420$. The total costs after 4 years of production is $€28.564 * 40876 + €476220 = €166269$. Thus after 4 years the total projected profit is €1673151, or the difference between revenue and total costs after 4 years. The potential profit is greater however, as economies of scale and reduced transport costs through a highly integrated supply chain could reduce variable costs.



Fixed Costs (Appendix 19)	€476220
Variable Costs (Appendix 19)	€28.564 per unit
Break-Even Point	28975 units sold
<i>Break Even Point: $€28.564 * x + €476220 = 45 * x$, where x is the number of units produced. $x = 28974.2 \approx 28975$ when rounded up</i>	
Projected Profit After 4 Years	€1673151
<i>Projected Profit = Revenue - Total costs = €1839420 - €166269 = €1673151</i>	

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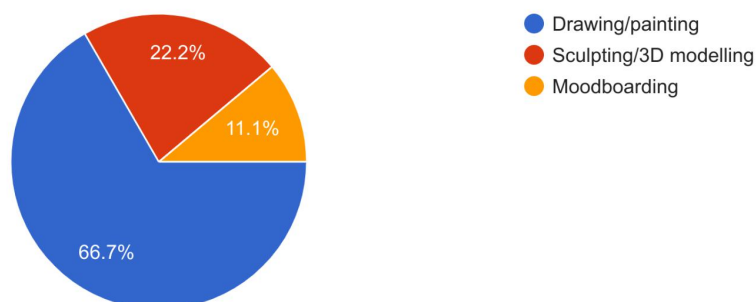
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Appendix

Appendix 1 - Primary research questionnaire interviewing art students at an international school.

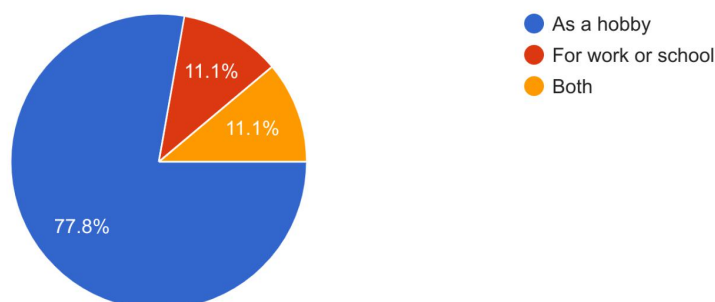
Do you do any of the following types of visual arts?

9 responses



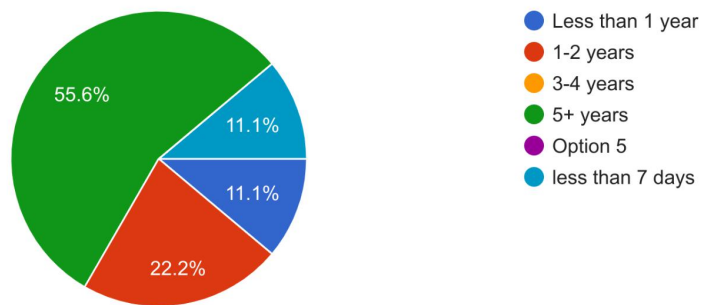
Do you do visual arts as a hobby?

9 responses



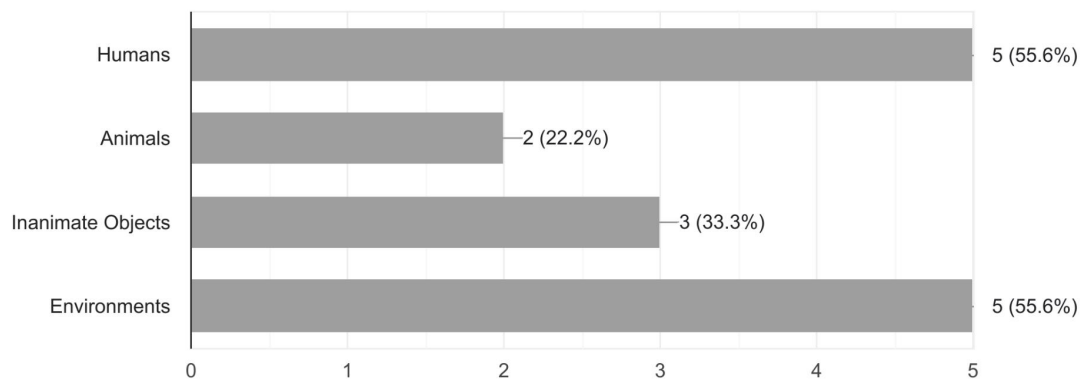
How long have you been learning and practicing art for?

9 responses



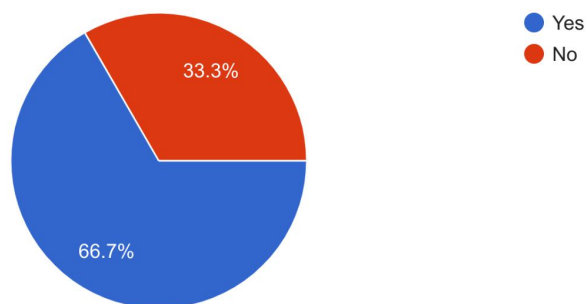
What do you usually depict as your subject?

9 responses



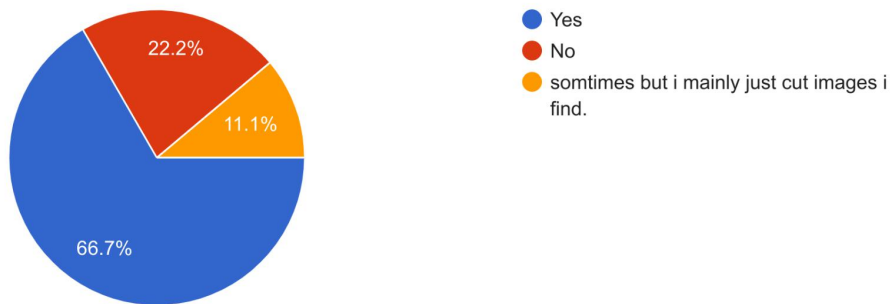
Do you usually use reference (such as images or models) material to assist your work?

9 responses



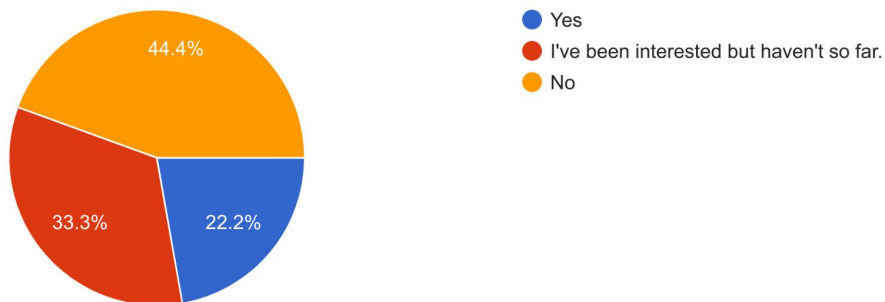
Have you ever had difficulties acquiring adequate reference material? (finding images, finding or making models, etc)

9 responses



Have you ever used an art mannequin as a referencing tool?

9 responses



(Simple

wooden mannequin)

If yes, what were your opinions on it? Or if you are interested, why?

"It's useful for drawing bodies proportionally but it is limited to being a fixed body shape and lengths. It also can't help see ways to draw fingers or hair or other small details that would be nice to have on the model itself."

"I don't think it would suit moodboarding."

"i think it looks really cool but its only good for poses that are not dependent on objects"

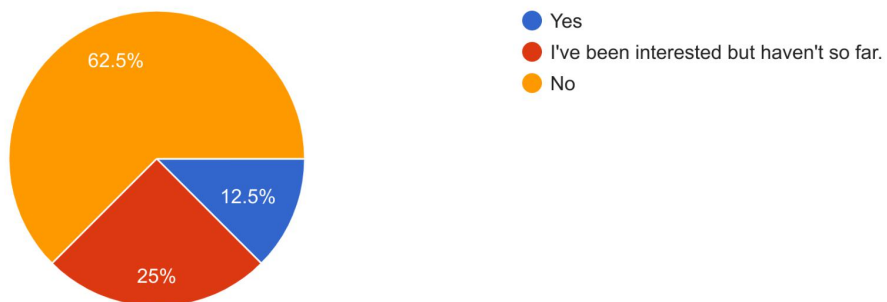
"i think it's really useful because any poses can be displayed"

"I think these models would be a good tool because I can get dynamic poses put of them that I usually can't find online"

"It is good but only for static poses as it's mobility is limited and the proportions are weird (at least in ikea one I used)"

Have you ever used an art mannequin, such as the one below, as a referencing tool?

8 responses



(Bodykun mannequin)

If yes, what were your opinions on it? Or if you are interested, why?

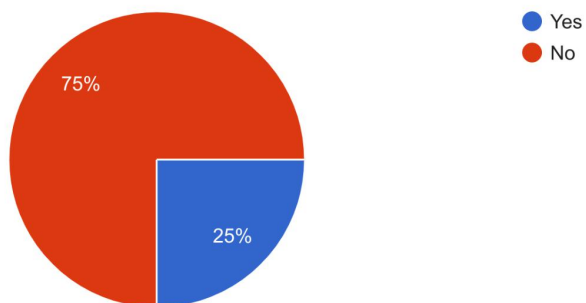
"Because I can create the exact pose I want"

"I would like to try using a mannequin and see how helpful it would be."

"It was useful was knowing the proportions and also you would move it to be the shape you wanted to be so that was nice too."

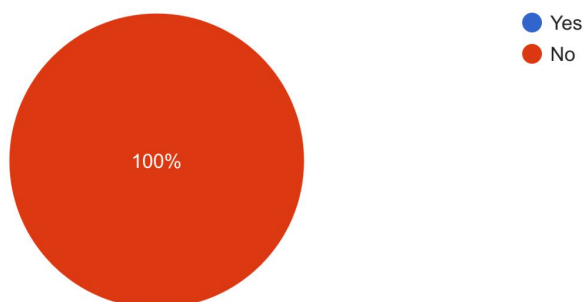
Do you make/Have you made custom mockups for use as reference? (i.e. out of craft materials such as cardboard, to set a scene properly)

8 responses



Do you go outdoors in order to find art reference yourself?

8 responses



What is the most money you would be willing to spend on one specific piece of art supplies (in USD)?

“5”
 “30”
 “25”
 “30-50”
 “20”
 “2”

Appendix 2 - Anthropometric Variables

Hand Length					
FEMALE N = 2208			MALE N = 1774		
Centimeters		Inches	Centimeters		Inches
18.05	Mean	7.10	19.38	Mean	7.63
.97	Std Dev	.38	.98	Std Dev	.39
21.50	Maximum	8.46	23.30	Maximum	9.17
14.90	Minimum	5.87	16.00	Minimum	6.30
Percentiles			Percentiles		
15.89	1 st	6.26	17.28	1 st	6.80
16.13	2 nd	6.35	17.52	2 nd	6.90
16.29	3 rd	6.41	17.67	3 rd	6.96
16.50	5 th	6.50	17.87	5 th	7.04
16.83	10 th	6.63	18.18	10 th	7.16
17.06	15 th	6.72	18.39	15 th	7.24
17.24	20 th	6.79	18.56	20 th	7.31
17.39	25 th	6.85	18.71	25 th	7.37
17.53	30 th	6.90	18.85	30 th	7.42
17.66	35 th	6.95	18.97	35 th	7.47
17.78	40 th	7.00	19.09	40 th	7.52
17.90	45 th	7.05	19.21	45 th	7.56
18.02	50 th	7.09	19.33	50 th	7.61
18.14	55 th	7.14	19.45	55 th	7.66
18.26	60 th	7.19	19.57	60 th	7.70
18.39	65 th	7.24	19.70	65 th	7.75
18.52	70 th	7.29	19.84	70 th	7.81
18.67	75 th	7.35	19.99	75 th	7.87
18.84	80 th	7.42	20.16	80 th	7.94
19.04	85 th	7.49	20.37	85 th	8.02
19.29	90 th	7.60	20.64	90 th	8.13
19.69	95 th	7.75	21.06	95 th	8.29
19.96	97 th	7.86	21.34	97 th	8.40
20.16	98 th	7.94	21.55	98 th	8.49
20.50	99 th	8.07	21.90	99 th	8.62

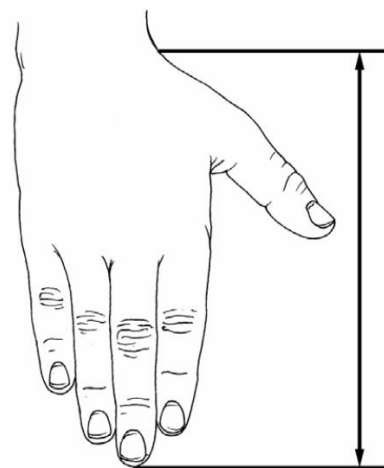


Figure 4.1 (NC State University)

	Men	Women	Difference	95% CI of the Difference		Significance
	Mean (SD)	Mean (SD)	Mean	Lower Bound	Upper Bound	P
Grip strength (kg)	43.0 (9.8)	26.4 (6.1)	-16.7	-18.5	-14.8	≤ 0.001
Pinch strength (kg)	9.7 (1.8)	6.3 (1.3)	-3.4	-3.7	-3.0	≤ 0.001

Table 2: Differences in grip and pinch strength between men and women.

Figure 4.2
(Gachette)

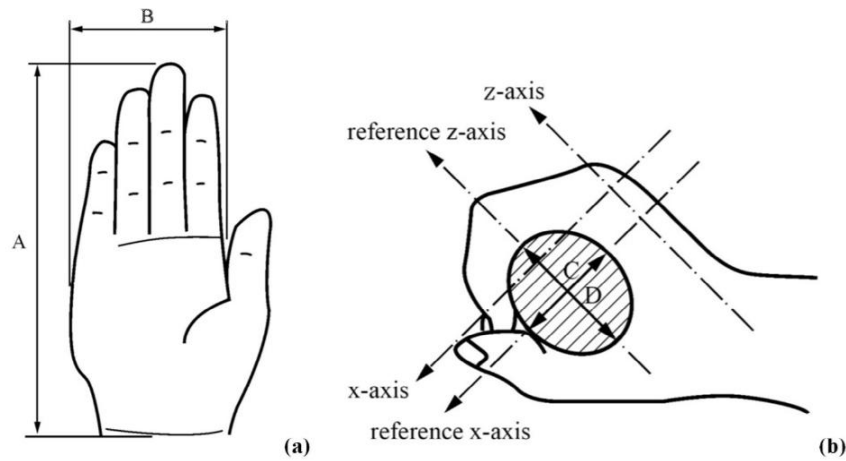


Figure 4.3
(Wang)

Appendix 3 - Calculations for PLA during product usage scenarios

	Tensile Strength at Yield[M1]	Max Compressive Strength [M1]	Gardner Impact [M1]	Flexural Strength [M1]	Density [M2]
PLA	52.5 MPa (Ultimaker)	68.4 MPa (A Kholil 4)	14.0J (Seas3D)	85.1 MPa (Iemai)	1.25g/cm ³ (Farah 5)
Necessary Value	51.7 MPa	49.5MPa	23.2J	49.5MPa	7.44g/cm ³

For all of these scenarios a sample part is used. It is defined as a cylindrical part with a length of 6cm and a diameter of 0.7cm made of 100% infill PLA.

Tensile Strength

The parts will need high tensile strength as they will be pulled apart often during building. The average pulling strength of a male is about 477.3Nm (Roymech). This should be the maximum pulling force a part will have to endure. This can be equated to pascals by applying it to the example part:

$$Pulling\ Force = \frac{477.3Nm}{(0.7cm)^2 * 6cm * \pi} = \frac{477.3Nm}{(0.007m)^2 * 0.06m * \pi} = 5.17 * 10^7 Pa = 51.7 MPa$$

Compressive Strength

Compressive strength is needed for when parts are attached together. The average pushing force of a male is 457.22Nm (Roymech). The maximum pushing force can be found through:

$$Pushing\ Force = \frac{457.22Nm}{(0.7cm)^2 * 6cm * \pi} = \frac{457.22Nm}{(0.007m)^2 * 0.06m * \pi} = 4.95 * 10^7 Pa = 49.5MPa$$

Gardner Impact

Parts will experience impact force if a mannequin is knocked over or dropped. It is possible the model will be used on taller workbenches, such as in an art class, so the average height of a workbench, which is about 86cm (WOOD Magazine), will be assumed to be the maximum dropping distance during use. Using the presumed weight of 2.75kg, we can calculate the impact force.

$$Impact\ Force = 9.81ms^{-2} * 0.86m * 2.75kg = 23.2J$$

Bending Strength

The most bending will be needed for ball joints, which need to flex when being joined together for the first time. This will require the ball joint and the outer shell to be pushed together, so the average pushing force will be used as an estimated maximum force the part will have to endure.

Density

Considering that "light manual work" is considered to be lifting an object of about 4.5kg (West Bend), a complete model should be a decent amount under this threshold. Assuming it should be half the light work mass, the total model should be equal to or less than 2.75kg.

Based on the test models, it is assumed a completed mannequin has around 40 individual parts, assumed to be a 6cm cylinder with a diameter of 0.7cm for simplicity.

