

# **Project report on Strandbeests**

Group 1

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## **Abstract**

This paper outlines the mathematical and mechanical analysis, as well as the prototyping and final assembly of the design of a Strandbeest.

Along with analysing animal-like walking motion, we also intend to investigate possible extended capabilities that can provide practical and/or aesthetical use. After looking into the core principles of a Strandbeest mechanism, we will additionally utilise our own calculated mathematical modelling to simulate alternative trajectories that can output a different result to an original Strandbeest motion.

After all of the analysis, we will move onto our prototyping and manufacturing process. We will look into the details of each prototype we created, what issues we found from each of them. Then we will take these findings and talk about how it helped us create our final assembly, and talk more about the assembly process. We will also discuss the finite element analysis of our components. We finally end with some reflections towards the whole project.



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# 1 Introduction

## 1.1 Project Aim

This project aims to design and develop a mechanical system that was inspired by the artist Theo Jensen's Strandbeest to explore alternate patterns within the original structure. By utilising complex linkage mechanisms, the original system mimics the natural walking motion.

Our new design aims to optimise energy efficiency and mechanical stability. The project will investigate the different cases in which the movement pattern of the Strandbeest can be altered, whilst providing further adaptivity and stability. This study hopes to contribute to the development of more versatile robotics that may be used for wider environmental applications.

## 1.2 Principle of Design

1) **Stability** : Ensuring that the structure remains balanced and stable while on the move is key in the designing process of Strandbeests. The weights of the sets of legs have to be distributed across the mechanism in a way that any tipping and collapsing is prevented. The interval at which each set of legs move have to also be precisely the same to avoid the Strandbeest from wobbling too much and risking toppling over.

2) **Energy efficiency** : Minimising energy consumption, whether it is powered by wind or by hand is important in engineering design. The power input should be able to sustain the continuous motion without any excessive strain on the system. All linkages should operate smoothly with minimal friction and lead to minimal energy loss in various conditions. Some further designs also include mechanisms to store the wind energy for when coastal winds are weak and keep the Strandbeests moving without utilising the sails.

3) **Mobility** : The linkage system should allow smooth fluid motion to imitate the natural walking patterns of an animal. It should also allow consistent forward progression with no out-of-pattern moves. The traced patterns of the tip of the leg also have a flatter area specifically because of the length component parameters, which further help to propel the sculpture forward.

### 1.3 Real life applications and significance

What might seem to be simple school projects could prove to have important uses in real life. The uses of these giant sculptures can range from preserving nature to studying the basic evolution of nature. Here are some examples on the wide range of applications for Strandbeests:



*Figure 1: Strandbeest on coastal beaches*

1) Winds from the seashore in coastal areas power the Strandbeests, which are converted into linear motion. Large models have larger sails, which can act as a wind energy store for when coastal winds die down. In the process of linear motion, they “move sand back up onto the nearby dunes to help preserve them from erosion by the rising sea.” [4]

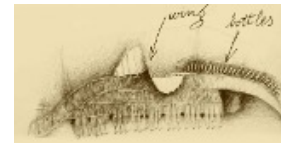
2) “By developing this evolution, I hope to become wiser in the understanding of existing nature by encountering myself the problems of the real Creator.” [6] Strandbeest design represents constant evolution which embodies natural selection, the ability to adapt to an environment. Nature inspired this mechanism, and Theo Jansen, to discover deeper through building these sculptures. (See Appendix B.1)

3) ‘The extinct beasts can be seen as artefacts or representatives of the period from the evolution of the beach animals.’ [7] This design displays evolution and progress over time, providing a tangible record of innovation and adaptation.

### 1.4 Comparisons to previous research and projects

#### Theo Jansen Mechanism

In the 1990s, Theo Jansen, a Dutch kinetic sculptor, started creating two-dimensional mechanism (Figure 2), which “when used in tandem with many others identical to it, can walk in a smooth forward motion” [9]. With the help of wind sails to utilise the wind, and empty plastic bottles pumped to high pressures to store energy, the Strandbeests are built to move itself with the power of nature.



*Figure 2: Original Strandbeest schematic [1]*

Throughout his research and development, Jansen discovered more than 1500 kinds of possibilities on the Strandbeest’s leg systems that can directly change the trajectory of each leg. This is exactly our aim for the project, to discover some of these possibilities and to then discuss further about the potential of the new combination of lengths. Jansen then calculated

the best 100 dynamic simulations by computer and chose the movement that best resembled biological walking. This set of numbers for each link's length is labelled as the Holy Number, which provides the best match with the trajectory of the tip of the leg to biological walking.

The Jansen linkage was thus born. It consists of a “variety of different lengths of 10 rod combinations” [3], as well as a crank fixed off a set pivot. As the crank turns, the position of the vertex linked to the origin changes, and drives the other vertices and links to move, creating 12 different types of distance configurations.

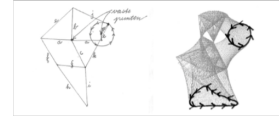


Figure 3: Jansen's linkage Strandbeest [3]

### SolidWorks

Below is a quadruped robot simulation with a Strandbeest walking mechanism developed in Turkey by SolidWorks in 2022. This model was designed to deal with concave obstacles and ramps, or any surfaces that are hard to reach for wheeled robots.

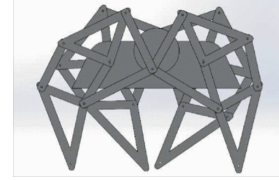


Figure 4: Quadruped mobile robot [5]

The Strandbeest is structured to have at least 2 sets of legs (4 legs), so the walking mechanism can be balanced (Figure 4). As the number of sets of legs increases, the central crank has to turn at a set interval which add up to 360 degrees, so the legs move one after another and can balance out. Each set of legs is also two four-bar mechanisms, each leg being one of the two.

SolidWorks used the Algodoo program to simulate the Strandbeest overcoming obstacles it is given. In the simulation, rubber is attached to the robot legs, and the floor is made of asphalt with a friction coefficient of 0.85, to simulate a real environment. Air resistance is ignored in the simulation. [5] After the team at SolidWorks ran tests, the result shows that Strandbeests can pass by both concave obstacles and ramps, which further proves the usefulness of these mechanisms.

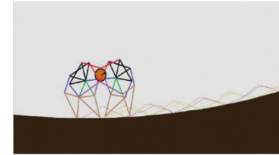


Figure 5: Strandbeest on concave obstacles [5]

### The Klann Mechanism

Though not a Strandbeest, the Klann mechanism is a similar mechanical system to one in its essence. Both systems aim to mimic walking movements using mechanical linkages.

In 1994, Joe Klann designed the Klann linkage to mimic the walking of crabs.

His goal was to find a replacement for modern day wheels. The linkage contains “a fixed frame, a crank and 2 rockers all connected using pivot joints” [8]. His hope was to discover the potential benefits of this linkage over standard vehicles.

The thing that the Klann mechanism can help us with when designing a Strandbeest system is the principle of converting rotary motion into linear, walking movements. Moreover, it is the complex structure of rods and linkages that simulate a reliable and stable cycle of motion. The Klann mechanism simplifies the walking motion by using fewer parts than the Strandbeest, providing potential to streamline our own mechanical system, reducing friction and mechanical failures.

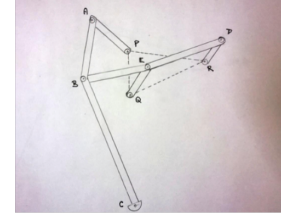


Figure 6: The Klann Mechanism [9]

### The TrotBot System

The TrotBot system is based on the mechanics of a horse running. The system combines the Klann and Jansen linkages due to the mechanism crank rotation. The movement of a TrotBot, however, is more variable than that of a Klann system. The footsteps are dynamic due to an 8-bar linkage. A feature added by researcher Wei Hexiang were toes, as they would increase the contact with the ground. Adding toes allowed TrotBot to be implemented in a quadruped version. (Appendix B.2 - B.3) [2]

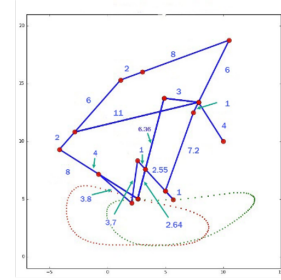


Figure 7: TrotBot Schematic [2]

An article also claims that nature has always chosen legs as the best mode of locomotion. Using linkages, researchers tried to mimic nature and come up with certain walking mechanism which will suite all types of terrains. They intended to design a replacement for tyres in load carrying trucks in mineral excavation belts which face a lot of wear and tear due to poor road construction. They replaced the front and rear axle along with the tyres with this unique mechanism where in each axle both front and rear had 4 sister pairs. (Figure 8) Thus, a basic Strandbeest had 8 pairs in total and overall, all 16 legs to support the system. [9]



Figure 8: CAD model of 2 sister pairs [9]

## 2 Mathematical Modelling

### 2.1 Vertex Position Calculation

Through this project, we attempt to discover new ways of modelling the movement of a Strandbeest. Although we do this by changing the lengths of each link, the vertices at which the links are connected are the ones that are changing constantly throughout the simulation.

The driving angle which varies from 0 to  $2\pi$  is labelled as theta, and the MATLAB simulation takes this changing value to determine the movement of the rest of the linkages. Except for the fixed vertices, all vertex positions take theta, or an extension of it through the distance of A from O, into account. There are a total of 7 vertices labelled A to G, in which vertex D is at a fixed location of  $(-m, -l)$ . This is the distance between the origin on the graph and D. In real life, this would translate to the vertical and horizontal distance between the central axis of the Strandbeest and the two points at which are fixed through another two sets of axes. Face BCD and EFG are fixed in size, meaning all the angles are set. As such, utilising sine and cosine rules to determine the locations of vertices with angles gamma and eta are thus possible, since these two angles are fixed at all times.

To complete the calculations, we drew out a basic schematic of the back leg (Figure 9). The reason for choosing the back leg is the two angles that have an extended dotted line from vertex D and F. The angles are calculated with the help of the two lines parallel to the x axis to simplify finding the positions of the vertices connected to them. These two lines also mean the  $\text{atan2}()$  function is used in MATLAB. This function calculates arctan and returns a value that is only between  $-\pi$  and  $\pi$ . To calculate the angle alpha,

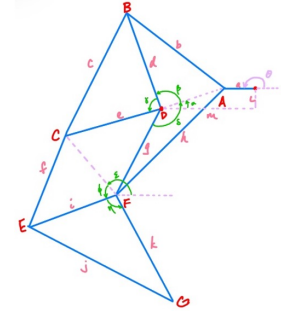


Figure 9: Schematic of one leg

$$\alpha = \text{atan2}(a \sin(\theta) + l, a \cos(\theta) + m)$$

Where the first calculation in the function is the opposite side to alpha, and the second calculation is the adjacent side to alpha. Similarly, we can also calculate angle epsilon,

$$\epsilon = \text{atan2}((e \sin(\alpha + \beta + \gamma) - g \sin(\alpha - \delta)), (e \cos(\alpha + \beta + \gamma) - g \cos(\alpha - \delta)))$$

On the other hand, the other angles can be calculated with the cosine rule even though some lengths change over time, such as CF, since there is no fixed link joining the two vertices. As such, we can take calculating angle phi as an example,

$$\phi = a \cos \left( \frac{i^2 + CF^2 - f^2}{2 \cdot i \cdot CF} \right)$$

Vertices A and D are at fixed locations, so other vertex positions can be calculated in reference to these two vertices and with the angles calculated. We can use basic trigonometry along with a combination of different angles to calculate the position of each vertex. For example, to calculate the position of vertex F, we would need to take the position of D and further combine it with the vector of  $\vec{DF}$ :

$$F = [-m + g \cos(\alpha - \delta), -l + g \sin(\alpha - \delta)]$$

Since this project is mainly to investigate the effect on the final motion of a Strandbeest through changing the lengths of different links, having a visualisation of the trajectory of the tip of the leg, vertex G, is crucial to doing comparisons. With this in mind, we have stored the positions of G for every increment and traced it out as a single (dotted) line. After some initial testing, we also found that visualising the actual movement of the leg in relation to the floor was very hard, so we also added an extra function to the code to save the minimum value of the y-position of G, and using `yline()` draw a straight line at that level. This makes it easier for us to compare the motion of the leg by having the trajectory line up with the floor.

## 2.2 Length of joints

With these calculations on a working simulation, we can proceed to changing the length variables and recording the new trajectories for vertex G in relation to the floor. In Theo Jansen's original model, there was a list of numbers that he discovered that produced the original motion of the Strandbeest (Figure 10). This set of numbers, known as the holy numbers, produce a trajectory with a long flat section at the bottom. This section is what propels the Strandbeest forward, as the leg "moves forward" in relation to the same point on the floor. The leg then lifts off the ground at the end of the flat section, returns to the original position, and lowers the tip back to the floor. Our testing would be to alter these numbers, produce new sets of variables, to produce different trajectories and thus provide a different function to the Strandbeest. Initial testing with the code also shows that there is a limit to the range at which the numbers can be changed. When the links collide or intersect with each other during the

```
a = 15.0; h = 61.9;
b = 50.0; i = 36.7;
c = 55.8; j = 65.7;
d = 41.5; k = 49.0;
e = 40.1; l = 7.8;
f = 39.4; m = 38.0;
g = 39.3;
```

*Figure 10: The Holy Numbers*

simulation, the calculations fail, and the simulation will not be able to finish properly.

With all of these in mind, we randomised a lot of simulations with different numbers for specific lengths. Here are some worth mentioning, and what functions it could potentially provide to the system.

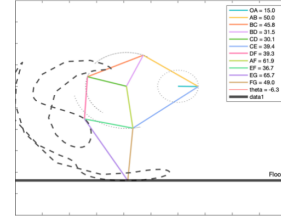
## 2.3 MATLAB Simulations

Before we discuss our simulation results, we should lay down the basics of our simulation program. The simulation models the left leg of the Strandbeest, and the right leg moves in the opposite rotation, out of phase by  $\pi$ . The simulation also traces the trajectory clockwise, which would be the opposite of what the forward leg's motion. Because of this, the trajectory should be analysed anticlockwise, and this should be done as some trajectories can provide two vastly different motions.

With the preparations done in section 2.1 and 2.2, we then utilised MATLAB to observe the changes in the shape of a trajectory when changing the values on the lengths of components of a leg. The below outlines a couple notable results that prove to be useful in certain situations.

To achieve figure 11, the following values had to be changed compared to the holy numbers:

- 1) C was decreased from 55.8 to 45.8
- 2) D decreased from 41.5 to 31.5
- 3) E decreased from 40.1 to 30.1
- 4) L decreased from 7.8 to 0.0



*Figure 11: Notable Simulation results 1*

The trajectory represents a large contact with the floor as well as big range of movement of the leg to the back and up. The trajectory appears very different from the original holy ratio one, it follows a kick movement back, after which the leg comes back to the floor but further down the road. The main part of the leg shows an 8 shaped movement.

The reason why we considered this shape is because it appears very different from the original path and we were hoping it would provide an insightful view on how a Strandbeest can move. However, after further consideration, this movement appears to be impractical, as well as rather hard to see happening in real life. The whole figure would be very unstable and wouldn't show any practically usable or even aesthetically appealing movements.