The maximum density is thus:

$$Density = \frac{2750g}{(40 * (0.7cm)^2 * 6cm * \pi)} = 7.44g/cm^3$$

Appendix 4 - Calculations for Cyanoacrylate during product usage scenarios

	Tensile Strength
Cyanoacrylate	9.652 MPa (Permatex)
Necessary Value	0.000342MPa

The tensile strength of cyanoacrylate is based on its tensile strength with sand-blasted aluminum, which should have a similar smooth texture to the magnets. The expected value is obtained from the maximum energy product of the magnets, which have a thickness of 1mm.

$$Pulling\ Force = 342kJm^{-3} * 1mm = 342000Jm^{-3} * 0.001m = 342Pa = 0.000342MPa$$

Appendix 5 - Calculations for Neodymium during product usage scenarios

	Maximum Energy Product
Neodymium	342kJ/m3 (Magnet Expert)
Necessary Value	85.9kJ/m3

The expected value is based on the weight of the model, which the magnets will have to hold in place. It is spread across the area of the magnets, which have a diameter of 1cm. The model is assumed to be 2.75kg

$$Pulling\ Force = \frac{2.75kg * 9.81ms^{-2}}{(1cm)^2 * \pi} = \frac{2.75kg * 9.81ms^{-2}}{(0.01m)^2 * \pi} = 85872Jm^{-3} = 85.872kJm^{-3}$$

Appendix 6 - Bill of Materials

The cost for 3D-printed parts using PLA was calculated based on their volume, which was used to estimate mass using the density 1.252g/cm³ (Farah, 3), and the price of PLA in Europe, which is €0.001875/g (Intratec).

Part Name	Quantity (Units)	Dimensions, lengthxwidthxheight (mm)	Volume (cm3)	Unit Cost (Euro, €)
Small Bone	6	28x14x14	3.033	0.007
Connector Bone	10	20x20x20	2.424	0.006
Single-hole bone	6	38x14x14	4.012	0.09
Triple-hole bone	10	68x14x14	7.616	0.018
Quad Bone	6	22x20x20	3.227	0.007
Stand (Bought)	1	165x165x6		8.95 (Stedaparts)
180° Linkage	6	64x14x10		0.017
Male End	1 per	35x14x10	2.543	0.006
Linkage	1 per	30x14x9.8	2.702	0.006
Female End	1 per	27x14x10	1.923	0.005
90° Linkage	6	48x14x10		0.012
Male End	1 per	35x14x10	3.285	0.008
Female End	1 per	27x14x10	1.923	0.005
Ball Joint	10	27x27x36.4		0.023
Ball Joint	1 per	24x24x28	7.672	0.018
Outer Shell	1 per	27x27x24.4	2.074	0.005
30° Ball Joint	8	27x27x36.4		0.023
30° Ball Joint	1 per	24x24x28	7.914	0.019
Outer Shell	1 per	27x27x24.4	2.074	0.005

Body Panel Clip	16	33x20x14		0.47
Body	1 per	33x20x14	3.118	0.007
Brad (Bought)	1 per	20x8x8		0.040 (Amazon)
Foot	4	39x36x12		0.223
Small End	1 per	21x20x12	3.243	0.008
Large End	1 per	24x36x12	6.886	0.016
Magnets (Bought)	2 per	10x10x1		0.200(Amazon)

Appendix 7 - Expert Appraisal

Is the color and texture of the mannequin helpful or distracting? [A1, A2]

For the target audience a neutral base color is the best so it is appropriate. Allows artists to add their own colors.

Paper allows for drawing on top of the shells, adding further detail. Gives insight.

What difficulties might arise when constructing the model?

Some instructions would be needed to build the mannequin. The parts fit together intuitively, allowing people to build their own designs.

The freedom to add your own paper shells is an advantage as it allows for more freedom. No additional cardboard necessary. Clips allow for a lot of freedom.

Is the stability of the mannequin an issue for posing? [F2, F3, F4]

It is an issue as it makes posing difficult. Limits the possibility of poses as the model is difficult to balance and easily topples

Do you think the size of the mannequin is adequate to be used comfortably? [S1, S2]

Large sizes could be used in groups, such as in classes. For individual use, a smaller model size would be preferable. It might be difficult to separate to store, as people might like to keep their models intact for a while.

Do the shells accurately convey shapes, or are the gaps too distracting? [D1, F6]

Overall, they convey the general shape correctly, even if there are some simplifications and inaccuracies such as gaps. It can be helpful for learning artists as it helps them understand the basics of form and shape.

Do you think the mannequin could be useful for amateur artists?

Depends on the price point for individual use. Schools might be willing to pay more if it is used in art classes. For persona-use, a smaller model might be preferable as it reduces used storage. Drawing from a figurine might limit the quality of the drawing when compared to living-subjects as it may not convey weight or sense of balance realistically.

Any additional comments?

Some different colors for the plastic could be appealing.

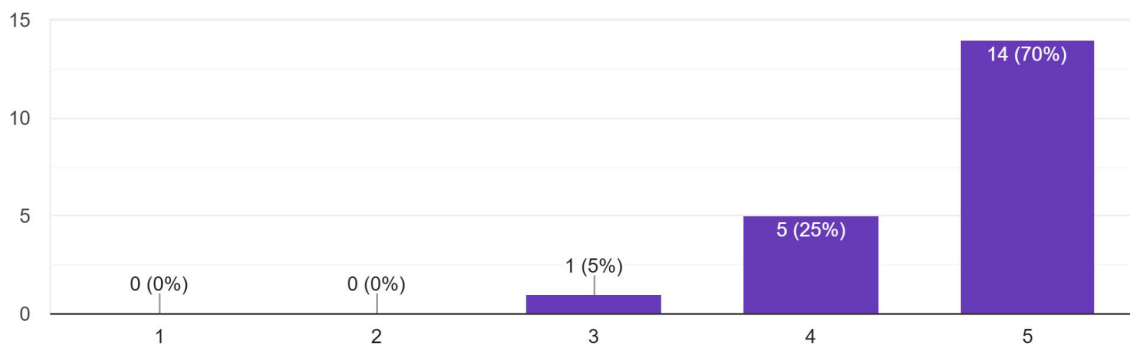
Appendix 8 - User testing session feedback survey

1 means disagree

5 means agree

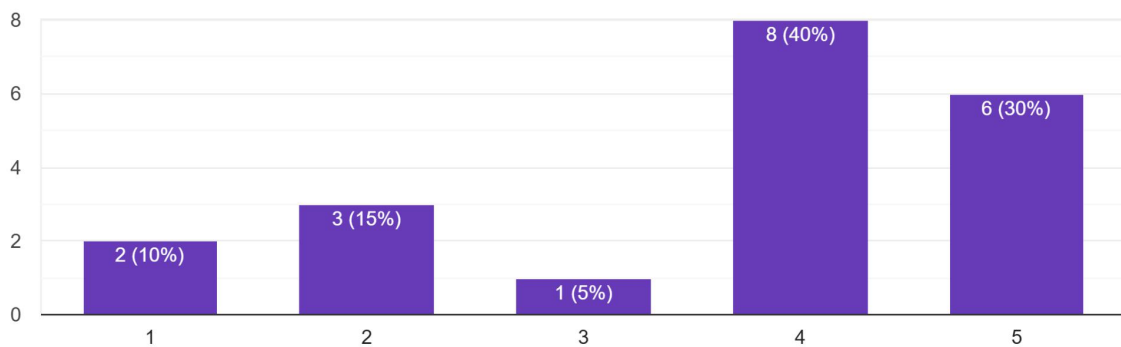
Overall, I found the mannequin a useful tool for drawing animals.

20 responses



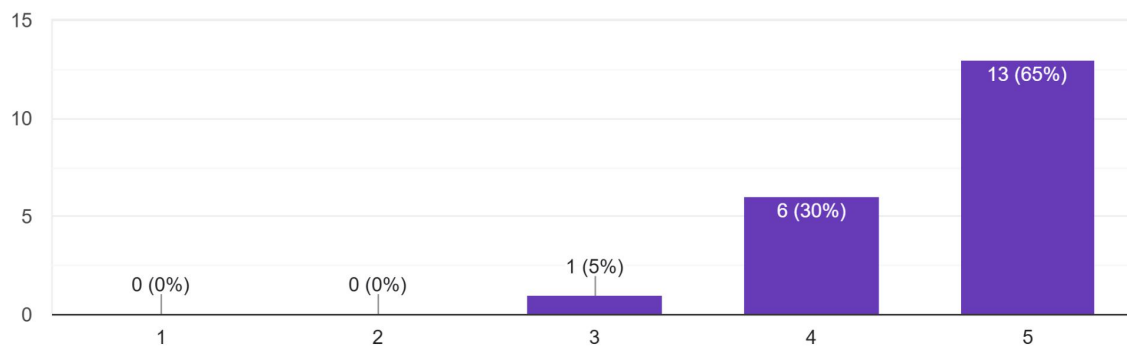
The parts of the mannequin weren't too simplified and geometrical and didn't affect my interpretation.

20 responses



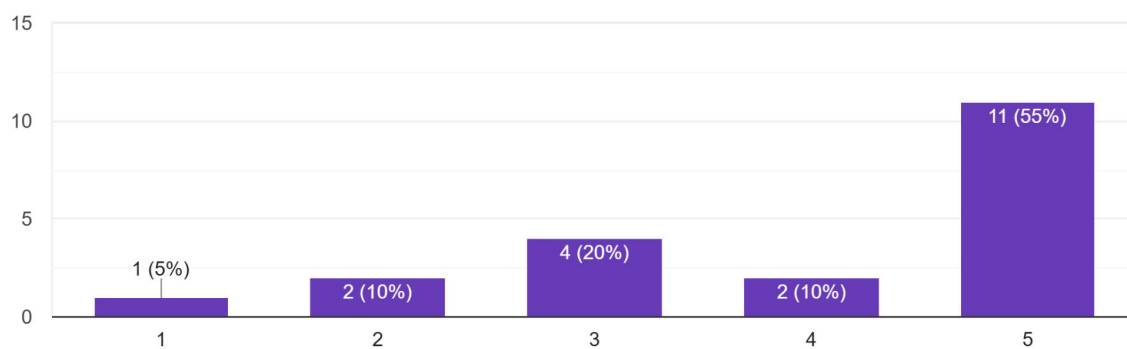
The paper shells helped me understand the overall shape of the animal.

20 responses



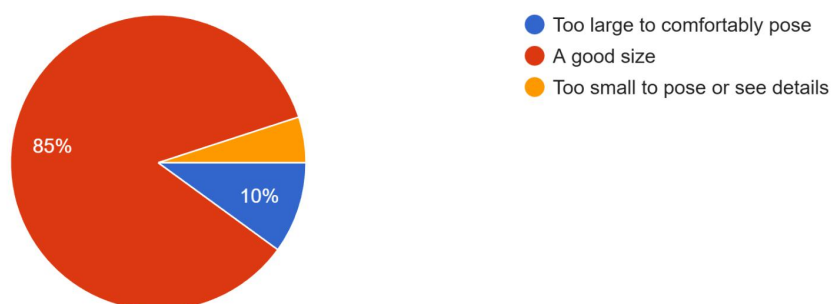
The color of the mannequin didn't impede my drawing.

20 responses



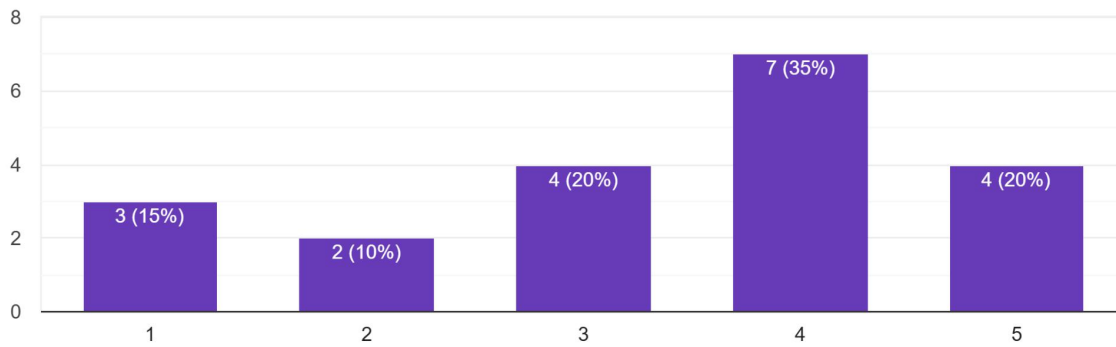
The model was

20 responses



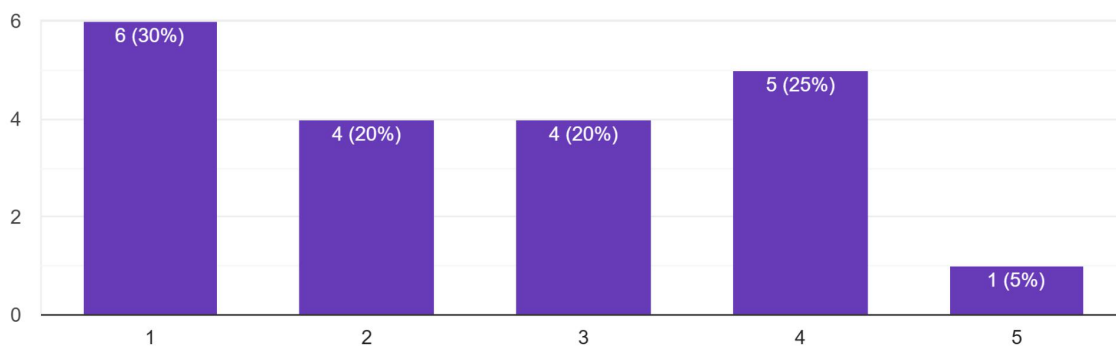
I was afraid the plastic parts of the model would break when posing.

20 responses



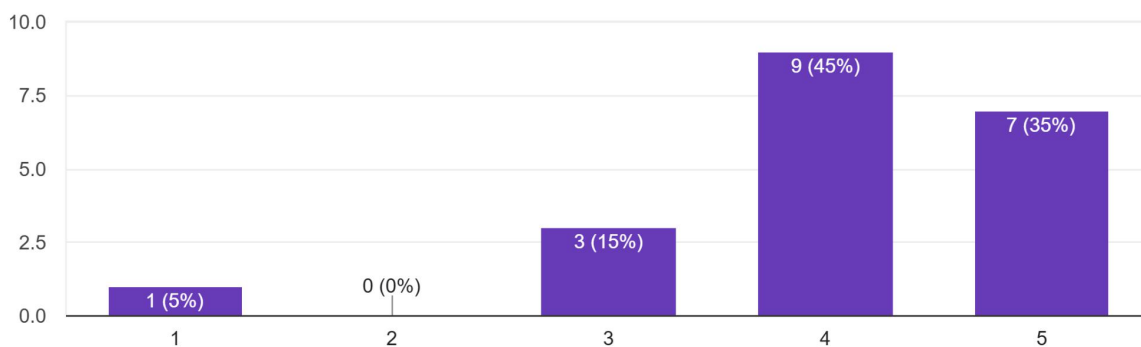
I was afraid the paper shells would break when posing the mannequin.

20 responses



Posing and balancing the mannequin was frustrating

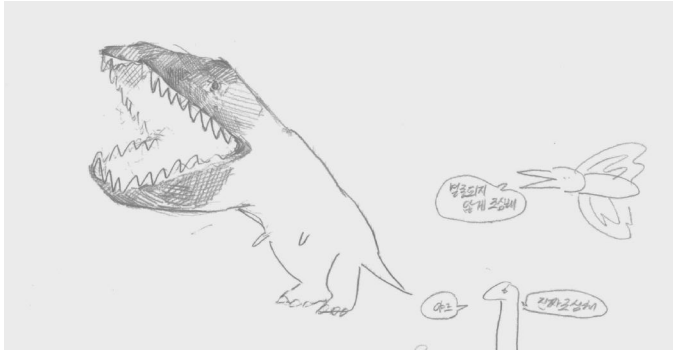
20 responses



Appendix 9 - User testing session drawings

For all drawings, the initial drawing from memory is on the left side, and the one made referencing the mannequin is on the right side.