To achieve figure 12, the following values have been changed compared to the holy numbers:



- 1) J was decreased from 65.7 to 40.7
- 2) K was increased from 49.0 to 70.0

The resulting trajectory is rather interesting, as it aligns with one of the specific motions we were looking to find. As the leg pushes the Strandbeest forward while touching the ground, it lifts up to a significantly high level. It then reaches out front and goes back down towards the ground. We can imagine this to be the Strandbeest walking up a set of stairs. As it reaches out at a high position, it will be able to set its foot onto the next step of the staircase, meaning it touches the ground at the earlier stages of the leg's descent. This means it gets into contact with the floor early and can push the rest of the Strandbeest up as it propels off its leg on the next step.

However, this motion also poses some limitations to our actual design. If we take these numbers and flip the leg left to right, the opposite side would be reaching backwards if we followed this method, which would go against climbing up a set of stairs. Instead, when taking this set of numbers into designing, we need to create two sets of the same leg facing the same direction. This would also mean the degrees of freedom would change, as now there needs to be two axels to move the two sets of legs. This could be changed by having a central axis and universal joints turning the two axes at the same time, but would pose a challenge to creating the framework holding the leg up.

In this model the values changed were the following:

- 1) F changed from 39.4 to 35.0
- 2) L changed from 7.8 to 0.0

This trajectory figure represents the movement that can bring a Strandbeest very far along the road with just one step. This design can be used for stepping over holes in the ground or even walking from a pole to a pole or just from one piece of land to another. The application of this enhancement can be useful when stepping over thin rivers, canals or thin rocks if used in nature with a diverse mix of terrains. This model would not need any significant changes to the original design, which means that the degrees of freedom will not change, and neither will the movement be unstable or unpredictable.

Finally, we have picked out another simulation in figure 14 as another notable result. In this model, we have changed the following:

- 1) A changed from 15.0 to 10.0
- 2) L changed from 7.8 to 0.0

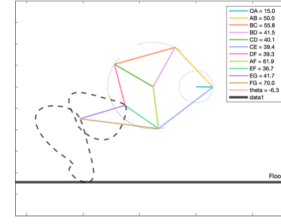


Figure 12: Notable Simulation results 2

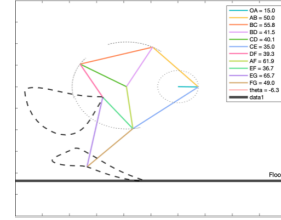


Figure 13: Notable Simulation results 3

This trajectory is very small compared to other simulation results, and we believe this can prove to be useful when traversing uneven or rocky roads. The small steps allow for the Strandbeest to adjust its tilt compared to the floor at a very small pace. This means there will not be large rocking motion between each step, creating a lower chance of the Strandbeest toppling over during its motion. This is very useful for when the machine is tasked to walk across rough terrain, while also maintaining its balance and causing minimal rocking to the body. This could be further extended to have the Strandbeest carrying load while crossing these terrains, and a balanced body would be very useful in ensuring the cargo is not damaged.

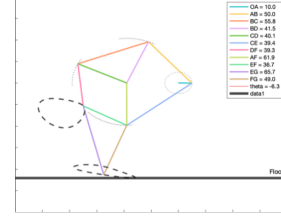


Figure 14: Notable Simulation results 4

### 3 Mechanical analysis

#### 3.1 Links

A Strandbeest combines fixed surfaces with links to create the motion of walking. The design contains 11 links of different lengths to form its motion, of which 6 are locked into place to form two triangles, while the other 5 move freely around its pivot.

Referring to Figure 9 previously, links BC, CD and BD form a set triangle of a specific area; and links EF, EG and FG form the other set triangle, also creating the tip of the leg. Link OA revolves around the central fixed pivot and is connected to link AB and AF. These two mechanisms alone can also be considered as crank-rocker mechanisms (Figure 15). AB acts as the coupler and creates a push-and-pull linkage between link OA and the fixed triangle BCD. AF also acts as the coupler and creates a push-and-pull linkage between link OA and the fixed triangle EFG. As the lengths of AB and AF are different, BCD and EFG move in different directions with different speeds at the same time. Following the set of Holy Numbers set by Jansen, the two triangles almost move at a perfectly opposite direction, where when BCD is pulled towards O while pivoted at D, EFG is pushed away from O.

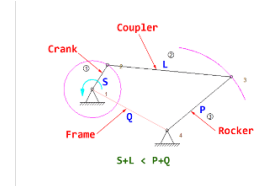


Figure 15: Crank-rocker mechanism

Links CE and DF connect triangles BCD and EFG to form a parallel-motion linkage. (Figure 16) Although link CD and EF do not move exactly parallel due to CE and DF possibly having different lengths, they produce similar motion to that of the parallel-motion linkage. As D is a fixed pivot, when vertex B is pushed or pulled by the crank-rocker mechanism, EFG is shifted around with an almost parallel motion to CD.

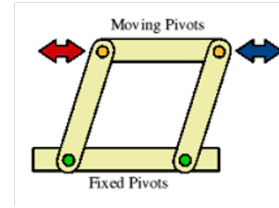


Figure 16: Parallel-motion linkage

### 3.2 Joints

For this system we will be utilising Revolute Joints (Figure 17) where two bodies are rotating around a common axis. The mechanism does not require any sliding or translating motion, however, it does require the joints to provide smooth but stable joint system. The friction will have to be kept minimal to reduce wear and energy wastage. These joints are easy to assemble and disassembled and are also considered to be secure in terms of staying in one place.

The joints will have to connect:

- Legs of a Strandbeest since those are made up of several parts
- Linkages that connect the legs together
- The parts where the legs connect to the main body

In our setup, there are 9 joints and 2 pivots per leg. We are aiming for 4 sets so there would be 36 joints and 4 pivots overall. All joints will also have to withhold vibrations from the movement as well as be lightweight enough to maximise mobility.

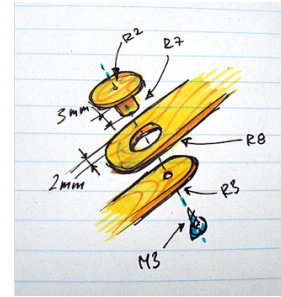


Figure 17: Revolute joints

### 3.3 Degrees of Freedom

The degree of freedom of an object are the set of independent displacements, or in our case, rotations, that specify the newly displaced position or orientation of that object. Under this definition, if we look at each joint specifically, they each have one degree of freedom, as they can rotate around one axis, and the link will move on the vertical plane. Each movement will directly impact the position of the body connected to it. This means there are 9 degrees of freedom on one leg of a Strandbeest.

However, when we look at the whole leg of the Strandbeest, there is only 1 degree of freedom, which is at vertex O. As the angle of the crank OA change, all the variable links and joints move to create one single motion, which generates the trajectory of the tip of the leg, and further from that the forwards walking motion of the leg.

## 4 Manufacturing

### 4.1 Initial Prototype

For our first prototype we made a cardboard model using the holy numbers, creating the original Strandbeest leg pair (Figure 18). We needed this prototype to test the dimensions, the design of the legs and also location of the joints. Since the cardboard was very thin, we used bent staples as joints. The prototype came out successful. The leg pair worked as it should, there was no overlapping between the links, the joints kept the model together well and the movement looked the same as the Matlab simulated version. However, when manufacturing this first prototype, we did come across some difficulties. The main one was the connection with the joints - there were no metal wires available to us in the laboratory. Hence, we had to use staples as joint alternatives. The staples were brittle and would easily break when trying to bend them. Nevertheless, the ones that managed to withstand bending turned out to be great alternatives, they held the cardboard well, as well as allowing enough movement for the legs.

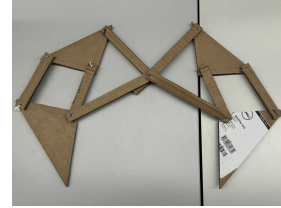


Figure 18: Prototype 1: Cardboard model

### 4.2 Iterations

After testing the basic Strandbeest model, we were confident in implementing our own calculated link lengths that would create a unique motion. For our next prototype we chose to laser cut the parts, using acrylic (Figure 19). We created CAD models with changed link lengths and decided to use dowels as joints. We have then assembled all the parts, gluing them together (4 triangles, 11 links and 16 dowel covers) (Figure 20). We came across some difficulties - we accidentally used the link lengths numbers from another simulation, so we then had to laser cut a few additional parts. Also, we glued some parts that should not have been glued together

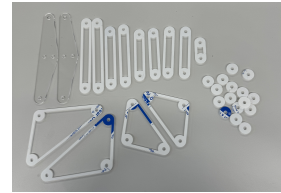


Figure 19: Prototype 2: Assembly process

by accident, which restricted the movement of one of the links. We solved the problem by filing half of one of the dowel covers off.

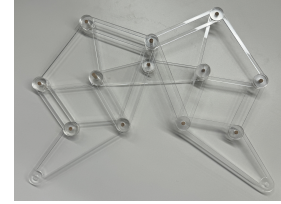
After creating the second prototype, we have come to realise that it was completely impossible to have normal walking movement with this model. At times during the rotation, the legs would both rise so high that the body of the Strandbeest would fall straight to the ground. As we wanted to achieve the motion of climbing stairs, the model has to have a period of time where it is walking level to the floor on a staircase. With this realisation, we have altered our design to have one pair of legs to only have one half with the lengths for the stair climbing module. The other legs use a set of numbers that allow walking on flat ground.

We also used many dowel covers with the idea of gluing them onto each end of the dowel, creating a shaft as a joint for the links to rotate about. Another issue we came across with these is that the dowels obstruct the motion of some links as they might overlap with each other. The large amount of covers used can also be a waste of material, as we print more than we need as a backup. However,

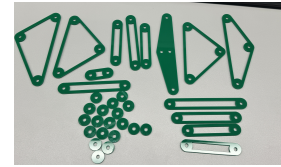
we also discovered that we could use only one dowel cover per dowel and instead glue the other end of the dowel directly onto the outermost joint. There is a risk that we accidentally glue other parts onto it, so we have to keep the other parts moving by hand while we wait for the glue to set. With this method, we ensure not only that we save material, but also that we avoid dowel covers extruding above the links and causing overlapping links to stick on the dowel covers.

With these new considerations in mind, we made one final prototype of the centre pair of legs, which has two sets of different numbers for two legs of different motion. In Figure 21, the left set of components is the one for walking on flat ground and the right set of components is the one for climbing the stairs. This prototype helps us test whether the legs can align with the floor properly and whether the newest design is feasible.

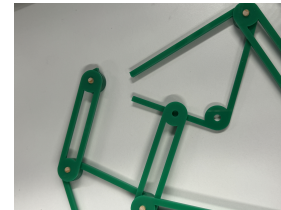
When assembling the third prototype we came across an issue concerning thickness of the links. The acrylic we used was 3mm in width and the widths of the triangle sides were just 5mm, which made the parts very fragile and susceptible



*Figure 20: Prototype 2: Acrylic model*



*Figure 21: Prototype 3: Assembly process*



*Figure 22: Prototype 3: The snap*

to breakage (Figure 22). So, when parts were glued together at the end, multiple parts snapped off after pressure was applied. Even though it was possible to glue them back together, it still showed how unstable the model is. Another issue is that the glue we used took longer to dry than the one used in the previous model. This meant that even if we thought that it had dried and left it alone, the glue did not fully dry, causing unwanted parts to stick together without us noticing. This additional gluing provided an extra risk that we might glue the wrong parts together by accident.

In the end, we still managed to arrange this model for the centre pair of the legs (Figure 23). Even though this model did not work perfectly and was not assembled properly, it still helped us gain insight into some the details we should change for our final product, especially concerning the widths that showed to be extremely brittle. We also made the dowels longer than expected, so some parts were not moving flush with each other. This means in our final design, we have to make the dowels have a smaller tolerance by being shorter, so the pieces can move freely but also flush with each other.

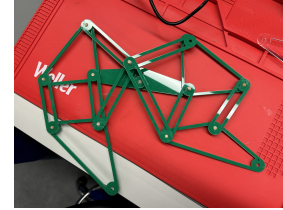


Figure 23: Prototype 3

### 4.3 Finite element analysis

With our final design concluded, we ran tests on Fusion for finite element analysis. Originally, we attempted to create an assembly for all the components combined so we can put force from the top down to test whether the legs can withstand it, but it seemed like a Strandbeest leg contains too many moving parts and so is too complicated for Fusion to calculate at the same time.

Hence, we picked out a few components to run the tests on. We chose to run the tests on the central crank as it takes the largest rotational moment, joint h as it is the longest and most likely to snap, and the two triangles as one is rotated back and forth very often, and the other is in contact with the ground, so will take the most load.

We have taken three profiles for each component. The first profile is the stress across the component when a force is acted on it. We assumed the force is 10N and the point at which the force is applied on is where we think the load is the highest on the component. The reason why we take it as 10N is that the weight of the whole design would approximately be 1kg, as one third of a meter squared of acrylic is about 3kg. Figure 24 is a test result for the stress on the two joint points of the EFG triangle on the leg for climbing stairs. This has the highest

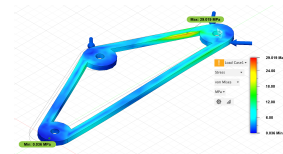


Figure 24: Triangle EFG of stair climbing leg

stress out of all the tested components, at a maximum of 29.019MPa at the edges closest to the joint connected with the most links. This means that there is a large force experienced in that small area, which makes sense because such joints have the highest load with multiple links that put pressure on the same point.

The second profile we have taken is the strain across the component when the same force is applied at the same point. The biggest impact is on triangle EFG of the leg for walking on flat ground. Figure 25 shows that the triangle bends a lot when the forces are applied. This is expected as well since not only is this triangle connected to three links which apply force on the joint, but also the leg is in consistent contact with the floor. The triangle is thus squeezed from the top and bottom of the component, and so it deforms quite a lot. The maximum strain recorded on the most bending edge near the joint with the most load is 0.009. The strain is relatively low across all strain profiles taken. This might be due to the material we are using being acrylic, and our framework involves an empty centre. Thus, bending is possible but the acrylic material makes it less easy to break by allowing a small bend.

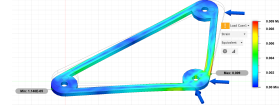


Figure 25: Triangle EFG of flat ground leg

Finally, the third profile we took is the displacement of the components from their original design. We expected the more thin and longer components to have a higher displacement away from the original, as the other end of the component will experience a higher moment due to a longer distance away from the pivot. This proves to be true with the different joints. Joint h of the stair climbing leg, being the longest joint in the whole design, has the highest displacement from origin of 7.432mm (Figure 26). Another thing we noticed is that the concerns of the crank taking a lot of load causing deformation is not necessary. This is because the crank itself is very short, and the moment on the end of the crank is thus very low.

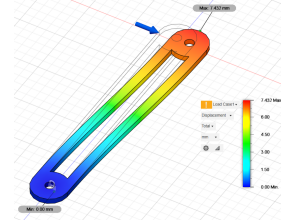


Figure 26: Joint h of stair climbing leg

## 4.4 Final Assembly

After multiple prototypes, we felt confident building the final model, considering all the mistakes we made beforehand, and implementing all the changes needed to make the final version perfect. We made a choice to utilise 3mm acrylic once again and use wooden dowels and joints. We laser cut all the parts needed, 18 dowel covers, 4 triangles and 9 linkages per each leg set (Figure 27). With three leg pairs that came down to 4 bases, 54 dowel covers, 12 triangles and 27 linkages for the entirety of the final Strandbeest model. We used 3 sets of legs, the two on the outside were in pink acrylic and the one inside was bright



green. We believe that this difference of colours turned out to be an advantage since you could more clearly see and appreciate the beautiful movement of the Strandbeest, and easily differentiate the two different motions of the legs. While we were in the process of putting all the parts together, we had to use some of the parts from the prototypes of our Stranbeest (for example, dowel covers) since we simply did not laser cut enough for the final model.