Student A



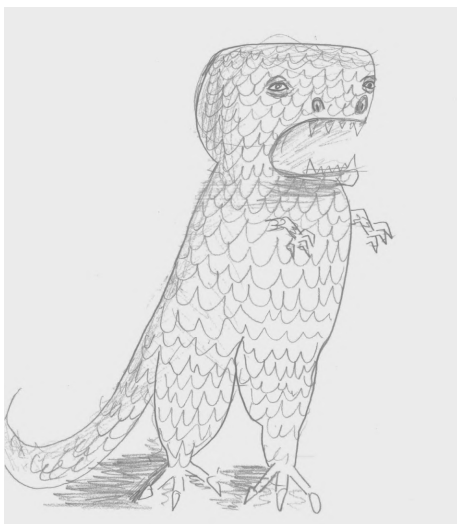
Student B



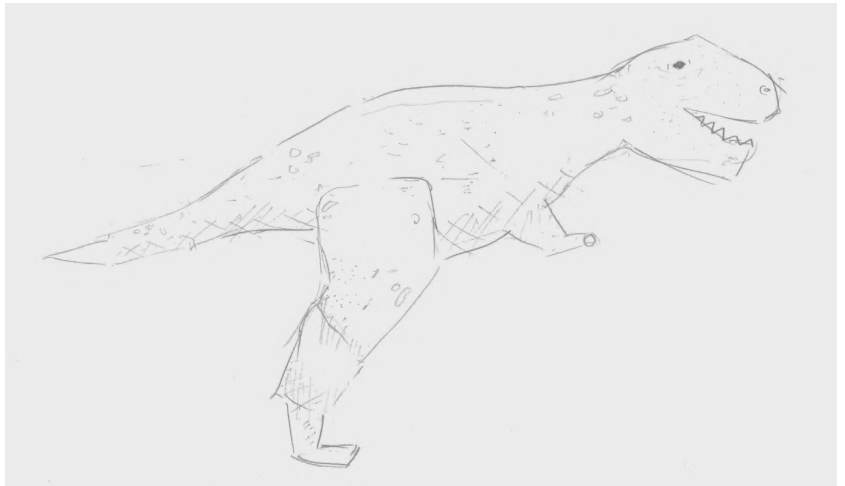
Student C



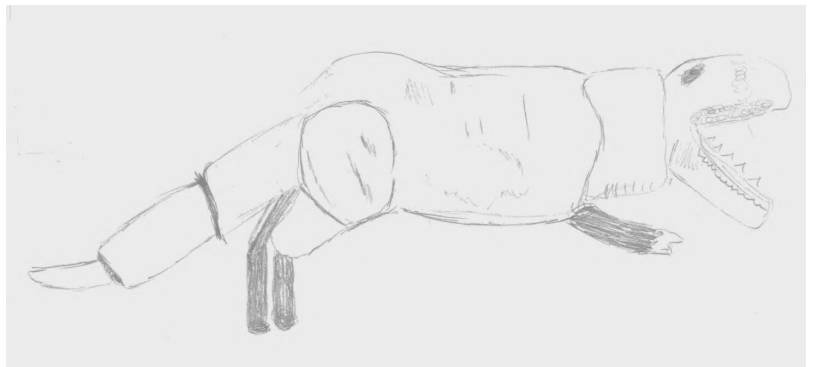
Student D



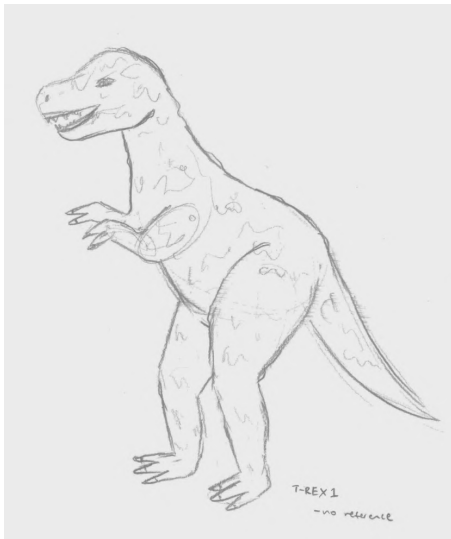
Student E



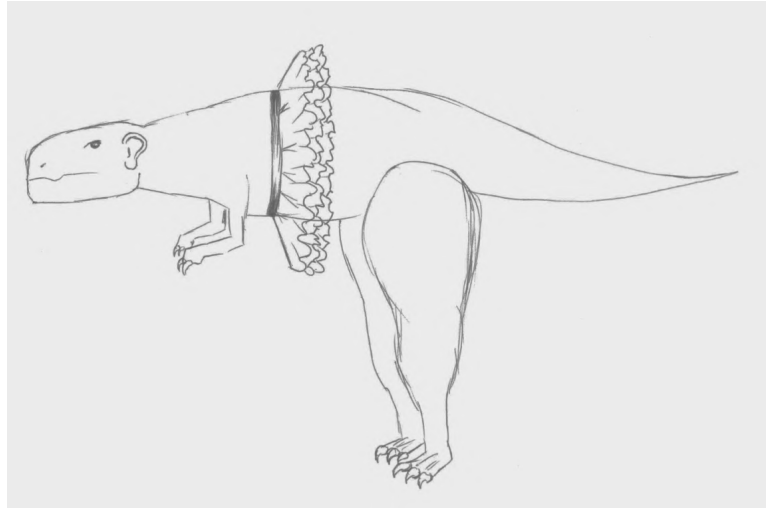
Student F



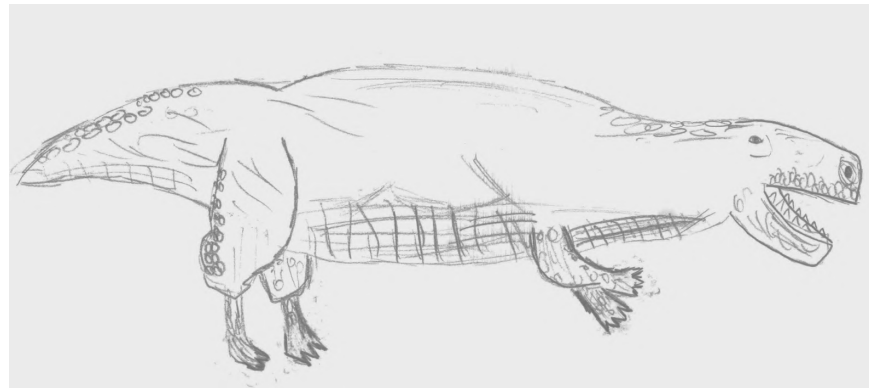
Student G



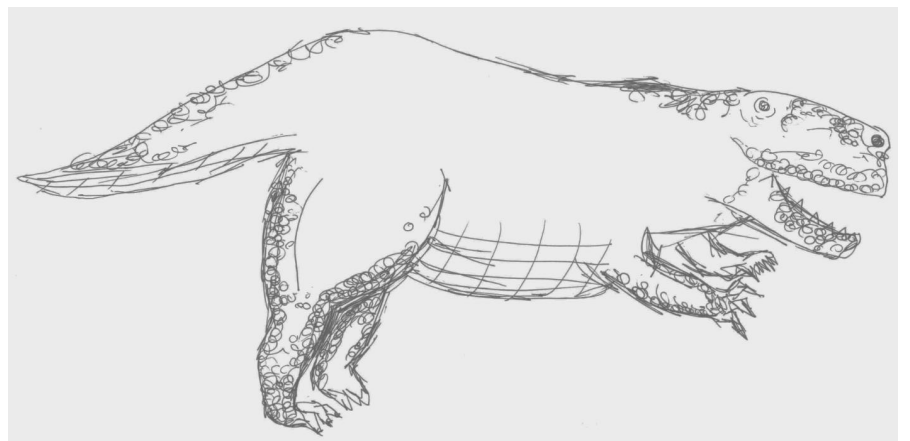
Student H



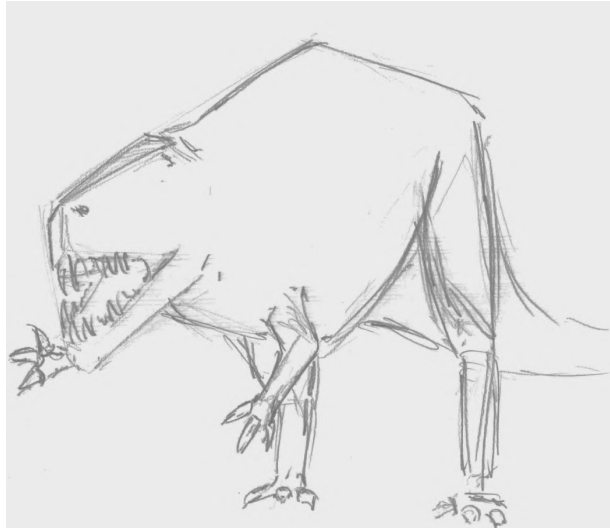
Student I



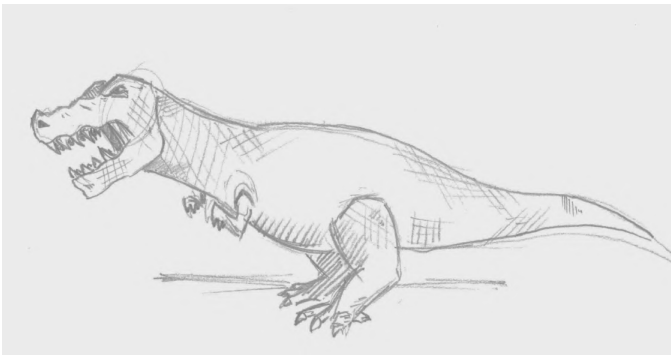
Student J



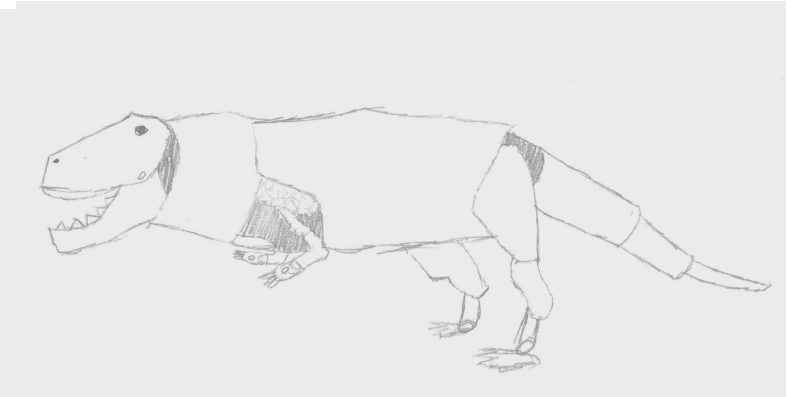
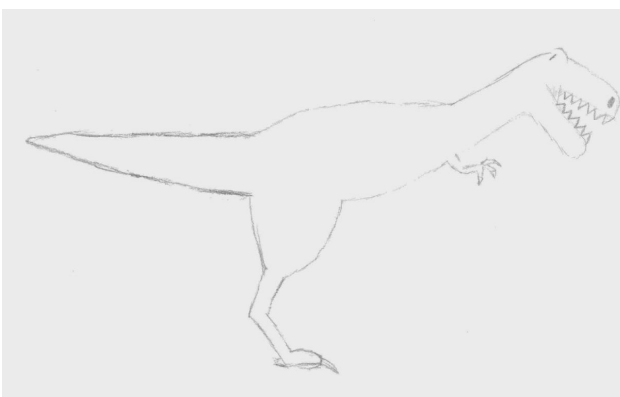
Student K



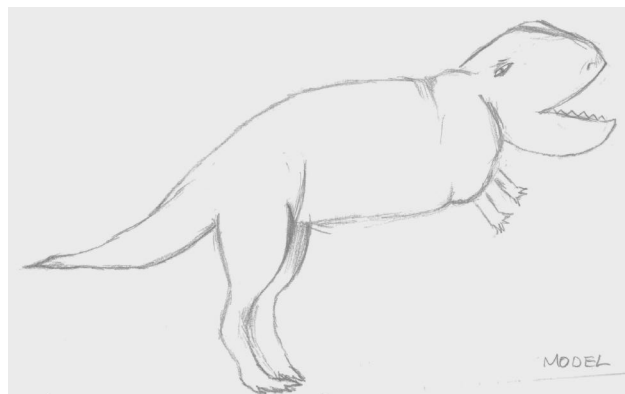
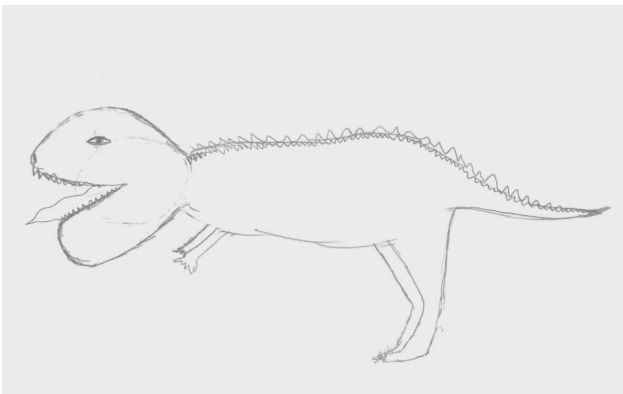
Student L



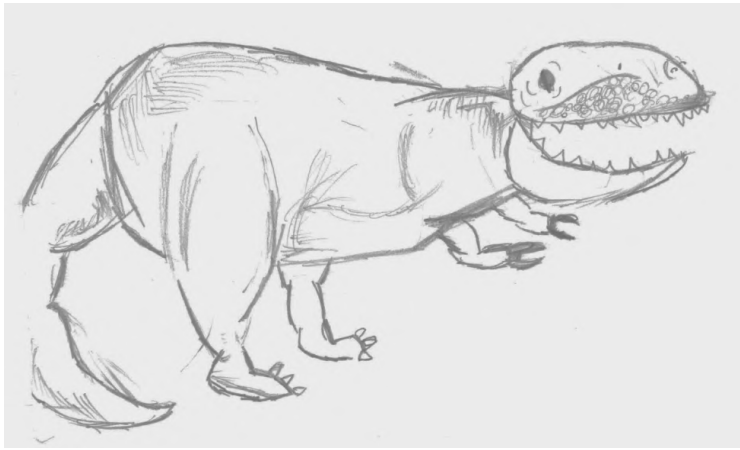
Student M



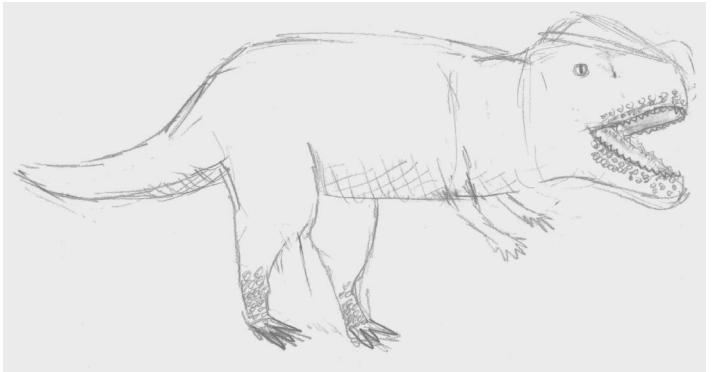
Student N



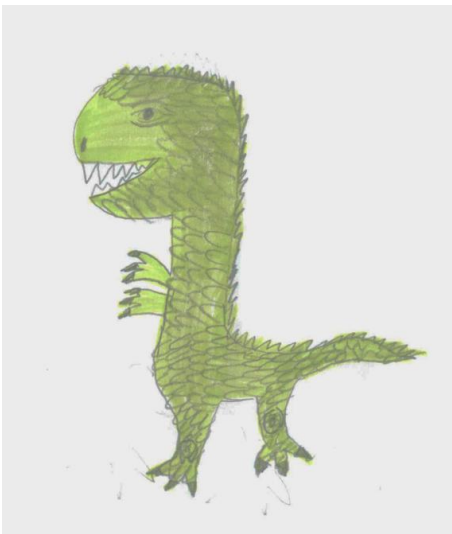
Student O



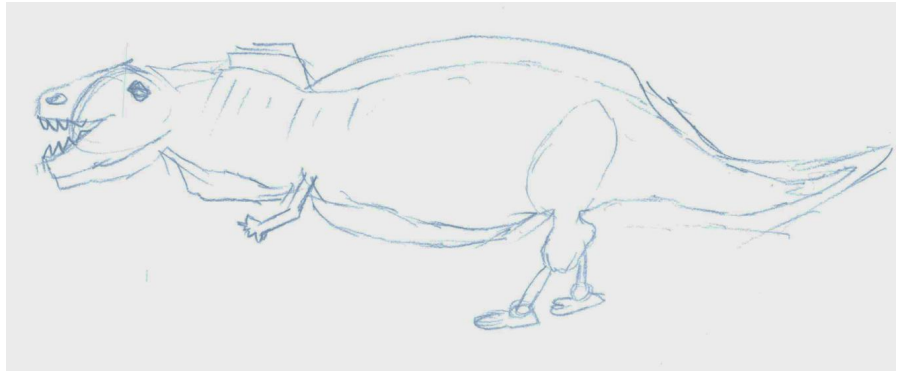
Student P



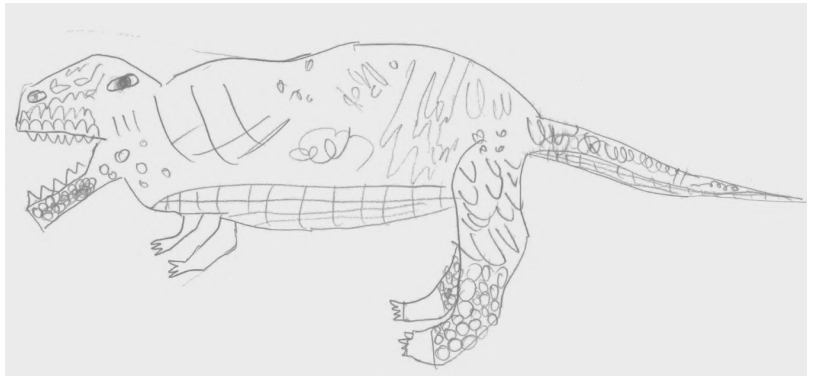
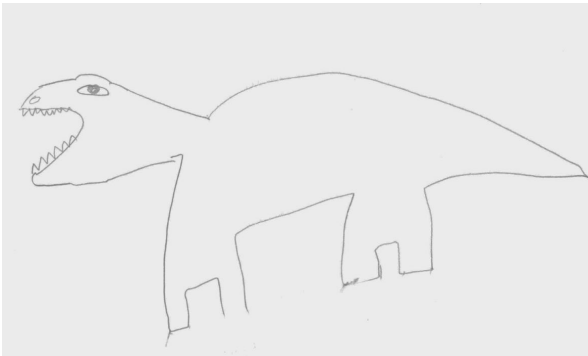
Student Q



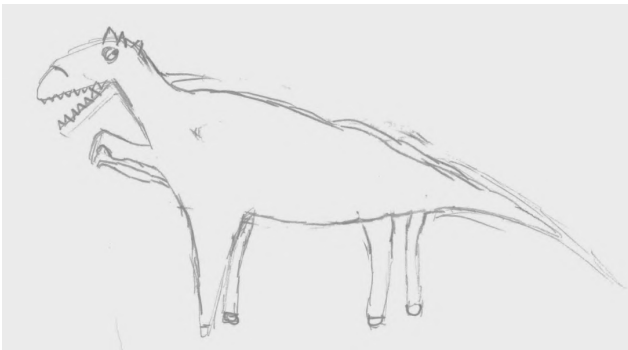
Student R



Student S

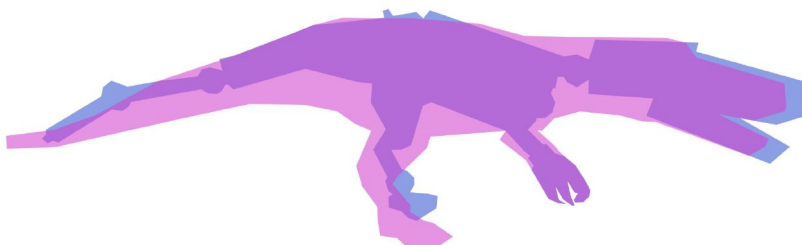


Student T

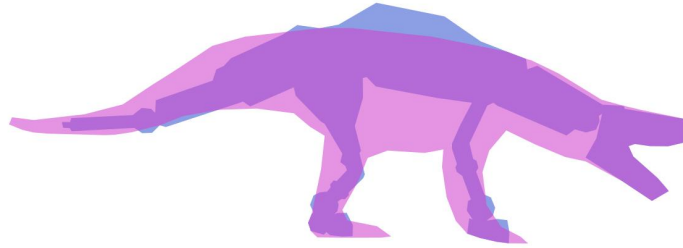


Appendix 10 - Performance Testing

Torvosaurus tanneri model to actual counterpart comparison (Wierum)



Prestosuchus chiniquensis model to actual counterpart comparison (SpinolnWonderland)



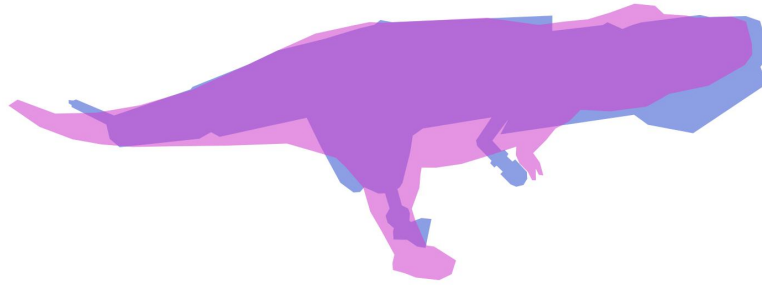
Hatzegopteryx thambema model to actual counterpart comparison (Ashbridge)

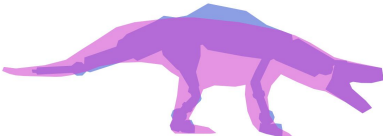


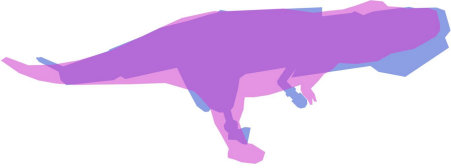
Grus grus model to actual counterpart comparison (Trepte)



Tyrannosaurus rex model to actual counterpart comparison (Palmer)



Animal Model	Area of model silhouette (square units)	Area of actual silhouette (square units)	Lateral silhouette area compared to desired area
Torvosaurus tanneri 	12552.57	16343.07	77%
Prestosuchus chiniquensis 	10214.13	14147.64	72%
Hatzegopteryx thambema 	10225.74	11719.59	87%
Grus grus 	7827.63	7309.88	107%

Tyrannosaurus rex	20490.69	22527.03	91%
			
Average	12262.20	14409.40	85%

Appendix 11 - Natural Environment Testing

Pictures were taken every 2 minutes to demonstrate the deterioration of the model.

0 minutes



2 minutes



4 minutes



6 minutes



8 minutes

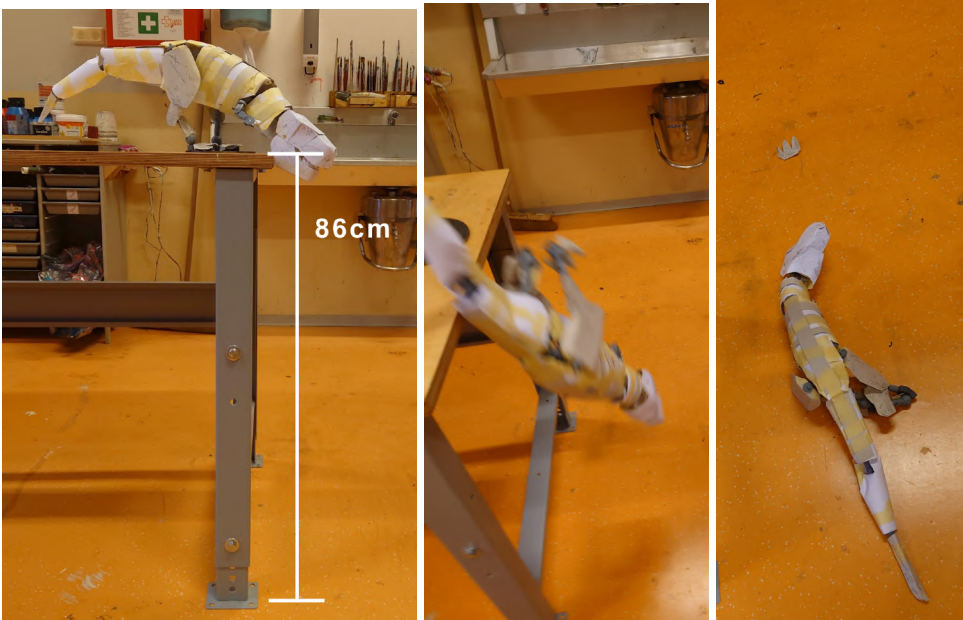


10 minutes



Appendix 12 - Destructive Testing

Example of a trial



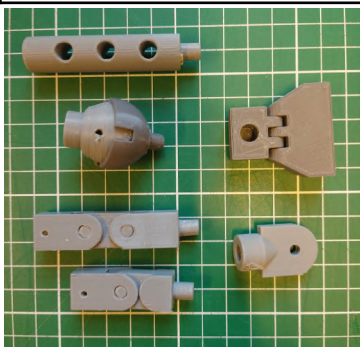
Damaged Parts	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Total
Paper shell	0	0	0	0	1	1
Small Bone	0	0	0	0	0	0
Connector Bone	0	0	0	0	0	0
Single-hole bone	0	0	0	0	0	0
Triple-hole bone	0	0	0	0	0	0
Quad Bone	0	0	0	0	0	0

Clip	0	0	0	0	0	0
180° Linkage Male End	0	0	0	0	0	0
Center Linkage	0	0	0	0	0	0
Linkage Female End	0	0	0	0	0	0
90° Linkage Male End	0	0	0	0	0	0
Ball Joint	0	0	0	0	0	0
Outer Shell	0	0	0	0	0	0
30° Ball Joint	0	0	0	0	0	0
Foot Large End	0	0	0	0	0	0
Foot Small End	0	0	0	0	0	0
Separated Connections	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Total
Peg Joint	0	1	4	1	2	8
Paper Shell	0	1	1	0	1	3
180° Linkage	0	0	0	0	0	0
90° Linkage	0	0	0	0	0	0
Ball joint	0	0	0	0	0	0
30° Ball Joint	0	0	0	0	0	0
Foot	0	0	0	0	0	0

Appendix 13 - Tolerance Testing

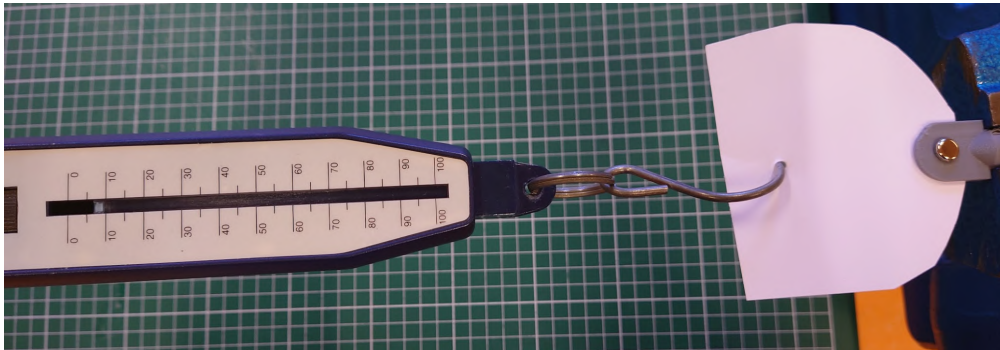
Connections	Force to Separate (N)
Paper shell to clip	10
Male to female parallel	
Small Bone	100
Connector Bone	100
Single-hole Bone	15
Triple-hole Bone	10
Quad Bone	70
Average	59
Range	90
Male to female perpendicular	
Small Bone	100

Connector Bone	80
Single-hole Bone	100
Triple-hole Bone	60
Quad Bone	90
Average	86
Range	40
Female to male parallel	
Small Bone	30
Single-hole Bone	15
Triple-hole Bone	55
Quad Bone	20
Foot	30
Clip	5
Average	26
Range	50
Female to male perpendicular	
Single-hole Bone	80
Triple-hole Bone	40
Quad Bone	10
Foot	5
Average	34
Range	75
Subassemblies	
180° Linkage	100
90° Linkage	100
Ball Joint	30
30° Ball Joint	20
Average	63
Range	80

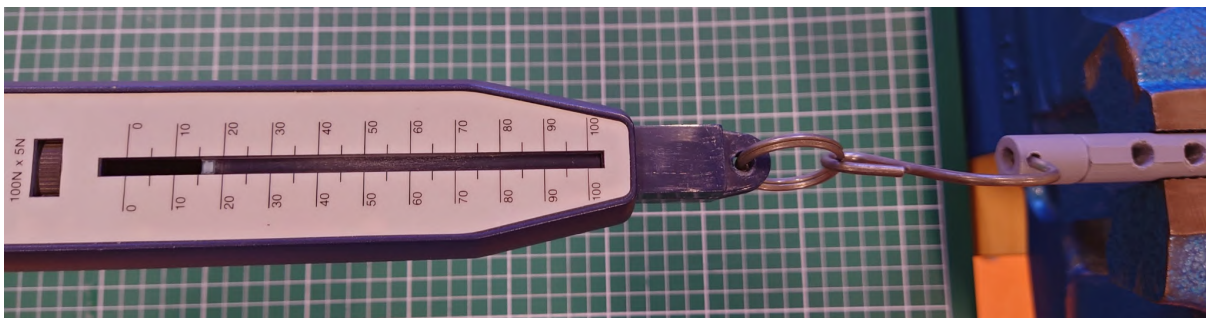


The following images show the position of the part during the test. The spring is not fully tensed, hence it shows a lower value than the actual separating force. Some parts had holes drilled into them to allow fitting of the hook for pulling.

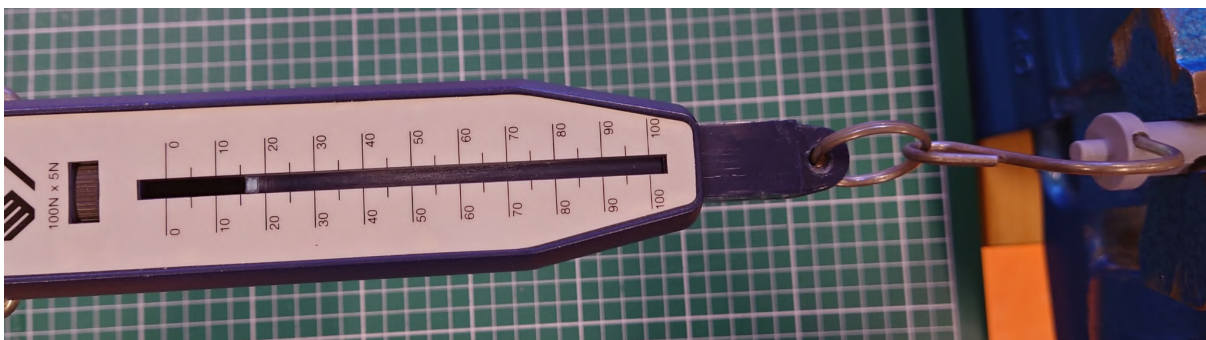
Paper Shell to Clip



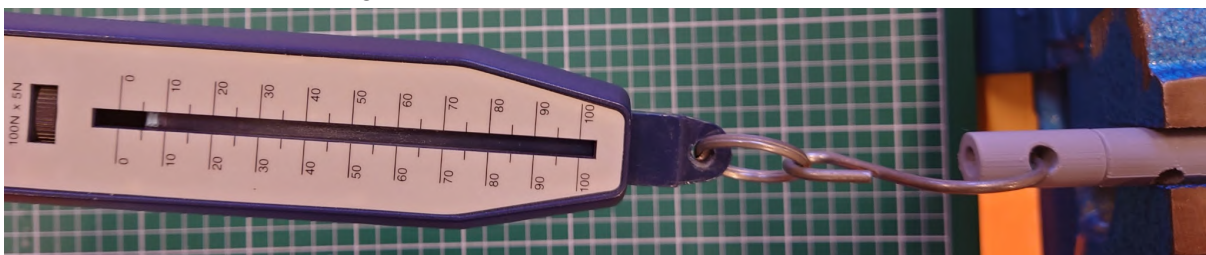
Male to Female Parallel Small Bone



Male to Female Parallel Connector Bone



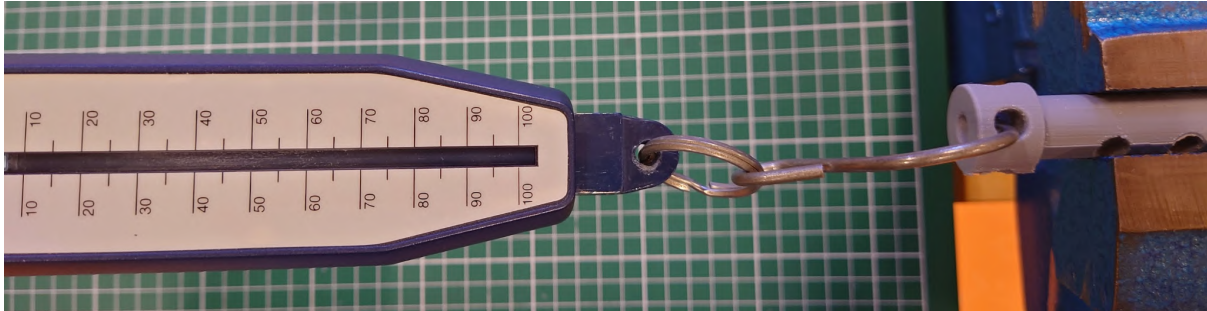
Male to Female Parallel Single-hole Bone



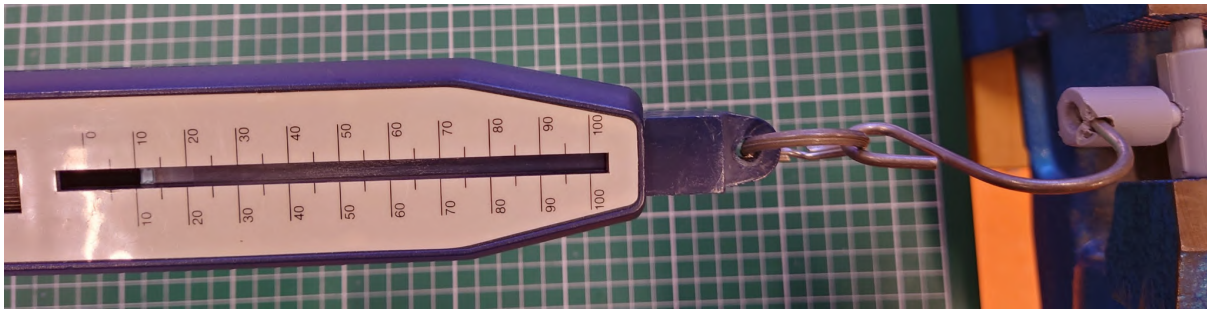
Male to Female Parallel Triple-hole Bone



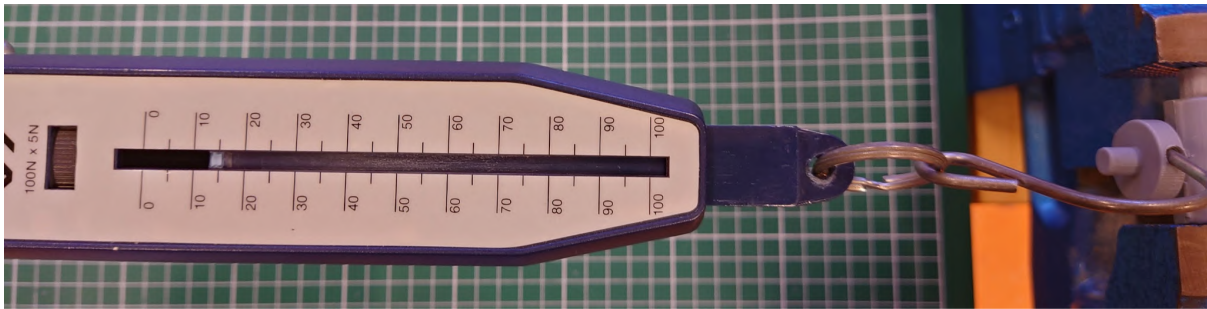
Male to Female Parallel Quad Bone



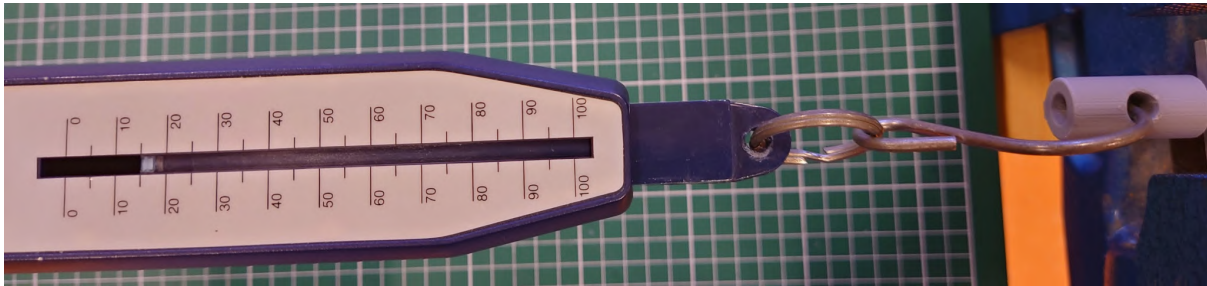
Male to Female Perpendicular Small Bone



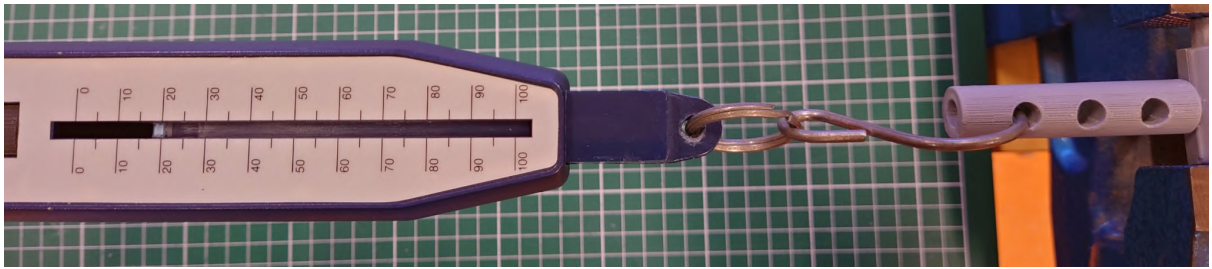
Male to Female Perpendicular Connector Bone