Figure 27: Final model laser cut

When assembling all the part together for the final model we came across an issue of gluing all the parts together: the glue took too long to dry and ended up not being sticky enough. After constructing the whole model we realised that one of the dowel covers detached from the dowel, which meant that one of the leg pairs was no longer attached to the rest of the model. Unfortunately, this dowel is quite deep in the centre of the Strandbeest, making it impossible for us to reach in there and fix it. We suspected it might be the repetitive glueing onto the dowel creating a layer of glue on top of the dowel, making further glueing ineffective. In addition, there was a piece of a dowel sticking out from one of the dowel covers, resulting in slightly restricted movement. This problem was solved by cutting the tip of the dowel out using a flush saw. These two issues both emerged after we have already assembled the whole model, which made it particularly difficult for us to solve, since taking the construction apart was not an option we can consider. We used super glue, so the only way to take pieces apart would be cutting them. However, this would have added even more manufacturing time as well as a high risk of the linkages breaking.

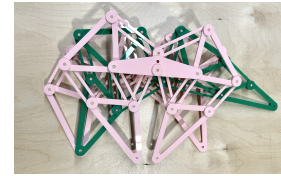


Figure 28: Final Strandbeest model

The pink leg sets in figure 28 represent the model that walks on flat ground, whilst the green one has components of staircase walking. The difference in colour has definitely made it easier for us to assemble the Strandbeest. Moreover, the fact that the final model acrylic is not transparent helped with construction. For all three pairs we had to cut 27 dowels that acted as joints.



Figure 29: Dowel - dowel cover spacing issue

It was inevitable for us to come across some issues during the assembly process that have considerably slowed us down. Initially, the laser cutter appeared to perform slightly differently on the two days we used it. The diameters of the holes in the links and triangles varied, even though we used the same 3D model. That meant that we had to



file some dowels, while other dowels were too small for the holes (figure 29). Another problem was linked to the gluing process. The glue brushes were too big to neatly fit them into the holes to glue dowels to them. This meant that the glue is spread across the dowels covers. Some types of glue provided also took too long to dry, which was not ideal because we needed to adjust the linkages while gluing to ensure they didn't stick to the wrong surfaces and hinder necessary movement.

While constructing the final model, we also needed to make sure that the dowels we glued to the dowel cover were 90 degrees straight up. We used a ruler to ensure a perfect right angle to ensure fluid movement but also avoid any unnecessary wobbling.

Additionally, we did have to use quite a lot of material for all our prototypes and the final model. However, we did make sure to space the parts smartly, so that as much material would be saved. We had to rotate the triangles around as well as place dowels inside of the space in triangles. However, this meant that when we completed this final assembly, all the material and effort gone into the previous prototypes are not wasted as we found out about most of these issues with the prototypes, and made sure to avoid bumping into the same issues again in the final assembly.

## 5 Conclusions and reflections

While manufacturing the prototypes and final product, we ran into various issues. We designed our initial model to be too perfect, forgetting to leave enough tolerance for the dowels. The original design was also planned to be a 3D print, which printed some of the joints as a connected part to some components. This raised various issues. The lack of tolerance would have meant we would not be able to fit the parts together. The estimated print time for one pair of legs was also very long compared to laser cutting the same amount, and 3D printing would have wasted a lot of material. We believe our decision to switch our design to adapt to laser cutting instead was a great solution. Not only did it mean we can make multiple prototypes and discover issues easier, it also meant we could afford doubling the size of the model, so the motion would be much clearer to observe.

The other issue we had was with the dowel covers. The covers were a simple way of making the joints, where either side of the dowels would have a "stopper" and all the components inside could freely spin. However, not only was the amount of dowel covers resulting in waste of material, but the covers would also obstruct movements of the longest joint (Joint H) in particular, causing the leg to get stuck or hit the cover and not be able to move forward. To resolve this, we made a swift decision of removing half the dowel covers and glueing one end of the dowel to a component instead; since it will not only act as a stopper, but all

components can still freely rotate around the joint. This extended to another issue with glueing, as sometimes the glue would seep through the layers and glue onto other supposedly free rotating parts. We solved this by making the dowels longer so we could glue the components together while having sufficient space in between.

Despite all the challenges encountered, we were on track of finishing the originally planned sections in the report and the practical work ahead of time, which meant we had sufficient time to deal with unexpected issues. Overall, we have managed to clear through all the required steps we planned to completing the project, and even managed to make room for extra prototypes, which ended up helping us get an even clearer idea of underlying issues we did not discover.

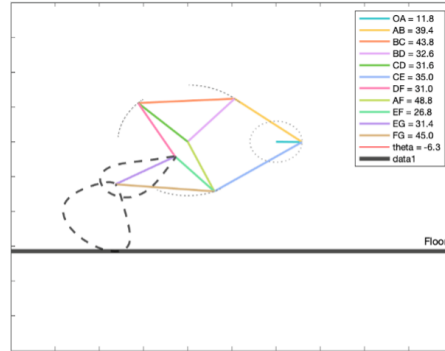
In terms of our goal for this project, we did discover new sets of numbers which could make the original Strandbeest serve a new function. Our new Strandbeest utilises a set of numbers which model small steps on flat ground, and a set of numbers which could be used to reach up and climb a step of stairs. We picked the model that gives smaller steps as we wanted to prevent the Strandbeest from falling over when climbing the stairs. We only chose to do half of the pair as the stair-climbing leg, as the leg moving in reverse does not serve any purpose. Overall, the goal of the project is met with a successful final product.

## Appendix A: MATLAB Simulations

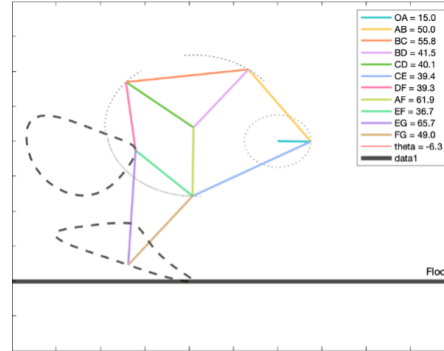
Throughout this investigation, we ran numerous simulations with our mathematical modelling program. Below are some of the unique ones that we did not mention in the previous mathematical modelling section before we arrive at our final observations.

| Length   | Holy Number | New data values |      |      |      |      |      |      |      |      |      |      |      |
|----------|-------------|-----------------|------|------|------|------|------|------|------|------|------|------|------|
| a        | 15.0        | 11.8            | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 |
| b        | 50.0        | 39.4            | 50.0 | 50.0 | 50.0 | 61.9 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| c        | 55.8        | 43.8            | 55.8 | 55.8 | 55.8 | 55.8 | 55.8 | 55.8 | 55.8 | 55.8 | 55.8 | 45.8 | 55.8 |
| d        | 41.5        | 32.6            | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 | 41.5 |
| e        | 40.1        | 31.6            | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 |
| f        | 39.4        | 35.0            | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 45.0 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 |
| g        | 39.3        | 31.0            | 39.3 | 39.3 | 39.3 | 39.3 | 39.3 | 45.0 | 39.3 | 39.3 | 39.3 | 39.3 | 39.3 |
| h        | 61.9        | 48.8            | 61.9 | 61.9 | 61.9 | 50.0 | 61.9 | 61.9 | 61.9 | 61.9 | 61.9 | 61.9 | 51.9 |
| i        | 36.7        | 26.8            | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 | 36.7 |
| j        | 65.7        | 31.4            | 65.7 | 65.7 | 65.7 | 65.7 | 65.7 | 65.7 | 75.7 | 65.7 | 65.7 | 65.7 | 65.7 |
| k        | 49.0        | 45.0            | 49.0 | 49.0 | 70.0 | 49.0 | 40.0 | 49.0 | 49.0 | 49.0 | 59.0 | 49.0 | 49.0 |
| l        | 7.8         | 0.0             | -7.8 | 0.0  | 7.8  | 0.0  | 7.8  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| m        | 38.0        | 40.0            | 38.0 | 38.0 | 38.0 | 38.0 | 38.0 | 43.0 | 38.0 | 38.0 | 38.0 | 38.0 | 38.0 |
| Figure 9 |             | A.2             | A.3  | A.4  | A.5  | A.6  | A.7  | A.8  | A.9  | A.10 | A.11 | A.12 | A.13 |