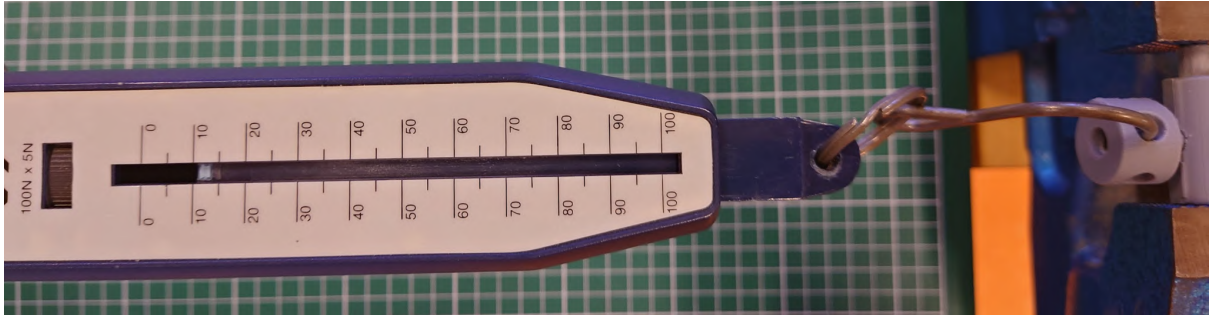
Male to Female Perpendicular Single-hole Bone



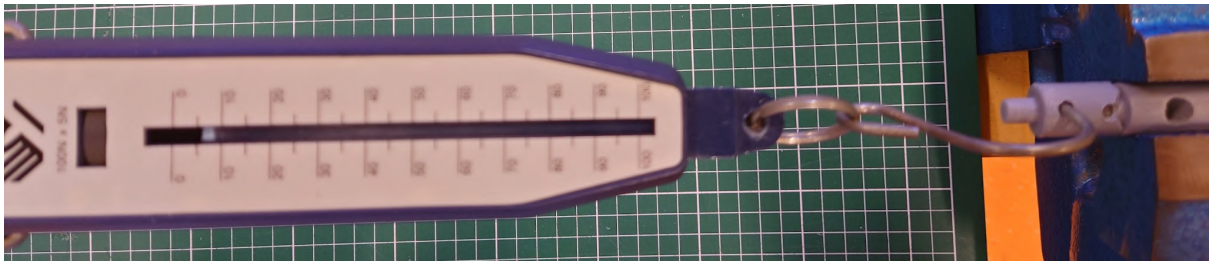
Male to Female Perpendicular Triple-hole Bone



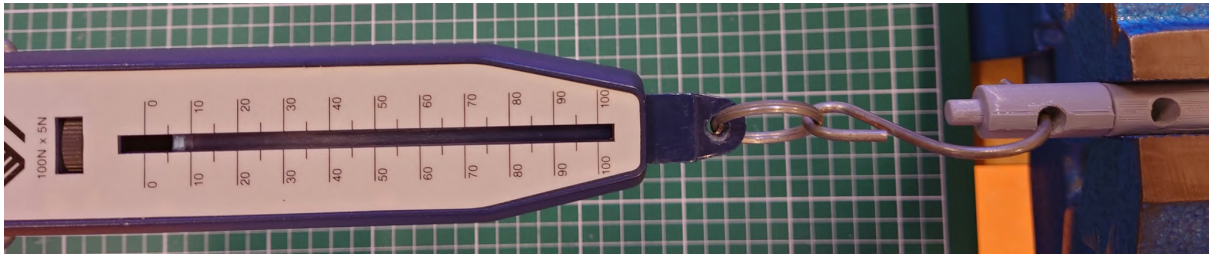
Male to Female Perpendicular Quad Bone



Female to Male Parallel Small Bone



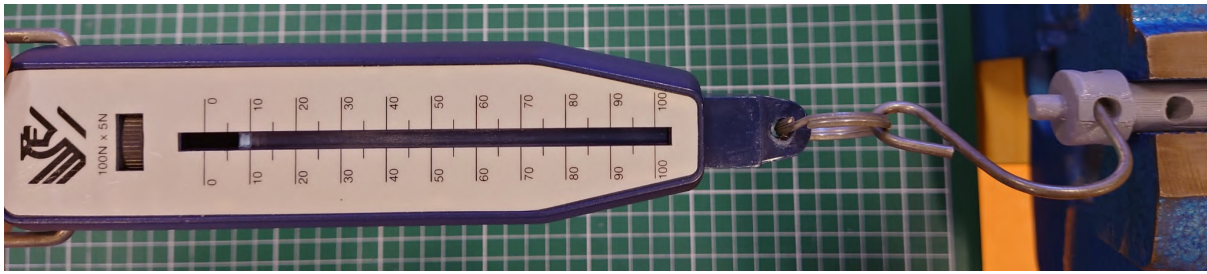
Female to Male Parallel Single-hole Bone



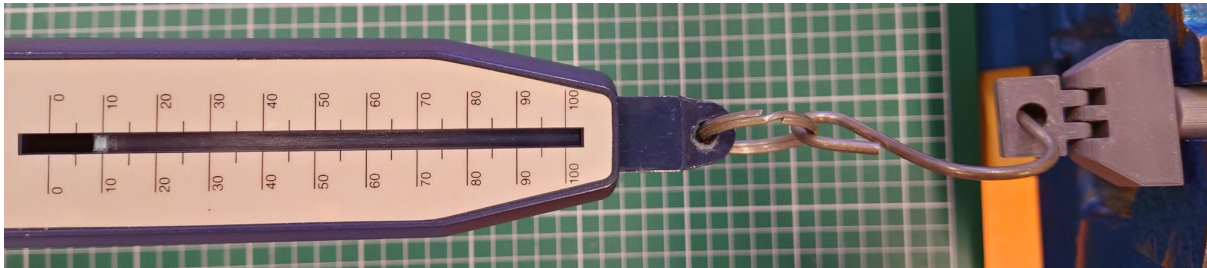
Female to Male Parallel Triple-hole Bone



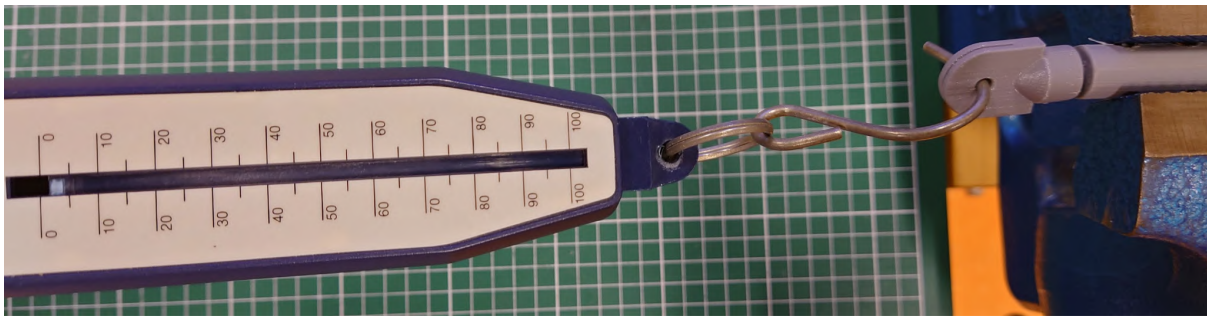
Female to Male Parallel Quad Bone



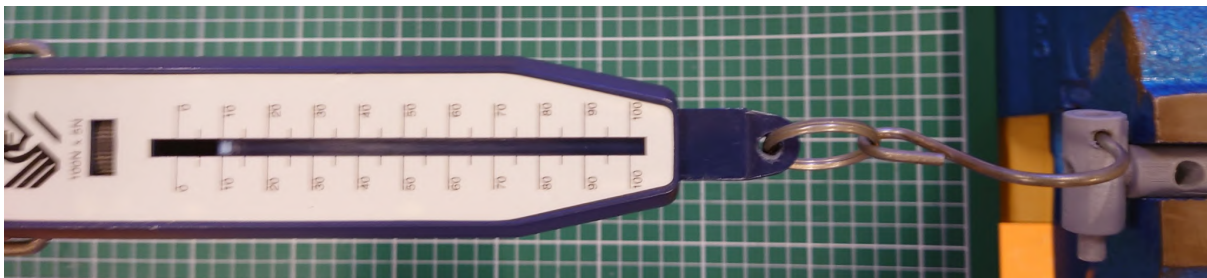
Female to Male Parallel Foot



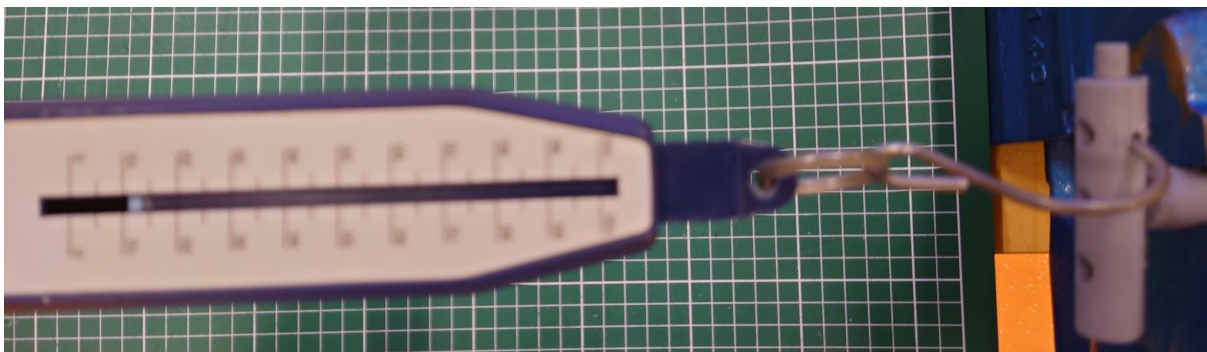
Female to Male Parallel Clip



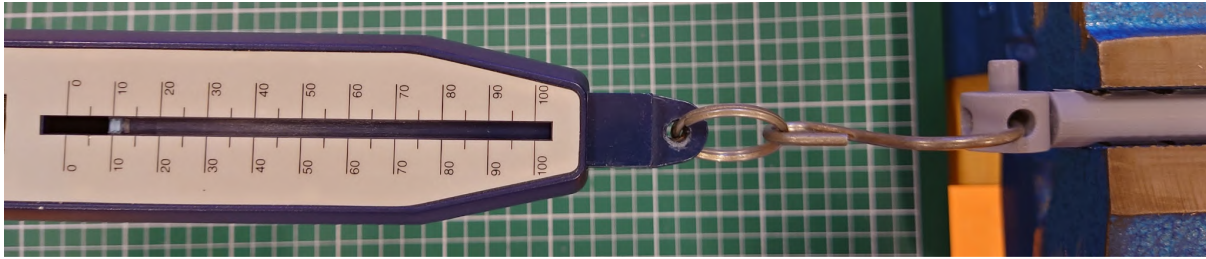
Female to Male Perpendicular Single-hole Bone



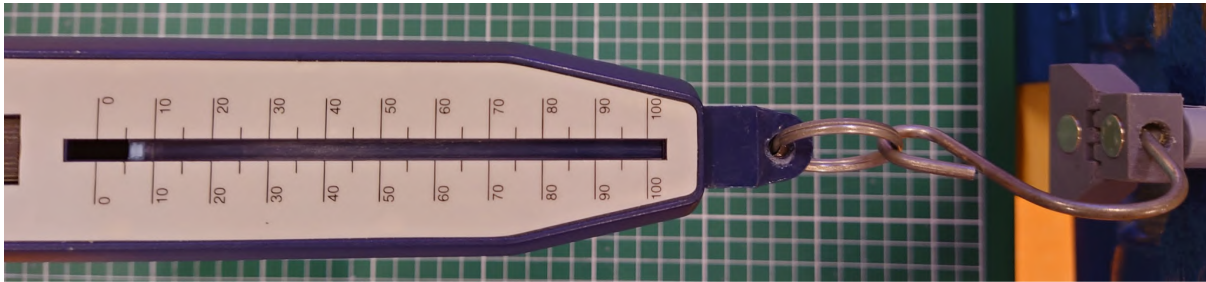
Female to Male Perpendicular Triple-hole Bone



Female to Male Perpendicular Quad Bone



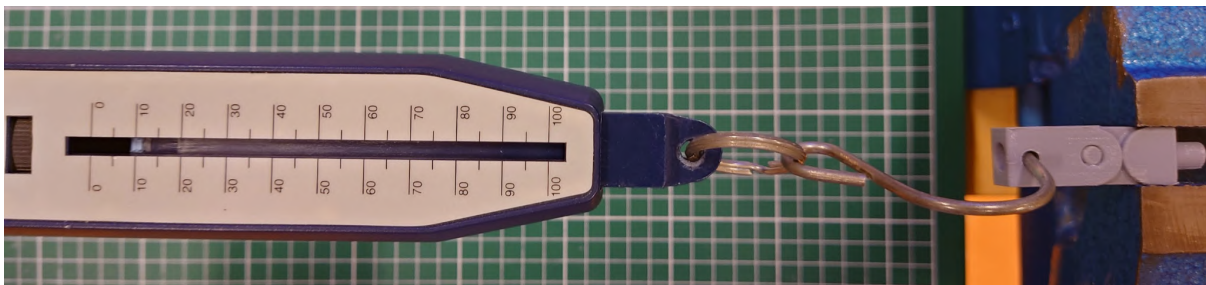
Female to Male Perpendicular Foot



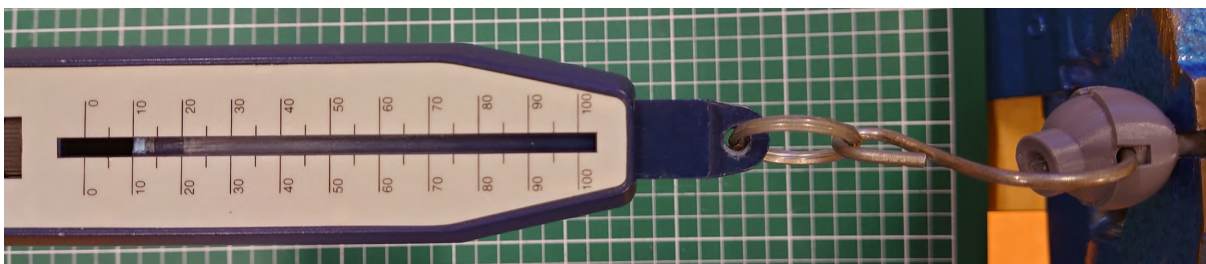
180° Linkage



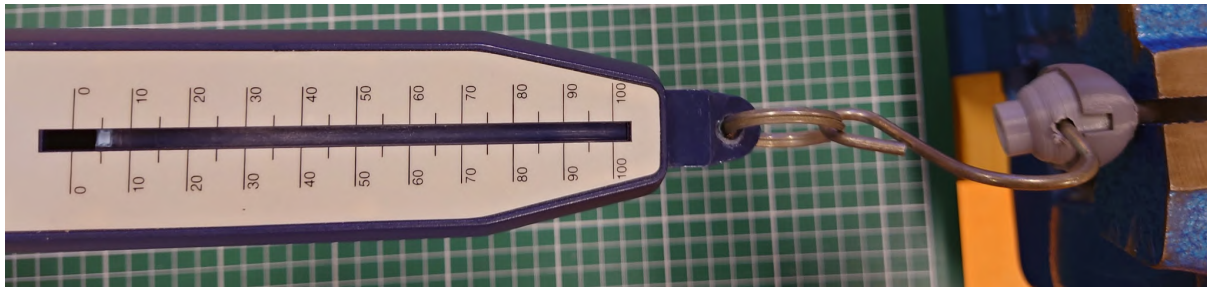
90° Linkage



Ball Joint



30° Ball Joint



Appendix 14 - Package Weight and Size Calculations

Using the volume of the individual PLA parts (Appendix 6), and multiplying it by the density of PLA, 1.02g/cm^3 (Plastim), we can obtain the mass of any specific part. For the clips, the density of TPU, 1.24g/cm^3 (Iemai) is used instead. Summing together all the masses of the 3D-printed parts together with the steel stand and brass brads, we can obtain the total mass of the packaging.

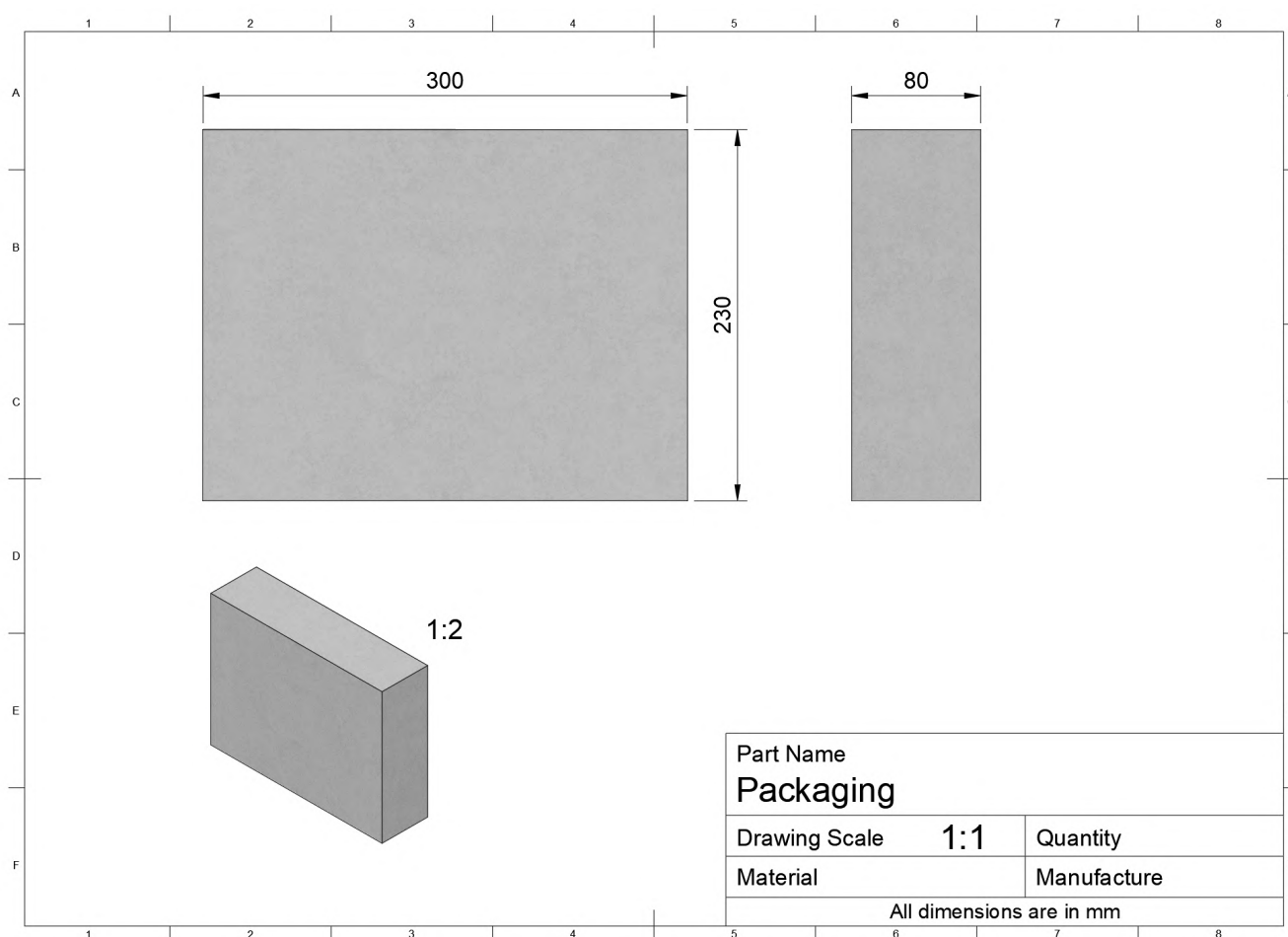
Part Name	Volume (cm3)	Mass (g)	Quantity	Total Mass (g)
Small Bone	3.03337	3.0940374	6	18.5642244
Connector Bone	2.42353	2.4720006	10	24.720006
Single-hole bone	4.01176	4.0919952	6	24.5519712
Triple-hole bone	7.61589	7.7682078	10	77.682078
Quad Bone	3.2269	3.291438	6	19.748628
Clip (TPU)	10.849262	13.45308488	16	215.2493581
Linkage Male End	3.973214	4.05267828	12	48.63213936
Center Linkage	5.915722	6.03403644	6	36.20421864
Linkage Female End	4.118607	4.20097914	12	50.41174968
Ball Joint	7.671931	7.82536962	10	78.2536962
30° Ball Joint	7.913628	8.07190056	8	64.57520448
Outer Shell	2.074255	2.1157401	18	38.0833218
Foot Male End	5.971847	6.09128394	4	24.36513576
Foot Female End	8.63406	8.8067412	4	35.2269648
Pin	1.798348	1.83431496	14	25.68040944
Stand (Purchased)		989.5	1	989.5
Magnets (Purchased)		1.6	8	12.8
Total				1758.568696
Packaging (30% of total weight)				535.2747318
Final Total				2319.523838

The packaging is assumed to be 30% of the total weight, which is the median in packaging to total weight percentages for packaged groceries (Pongrácz 249).

Transportation fees of the package from Eindhoven to Amsterdam, where weight of the package is 2.319kg with a size of 300mmx80mmx230mm (UPS) are shown below:

☐ OUR RECOMMENDATION 01/30 By 10:30 €15,46 UPS Express	☐ LOWEST COST 01/30 By End of Day €10,30 UPS Standard	☐ FASTEST 01/30 By 09:00 €26,18 UPS Express Plus
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These volumes were also multiplied with the costs for ABS and TPU (Appendix 16) respectively in order to determine the price.



Appendix 15 - Estimating the Number of Art Students in the EU and Netherlands

In 2022, there was a total of 98591 design, art, languages and history students in secondary and tertiary schools in the Netherlands (CBS). According to 2014 data, 40% of students in culture-related fields of education in the Netherlands studied arts (Eurostat). The number of art students in the Netherlands is thus estimated through:

$$98591 * 0.4 = 39436,4 \approx 39436$$

It can be assumed there are about 39436 art students in secondary and tertiary education in the Netherlands.

In 2023, in the EU in total there were 2.6 million students taking culture-related tertiary education (Eurostat), about a quarter of which studied arts (Eurostat). The number of tertiary art students in the EU is thus estimated through:

$$2600000 * 0.25 = 650000$$

In 2023, 49.1% (Eurostat 3) of the 18.3 million students (Eurostat 2) in upper secondary education were studying in vocational schools. Assuming that a similar proportion to tertiary students, 15% (Eurostat), are studying in culture-related fields, then we can find:

$$18300000 * 0.15 = 2745000$$

Assuming about a quarter of the secondary students in culture-related studies are studying art, we can find that;

$$2745000 * 0.25 = 686250$$

Population of Art Students in the Netherlands	Population of Art Students in the EU	Population of Art Students in the EU Excluding Netherlands
39436	1336250	1296814

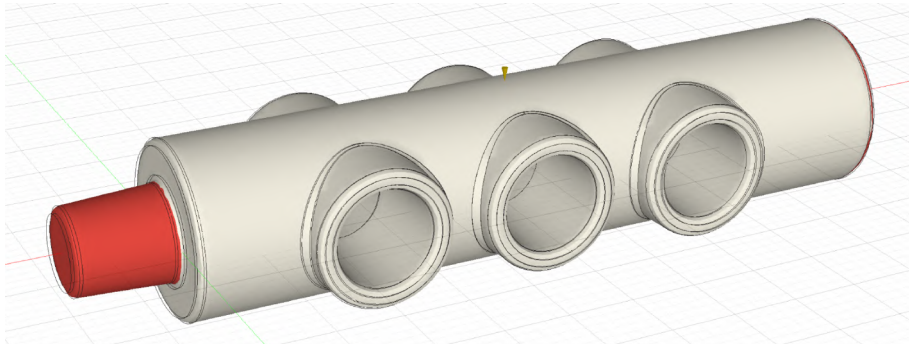
Appendix 16 - Justification of ABS Plastic

Material	Tensile Strength at Yield [M1]	Max Compressive Strength [M1]	Gardner Impact [M1]	Flexural Strength [M1]
ABS	48MPa (SpecialChem)	69MPa (Matmake)	50.8J (ACPlastics)	66.8MPa (ACPlastics)
Nylon 6	76MPa (GEPlastics)	39MPa (Directplastics)	36.2J (Songhan)	110.3MPa (Resin Enterprise)
Polycarbonate	69MPa (Directplastics)	85MPa (PolySynthesis)	23.0J (City Plastics)	90MPa (Directplastics)
Acetal	65.6MPa (Laminated Plastics)	103.4MPa (Laminated Plastics)	200J (Piedmont Plastics)	82.7MPa (Laminated Plastics)
PLA	52.5 MPa (Ultimaker)	68.4MPa (A Kholil 4)	14.0J (Seas3D)	85.1 MPa (Iemai)
Necessary Value (Appendix 3)	51.7 MPa	49.5MPa	23.2J	49.5MPa

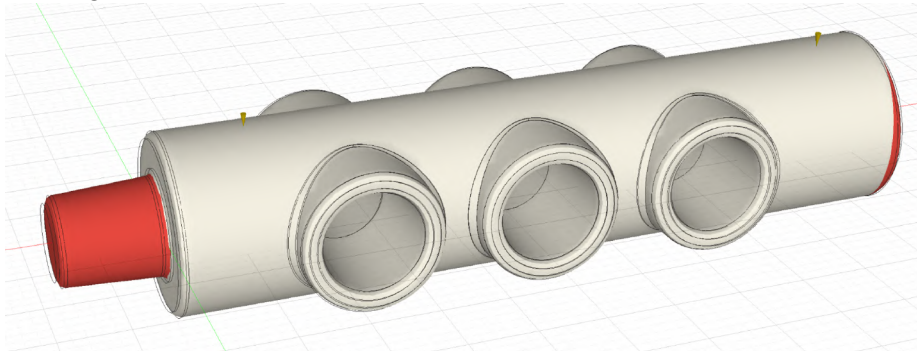
Material	Density [M2]	Cost [P1]	Water Absorption [M3]
ABS	1.04g/cm3 (Matmake)	€0.001638/g (Mike)	0.7% (Plastim)

Nylon 6	1.14g/cm3	€0.002024/g (Mike)	1.28% (GEPlastics)
Polycarbonate	1.20g/cm3 (Directplastics)	€0.002612/g (Mike)	0.36% (Plastim)
Acetal	1.41g/cm3 (Laminated Plastics)	€0.002352/g (Ren)	0.2% (Laminated Plastics)
PLA	1.25g/cm3 (Farah 5)	€0.001875/g (Intratec)	0.4% (Vinoth 7)
Necessary Value (Appendix 3)	7.44g/cm3	€0.0021/g	0.588%

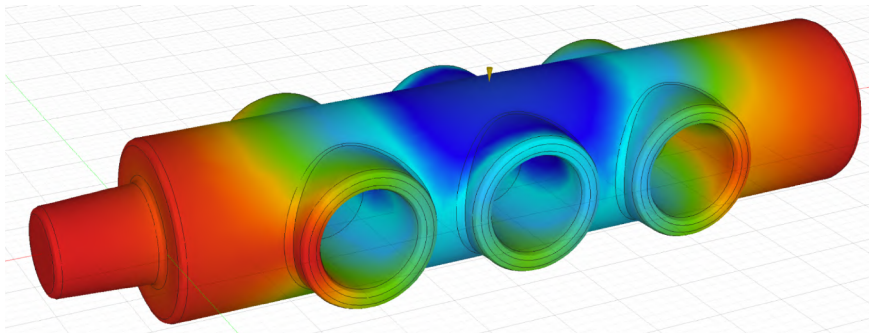
Appendix 16 - Injection Molding Simulations
 Triple-hole bone warpage test with single injection point
 Warpage = 0.208mm



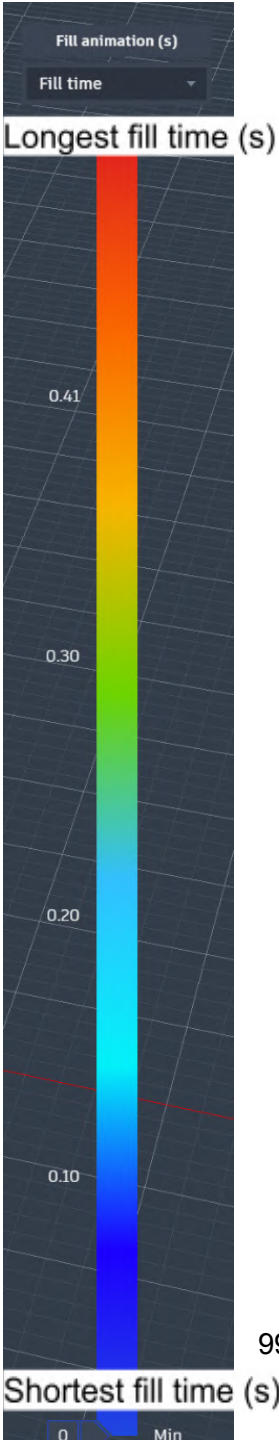
Triple-hole bone warpage test with two injection points
 Warpage = 0.207mm



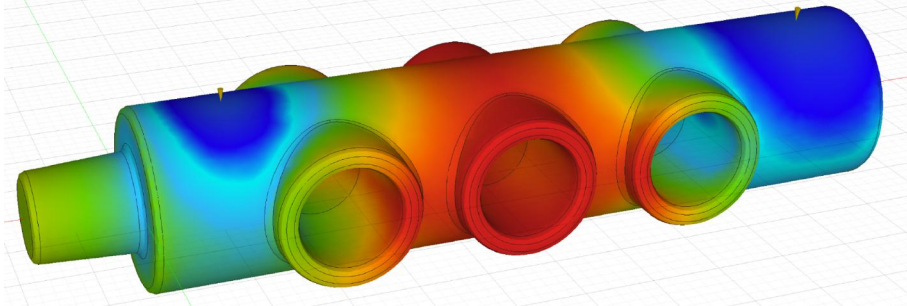
Triple-hole bone fill animation with single injection point
 Fill time = 0.41s.



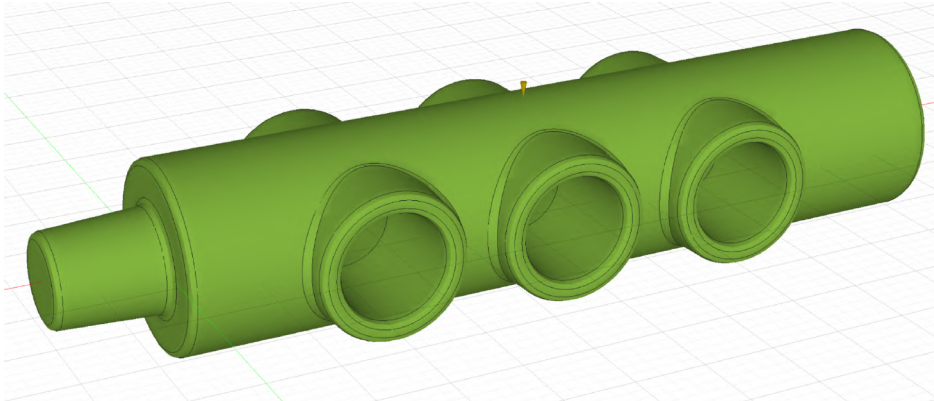
Triple-hole bone fill animation with two injection points



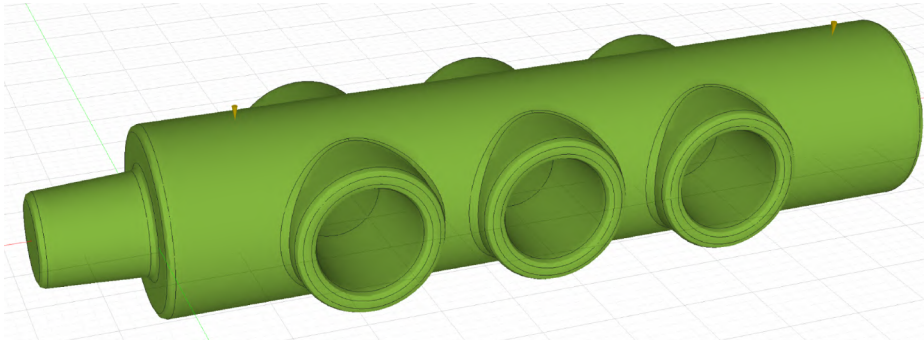
Fill time = 0.30s



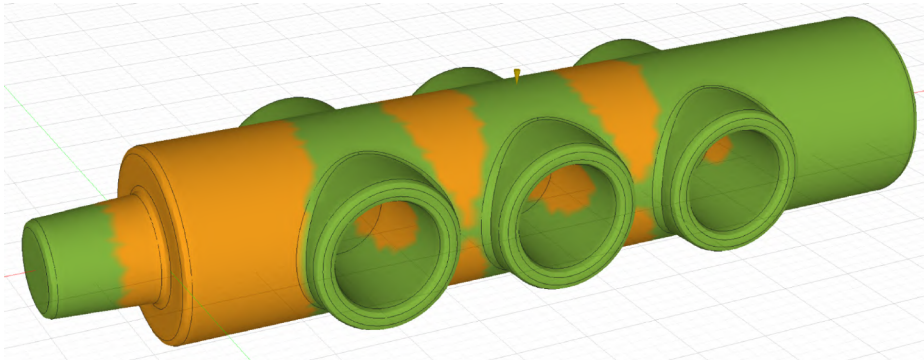
Triple-hole bone fill confidence with single injection point
Fill confidence = 100%