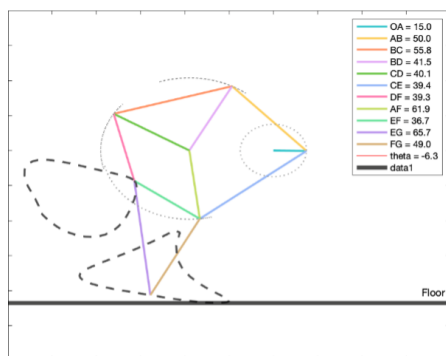
Appendix A.1: Table of numbers which generated the unique results below



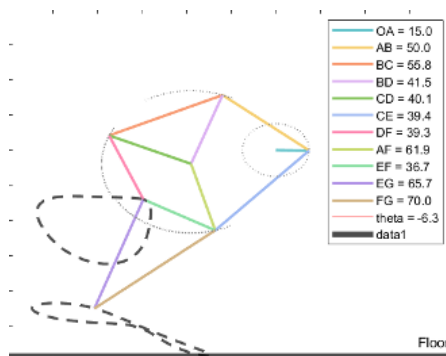
Appendix A.2



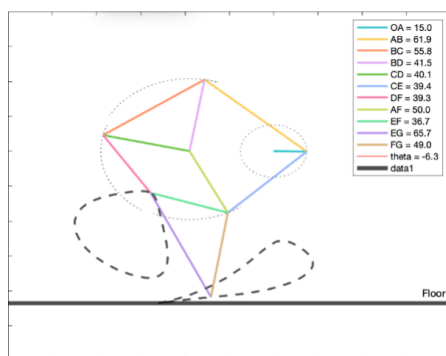
Appendix A.3



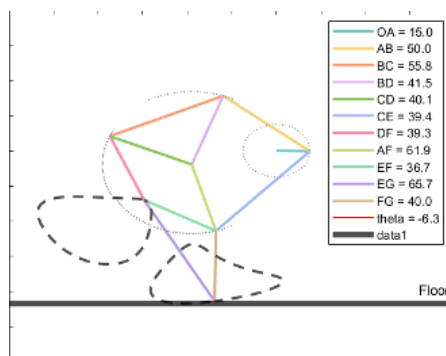
Appendix A.4



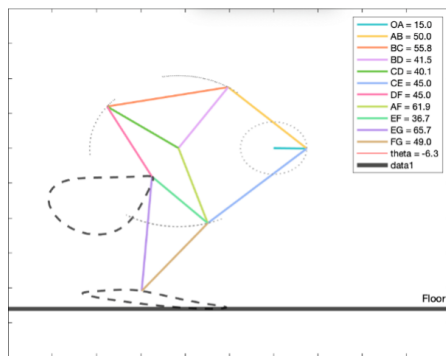
Appendix A.5



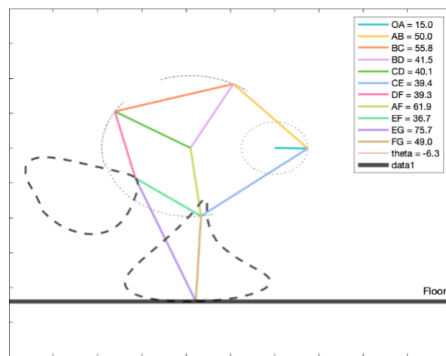
Appendix A.6



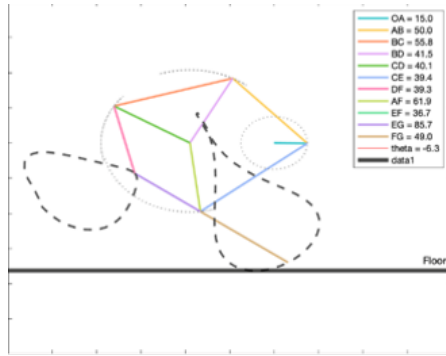
Appendix A.7



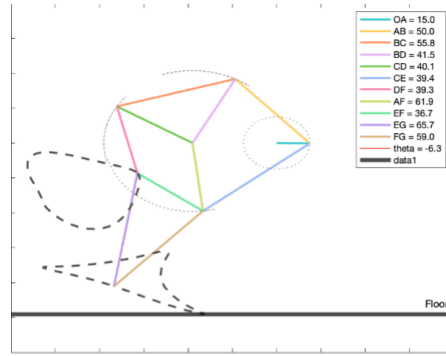
Appendix A.8



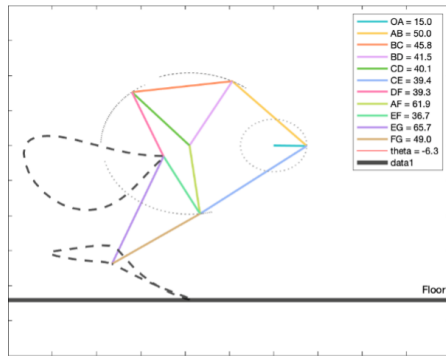
Appendix A.9



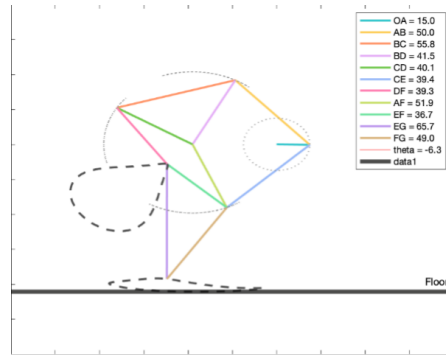
Appendix A.10



Appendix A.11



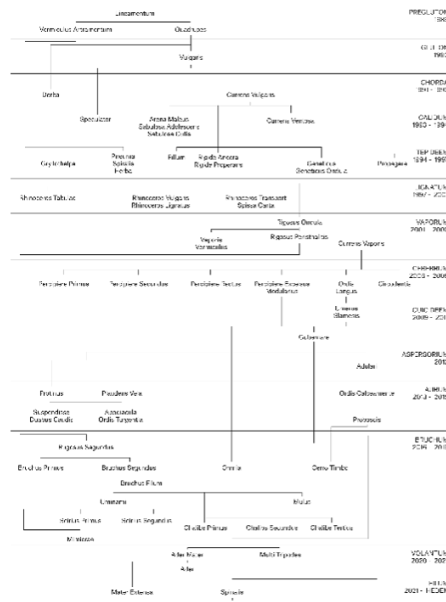
Appendix A.12



Appendix A.13

## Appendix B: Inspiration and initial references

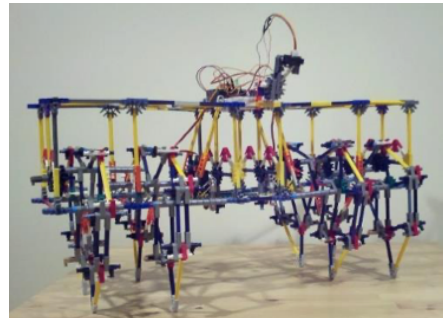
Here is the appendix for Part 1: Introduction section. Photos here have been referenced from the section mentioned.