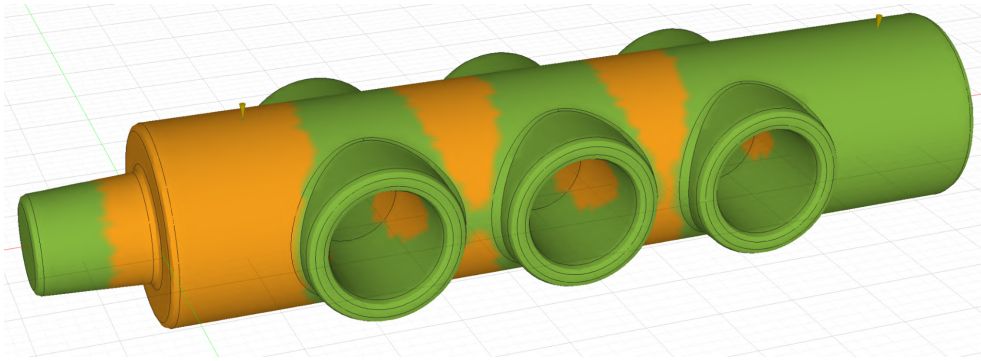
Triple-hole bone fill confidence with two injection points
Fill confidence = 100%



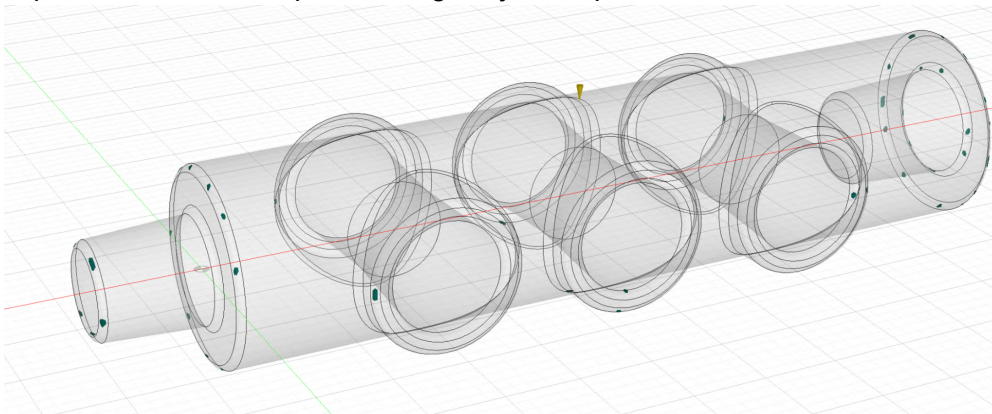
Triple-hole bone quality prediction with single injection point
High quality = 76.236%
Medium quality = 23.764%



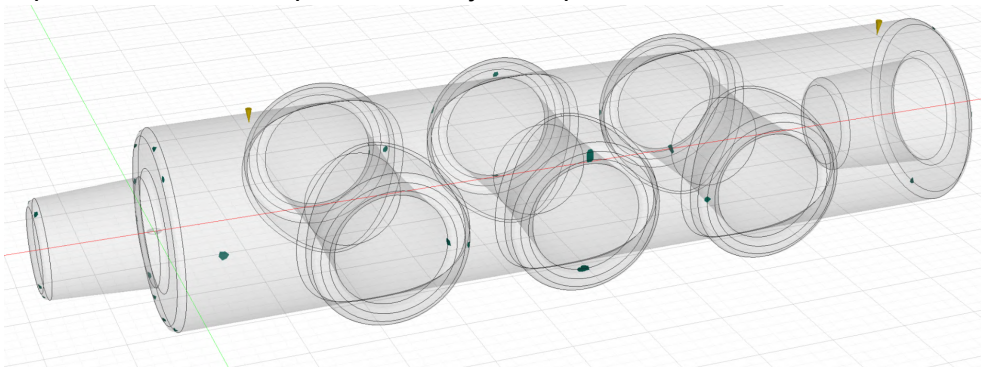
Triple-hole bone quality prediction with two injection points
High quality = 75.91%
Medium quality = 24.09%



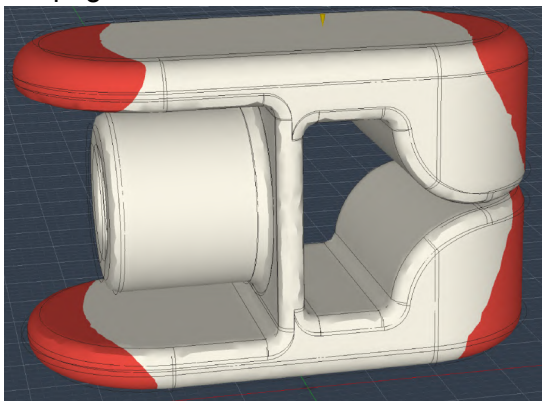
Triple-hole bone air traps with single injection point



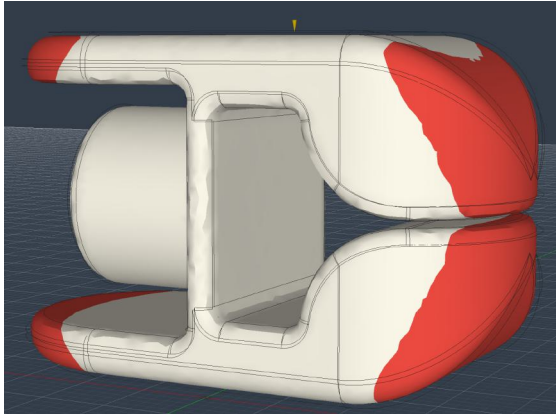
Triple-hole bone air traps with two injection points



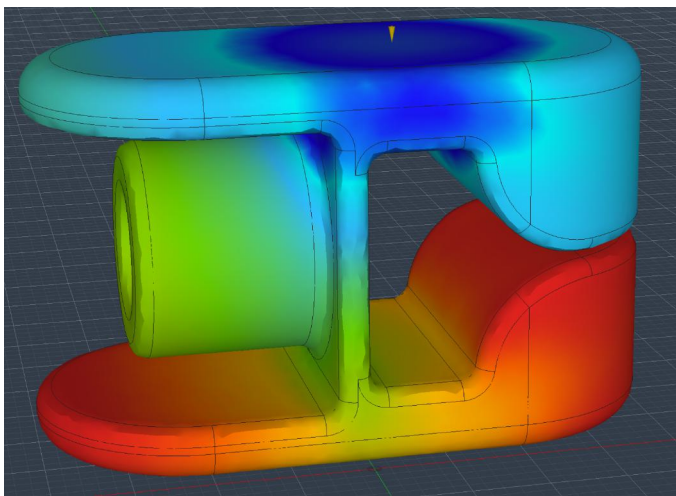
Body panel clip warpage test with non-rounded ends
Warpage = 0.427mm



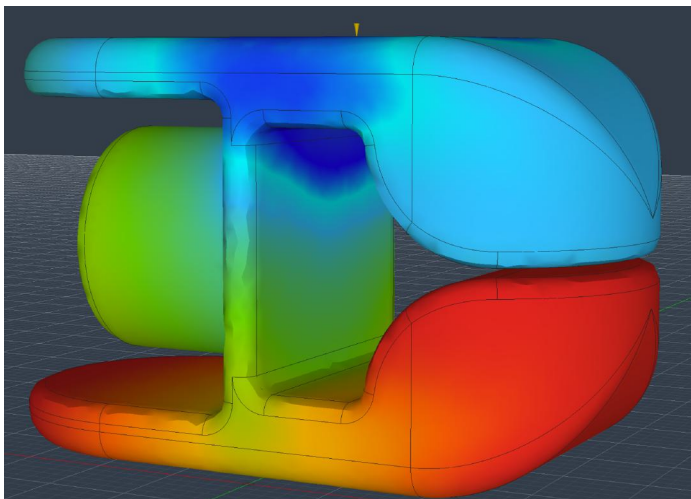
Body panel clip warpage test with rounded ends
Warpage = 0.419mm



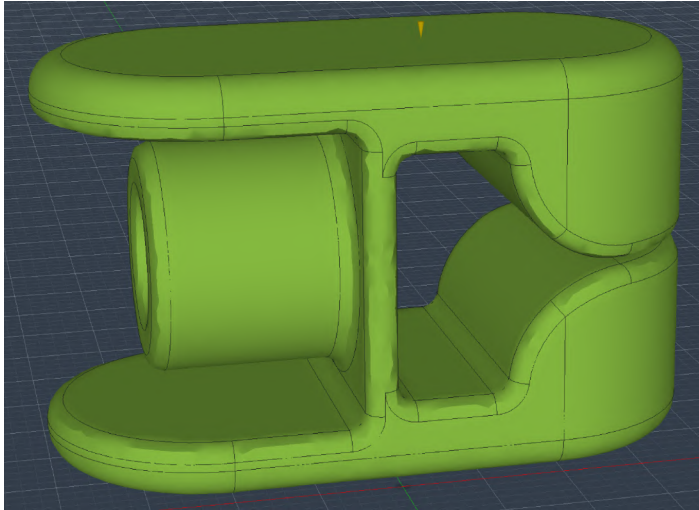
Body panel clip fill animation with non-rounded ends
Fill time = 0.20s



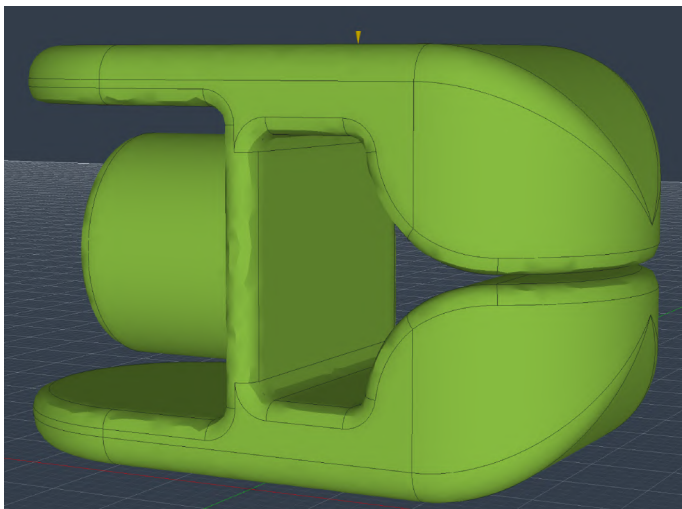
Body panel clip fill animation with rounded ends
Fill time = 0.20s



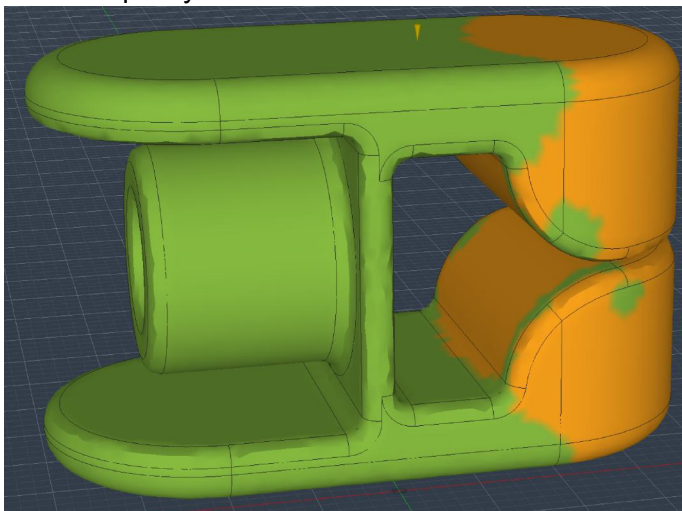
Body panel clip fill confidence with non-rounded ends
Fill confidence = 100%



Body panel clip fill confidence with rounded ends
Fill confidence = 100%

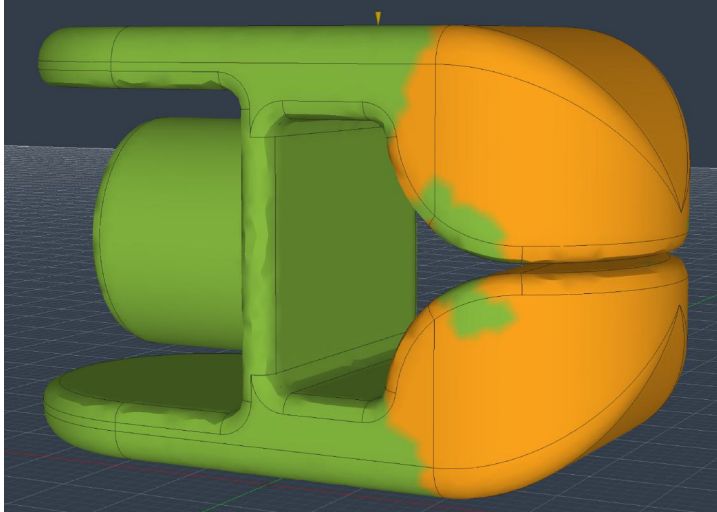


Body panel clip quality prediction with non-rounded ends
High quality = 69.693%
Medium quality = 30.037%

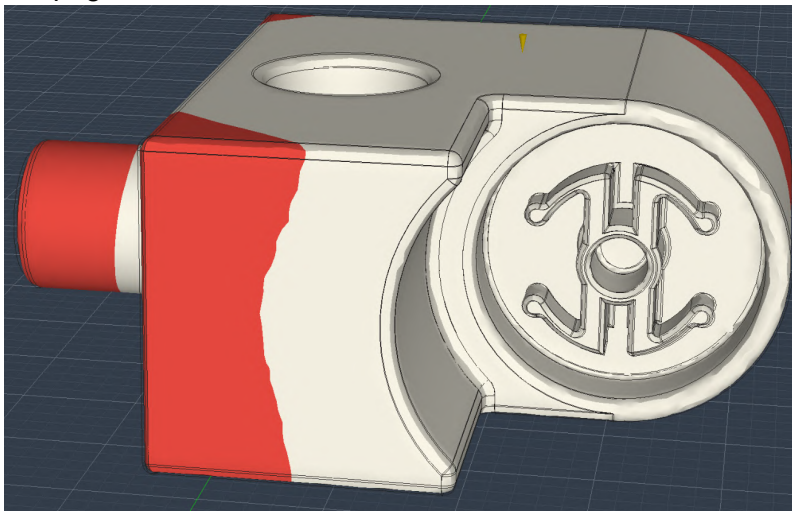


Body panel clip quality prediction with rounded ends
High quality = 70.807%

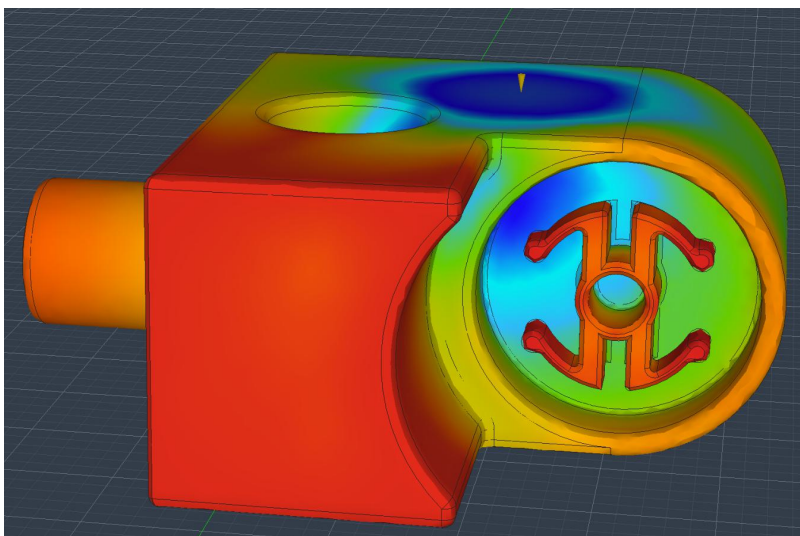
Medium quality = 29.193%



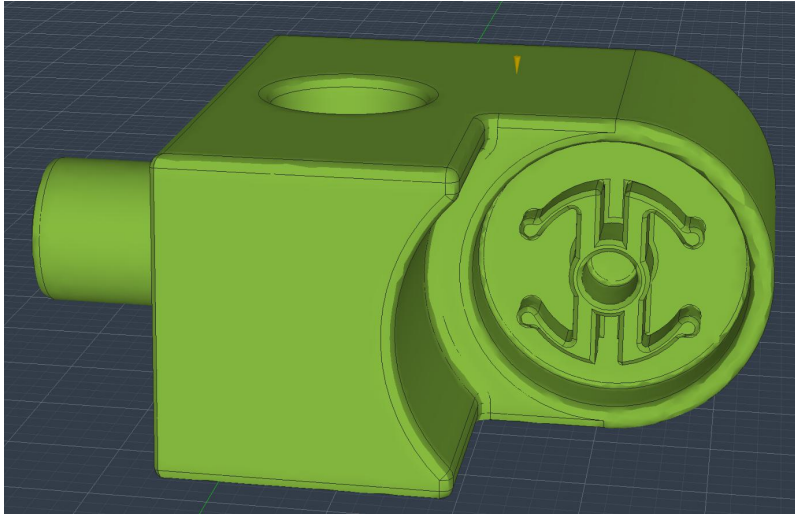
Foot part female end warpage test
Warpage = 0.113mm