Appendix B.1: The evolution family tree studied by Theo Jansen



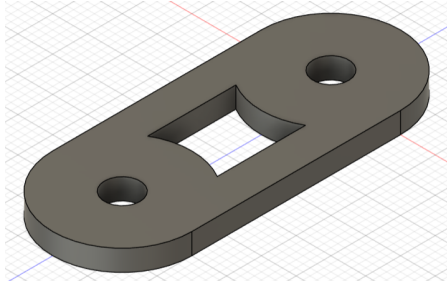
Appendix B.2: TrotBot with heel and toe linkages



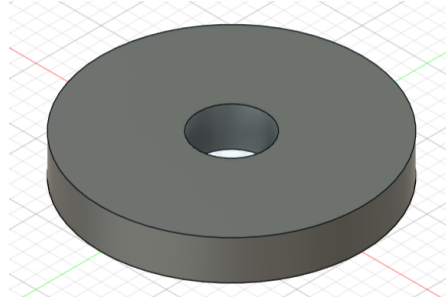
Appendix B.3: TrotBot with multiple sets of legs laid out horizontally

## Appendix C: Computer aided design

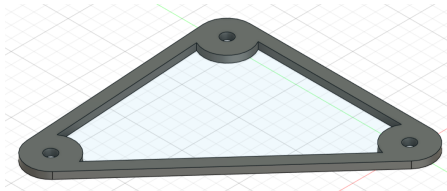
Throughout the design process, we have drawn up various CAD files as tests. The following files are the designs we used for the final laser cutting process for the final design.



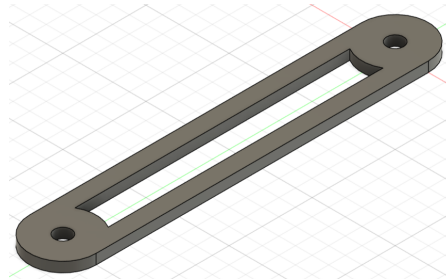
Appendix C.1: Crank



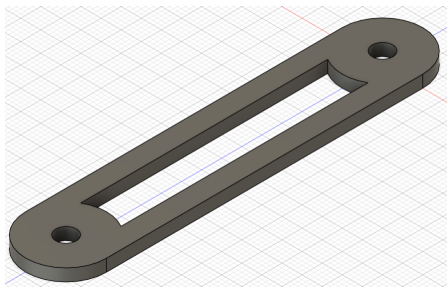
Appendix C.2: Dowel Cover



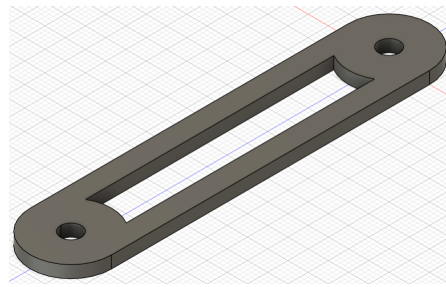
Appendix C.3: Triangle BCD (same across both models used)



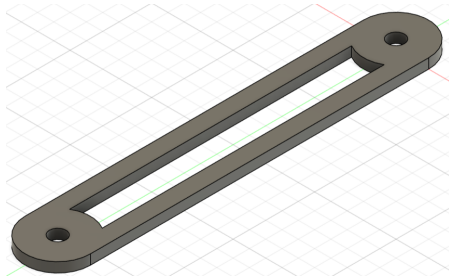
Appendix C.4: Joint b (same across both models used)



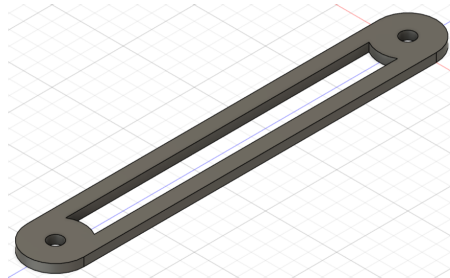
Appendix C.5: Joint f (same across both models used)



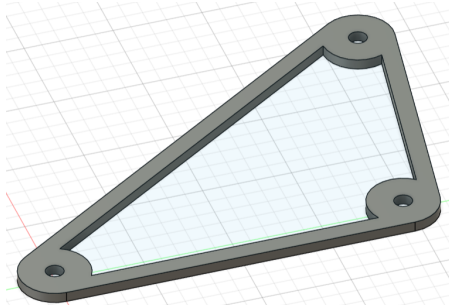
Appendix C.6: Joint g (same across both models used)



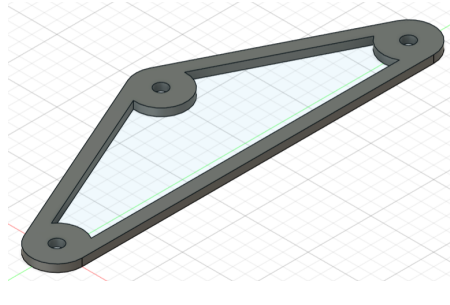
Appendix C.7: Joint h for flat ground leg



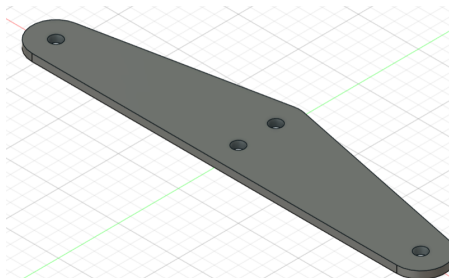
Appendix C.8: Joint h for stair climbing leg



Appendix C.9: Triangle EFG for flat ground leg



Appendix C.10: Triangle EFG for stair climbing leg

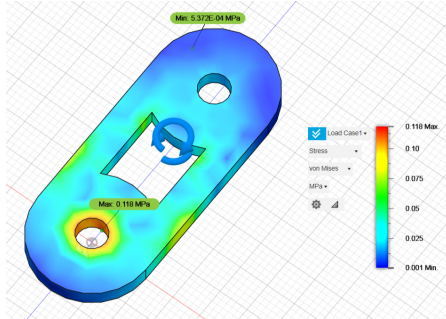


Appendix C.11: Base frame for fixed pivots

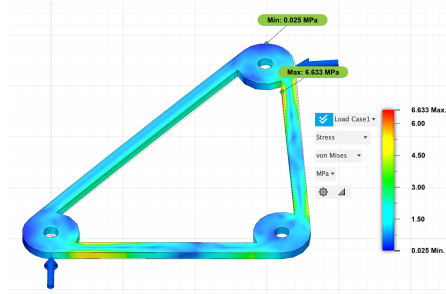


## Appendix D: Extra finite element analysis

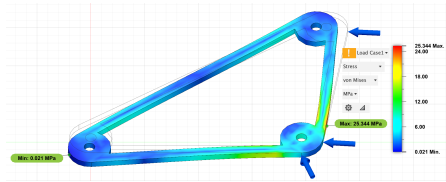
We have taken all stress, strain and displacement profiles for all components we have chosen. Below are the rest of the profiles that we did not mention in the sections above.



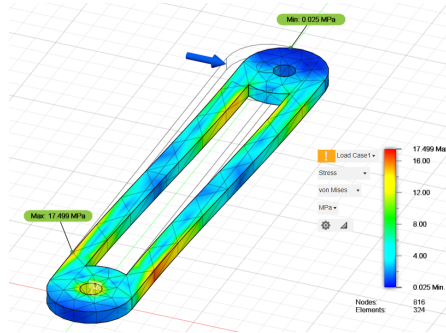
Appendix D.1: Stress on crank



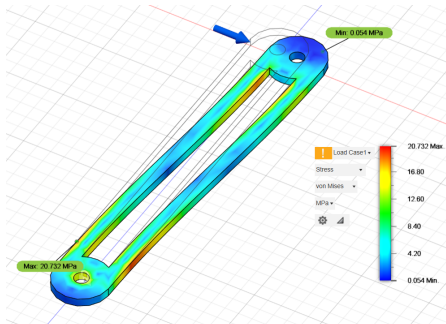
Appendix D.2: Stress on triangle BCD



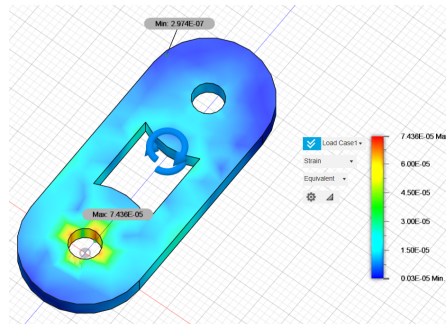
Appendix D.3: Stress on triangle EFG for flat ground leg



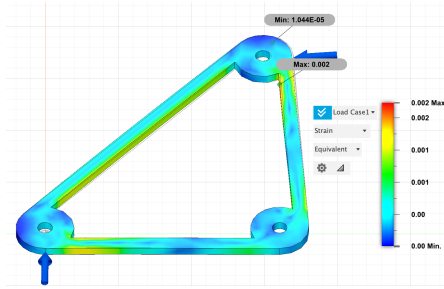
Appendix D.4: Stress on joint h for flat ground leg



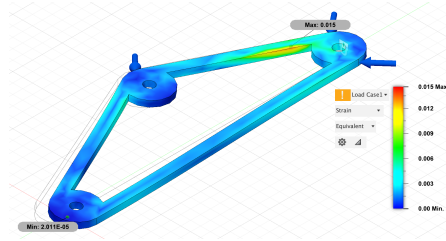
Appendix D.5: Stress on joint h for stair climbing leg



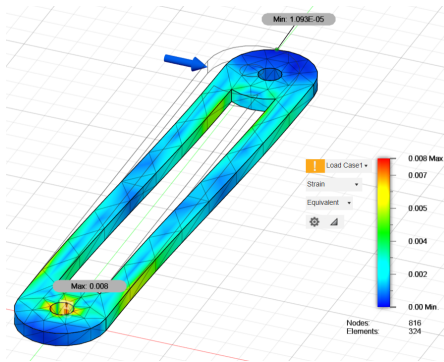
Appendix D.6: Strain on crank



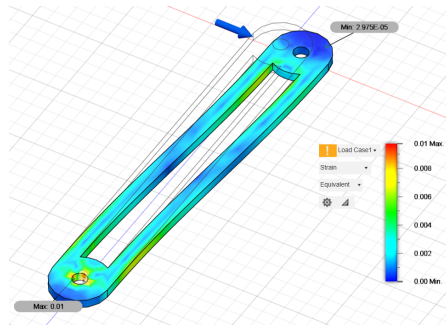
Appendix D.7: Strain on triangle BCD



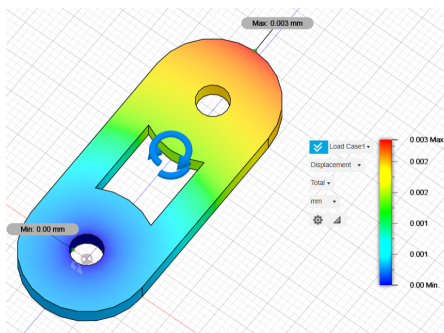
Appendix D.8: Strain of triangle EFG for stair climbing leg



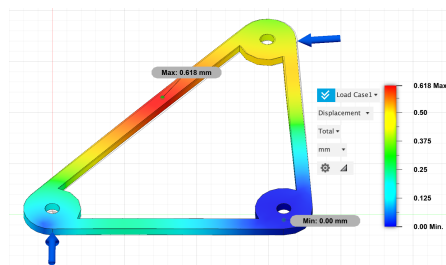
Appendix D.9: Strain on joint h for flat ground leg



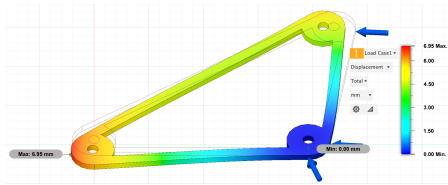
Appendix D.10: Strain on joint h for stair climbing leg



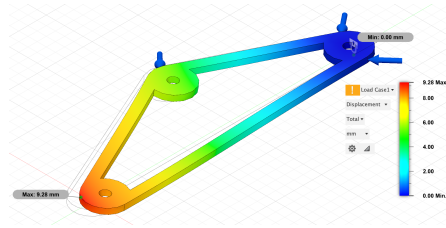
Appendix D.11: Displacement of crank



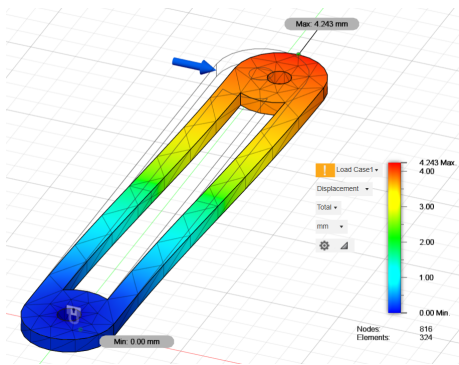
Appendix D.12: Displacement for triangle BCD



Appendix D.13: Displacement of triangle EFG for flat ground leg



Appendix D.14: Displacement for triangle EFG for stair climbing leg



Appendix D.15: Displacement of joint h for flat ground leg

## Appendix E: Assembly Process

The following are some snapshots from video footage we have taken of our assembly process



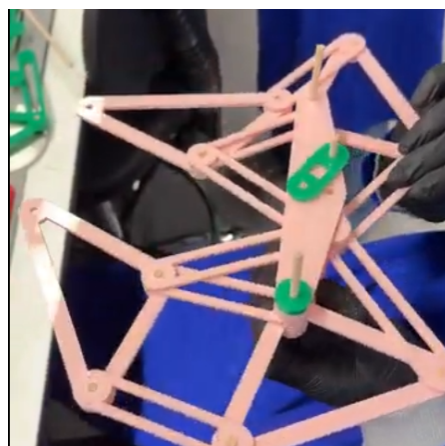
Appendix E.1: Laser cutting the two sets of flat ground legs



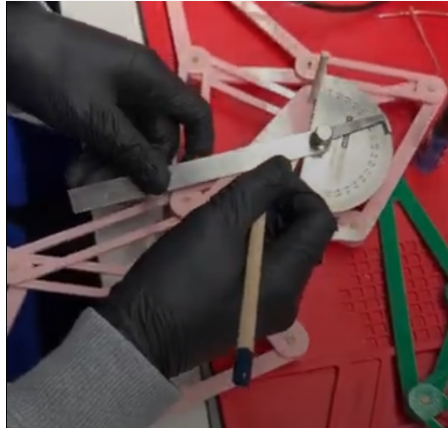
Appendix E.2: Glueing the first two sets of legs



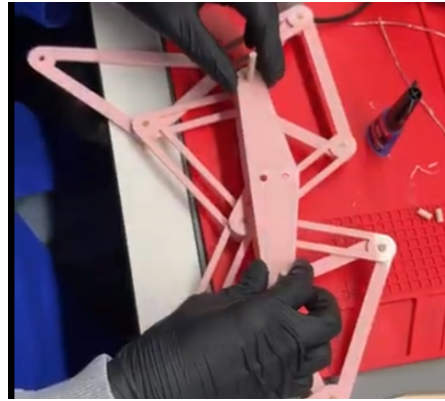
Appendix E.3: Glueing the longest dowels at point D on our original diagram onto the base which holds the legs together



Appendix E.4: Testing whether the system can spin properly with one set of legs



Appendix E.5: Measuring the angle difference (120 degrees) so the next crank for the next set of legs are out of phase by the correct degree



Appendix E.6: Slotting the base over the first set of legs so the next set can be layered on top of it

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*Figure 30:*  
*silly cat*