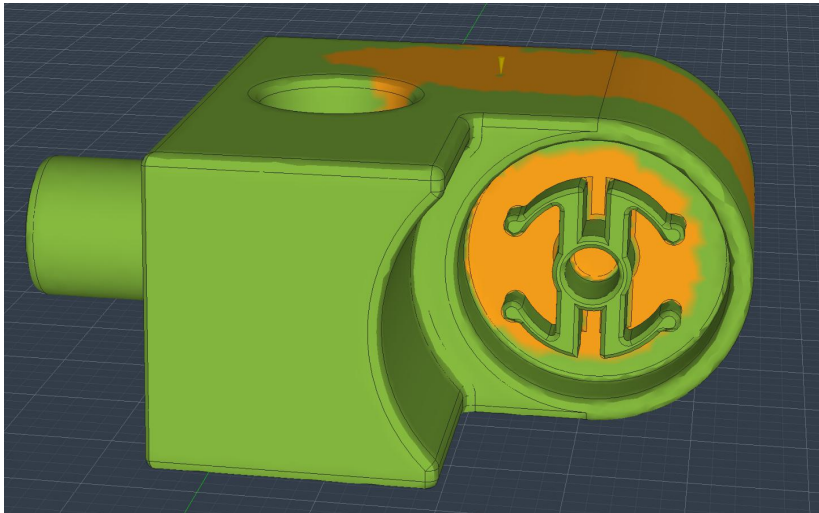
Foot part male end fill animation
Fill time = 0.41s



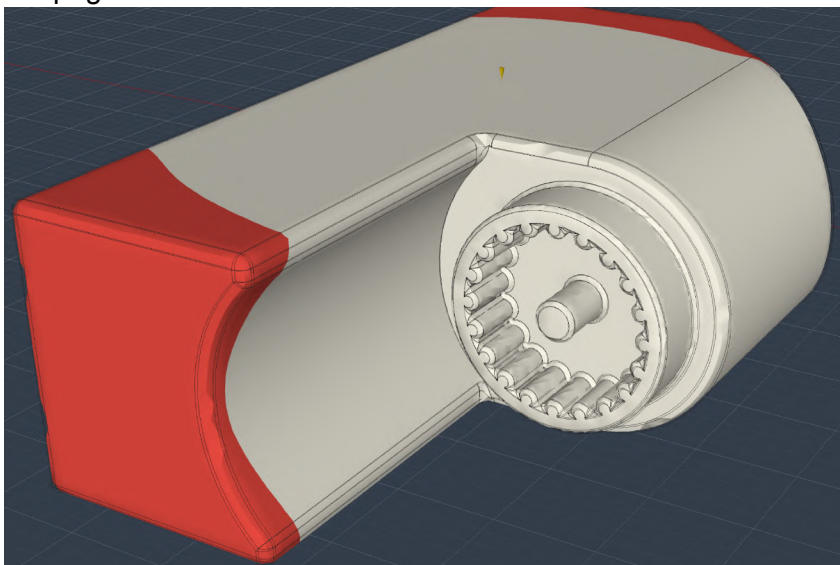
Foot part male end fill confidence
Fill confidence = 100%



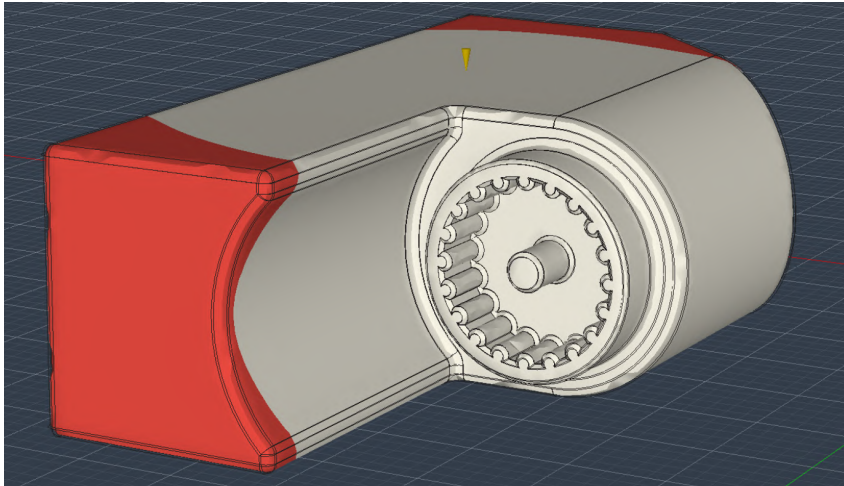
Foot part male end quality prediction
High quality = 75.153%
Medium quality = 24.848%



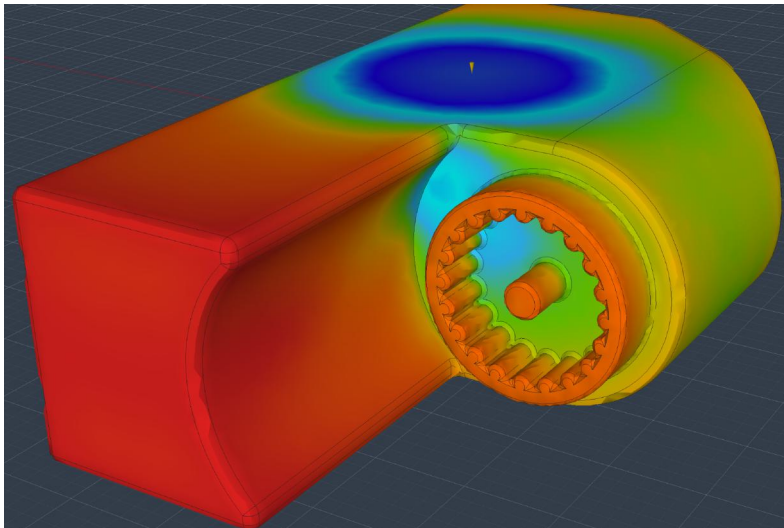
Foot part female end warpage test
Warpage = 0.135mm



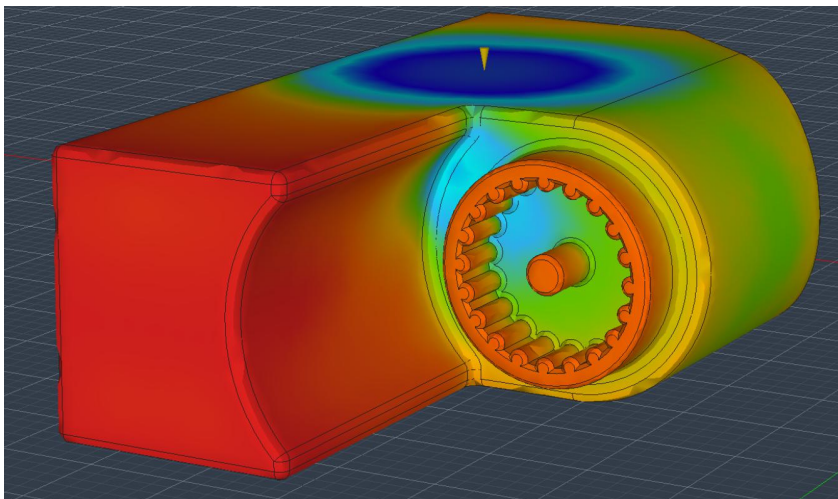
Foot part female end warpage test with draft angles
Warpage = 0.134mm



Foot part female end fill animation
Fill time = 0.41s

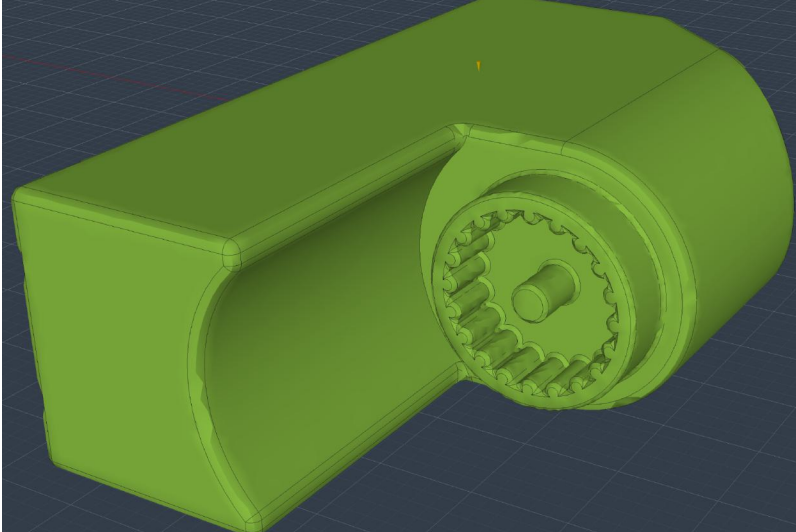


Foot part female end fill animation with draft angles
Fill time = 0.41s

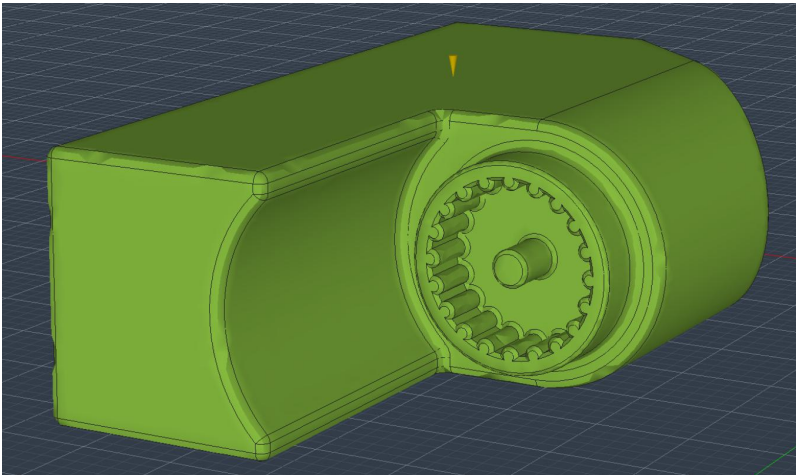


Foot part female end fill confidence

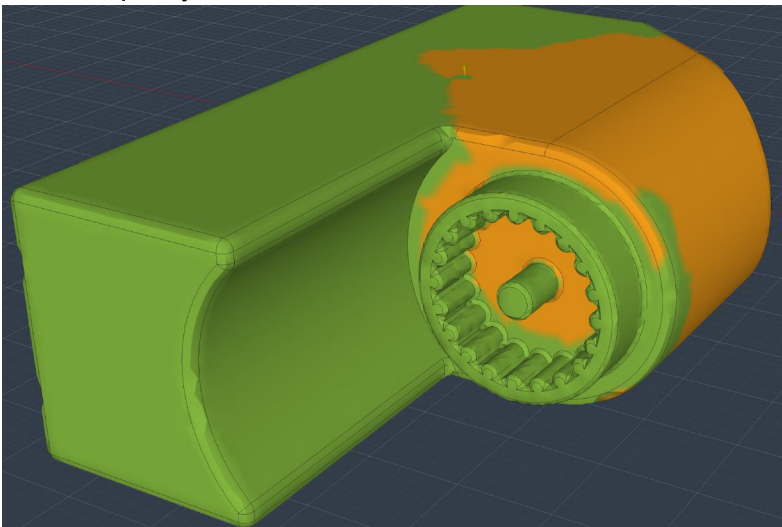
Fill confidence = 100%



Foot part female end fill confidence with draft angles
Fill confidence = 100%

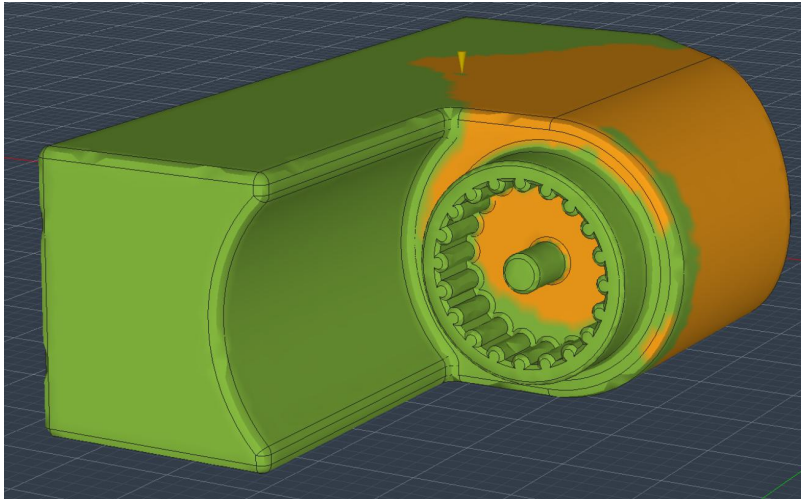


Foot part female end quality prediction
High quality = 77.458%
Medium quality = 22.542%



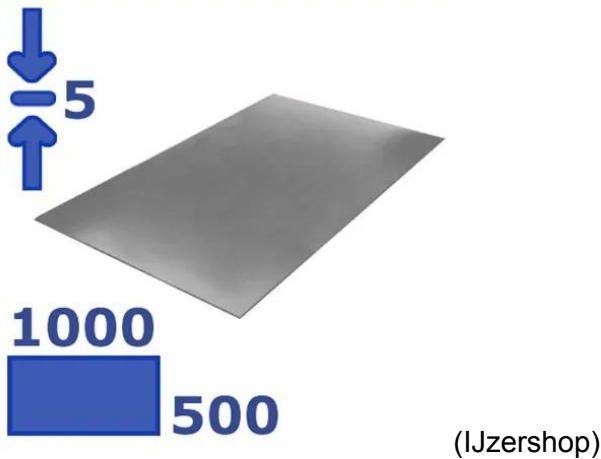
Foot part female end quality prediction with draft angles

High quality = 77.001%
 Medium quality = 22.999%



Appendix 17 - Steel Plate Price

The ideal steel plate would be 200mm x 200mm x 5mm (radius = 100mm), as a larger but thinner plate would still be stable while being far cheaper and reducing packaging and shipping costs. The price of a 1000mm x 500mm x 5mm steel plate was chosen, as the rounded plate could be cut out of this plate.



The plate cost € 62,17 (IJzershop), so by dividing the cost by the volume and multiplying by the volume of a rounded steel plate, we can approximate the cost.

$$\text{Cost/Volume} = \frac{€ 40,12}{(1000\text{mm} \cdot 500\text{mm} \cdot 2.5\text{mm})} = €0.000032\text{mm}^{-3}$$

$$\text{Volume of Round Plate} = (100\text{mm})^2 \cdot 2.5\text{mm} \cdot \pi = 78539.8\text{mm}^3$$

$$\text{Cost of Plate} = €0.000032/\text{mm}^3 \cdot 78539.8\text{mm}^3 = €2.51327$$

Appendix 18 - Body Panel Sheets Cost

The plastic sheets will be 230mm x 300mm x 0.5mm, so the total volume of one sheet is:

$$\text{Volume of 1 Sheet} = 230\text{mm} \cdot 300\text{mm} \cdot 0.5\text{mm} = 34500\text{mm}^3$$

When purchased in bulk, these sheets cost \$40.99, or about €34.43 for a sheet the size of 2000mm x 1000mm x 0.5mm (Beeplastic). Thus we can calculate the price per volume.

$$\text{Price Per } mm^3 = \frac{€34.43}{0.5mm * 1000mm * 2000mm} = €0.000034mm^{-3}$$

The price of one sheet is calculated as:

$$€0.000034mm^{-3} * 34500mm^3 = €1.18784$$

Appendix 19 - Fixed and Variable Costs

Variable costs are defined as the sum of labor, commissions, packaging, utility expenses and raw materials (Nickolas).

Considering a single part takes about 0.5s to mold, and 10 parts are molded at a time, and a single mannequin has 142 parts, then it can be assumed that it will take about 7.1s to mold all the parts needed for one set. The parts will have to cool down afterwards as well, which is assumed to triple the time taken. Gathering all the necessary parts and organizing them into the packaging can be assumed to take about 5 minutes.

$$142/10 * 0.5s = 7.1s$$

The total time to produce one product is:

$$\text{Total time taken} = 7.1s + 300s = 307.1s$$

The average salary of a factory worker in the Netherlands is €16/hr (Salary Expert). So the labor cost for 1 product is equal to:

$$\text{Labor cost} = \frac{€16}{60min * 60s} * 307.1s = €1.365$$

The total injection molding cost of 1 part using hardened-steel molds is about \$3 per part (Jaycon). As the parts produced for the mannequin are very small, it is possible to assume that one part will cost €0.05 to mold. Multiplying by the 142 parts gives:

$$\text{Injection molding cost} = 142 * €0.05 = €7.1$$

Corrugated cardboard packaging, which should be most suitable for the product, costs between \$1.38 and \$1.93 per product when produced in a mid-large run of 10,000 to 25,000 units (Greasey). An average is taken and converted to euros for the packaging cost.

Transport costs are assumed to be around €10.30 (Appendix 14).

Printing costs come from an assumed cartridge cost of €42, where each cartridge has a yield of 300 pages (Boye).

Variable costs in the Production of 1 Unit	
Item or Task	Cost (€)
Materials necessary for one product	8.2658
Injection molding process	7.10
Printing ink costs (Boye)	0.1428
Labor costs	1.365

Packaging	1.39
Transport Cost	10.30
Total	28.5636

Fixed costs include equipment, property costs, rent and interest.

The molds used will be hardened steel molds, which cost between \$2500 and \$5000 per part (Jaycon) and are suitable for medium runs of 5000 to 10000 parts. As the parts are quite small and simple, the molds will be assumed to be on the lower end, at \$2500 or €2100. It is multiplied by the number of different parts, which is 15.

The rest of the costs are taken from the lower-end average costs for starting a manufacturing business (Upmetrics). For some areas such as machinery, machinery set-up and legal fees, median values are used as injection molding machinery could be expensive and difficult to set-up.

Total Fixed Costs	
Item	Cost (€)
Molds for parts (Jaycon)	31500
Factory purchase and set-up	315000
Lease Deposits (Upmetrics)	12600
Machinery (Upmetrics)	58800
Machinery Set-up (Upmetrics)	3400
Inventory and Storage (Upmetrics)	42000
Quality-Control Equipment (Upmetrics)	8400
Annual Insurance (Upmetrics)	2520
Legal Fees (Upmetrics)	2000
Total	476220