DESIGN ENGINEERING

Module: PDE3400

DESIGNING A MORE SUPPORTIVE WHEELCHAIR

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This work is submitted in part fulfilment of the requirements for the degree of BEng Design Engineering, May 2021.

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1. INTRODUCTION

Spinal injuries have afflicted humanity for millennia with the first documentation appearing in a Egyptian document published approximately 2500 BC, named the *Edwin Smith Surgical Papyrus* after its initial discoverer, Edwin Smith, an early Egyptologist. Within this document, the original author (who is unfortunately not known), describes damage to a person's spine and the resulting 'unconsciousness' of their arms and legs. The author proclaims the described condition as 'an ailment not to be treated' (Hughes, 1988). Fortunately, throughout history, attitudes towards spinal cord injuries were becoming less pessimistic. By the 20th century, doctors such as Sir Ludwig Guttman and Donald Munro had adopted a more optimistic approach (Bodner, 2009) and recognised the need for a comprehensive care of the entire person; rehabilitation with a commitment to the entirety of the patient's needs. (Donovan, 2007). The wheelchair is key item in the rehabilitation of spine injuries.

According to the National Health Service, there are 1.2 million wheelchair users in the UK alone (NHS, n.d). This is approximately 1.8% of the population, a striking proportion. It is approximated that there are 1200 new cases of spinal cord injury, one that may necessitate wheelchair use, every year (McDaid et al., 2019). 35% of these injuries cause tetraplegia, a severe form of paralysis that affects most or the entire body.

Tetraplegia is caused by damage to the spinal cord and or brain, a result of diseases, conditions such as multiple sclerosis and muscular dystrophy and physical trauma such as sporting accidents, the latter cause is the most common (NSCISC, 2020). People with tetraplegia will often rely on the use of wheelchairs, or powerchairs when referring to motorised types rather than self-powered, to aid their mobility and support them throughout the day. Unfortunately, reports show that wheelchairs are lacking in their function, extended use bringing about a number of sitting-related problems (Valent et al., 2019).

2. AIMS

The aim of this project is to examine how the seat of a chair for a wheelchair can be improved to better support a person with tetraplegia by incorporating ideas from non-wheelchair related fields.

The design will be realised using CAD (Computer Aided Design) software, namely Solidworks to produce Force Element Analysis (FEA) studies to visualise and control how certain sections of the design will react when is use. FEA will also be used to examine how any unnecessary material can be removed with the intent of creating a lighter and cheaper final design. Prototyping using programmable boards will help visualise and inform the design process.

3. TETRAPLEGIA

Tetraplegia commonly referred to as quadriplegia, is a paralysis of both the upper and lower body as opposed to paraplegia which effects the lower half only. It results in the loss of movement and sensitivity of all four limbs including the torso. The severity and location of the paralysis is dependent on where on the spinal cord is damaged. There are a number of causes for this damage which are as follows: traumatic injury, neurological conditions such as cerebral palsy, tumours on spine and brain and autoimmune conditions such as multiple sclerosis.

These conditions create lesions, areas of damage or change, on the spine or brain. The location of this damage on the spine correlates to the severity of consequent symptoms, namely paralysis, tetraplegia in the most severe cases. In continuing this project, it is necessary to identify a specific case that the designed solution will address.

The ASIA (American Spinal Injury Association) Impairment Scale (2016) is used internationally to define sensory impairment and extent of any suspected spinal injury. The examination involves grading muscle power and sensation in each designated section of the body as specified in the ASIA Impairment Scale document. Each of these sections are classified according to the segment of the spine they are linked to. Once these results are recorded the level of paralysis completeness can then be determined using a scale from A to E, with A being complete paralysis (no sensory or motor functions preserved at all) and E being no issues with motor and sensory functioning.

This project will focus on C5 category tetraplegia. This means there is a lesion on the C5 vertebrae located in the neck, this entails certain motor and sensory abilities that will be considered throughout the project that are stated as follows: paralysis of the trunk and lower limbs with partial paralysis of the upper limbs. Good functioning of the bicep and deltoid muscles are retained but poor functioning of triceps, shoulder muscles, wrists and hands. Manual wheelchair use may be possible for short distances, but a power wheelchair is most common (Spinal Cord Medicine, 2002).

There are 420 new cases of tetraplegia in the UK every year who require constant care at an average cost of £1.87 million per person’s lifetime (McDaid et al., 2019). Improvements in wheelchair and mobility technology will provide a better quality of life and improvements in independence.

3.1. Pressure Ulcers

Immobility can cause incidental secondary health problems. One significant and pervasive health problem is pressure ulcers. Pressure ulcers, often named pressure sores, are defined by the NHS

(National Health Service) as injuries to skin and underlying tissue caused by prolonged pressure on skin (2020). Although any part of the body can be affected, certain areas are more prone than others such as the lower back and buttocks.

Pressure ulcers can be a debilitating and painful condition if left unattended. They start initially as painful sores that can gradually become necrotic if not dealt with sufficiently which can eventually cause severe health problems such as blood poisoning. One high profile victim of pressure ulcers onset by tetraplegia was Christopher Reeve, best known for his role as Superman, although after a sporting accident and subsequent paralysis, became an advocate for spinal cord injury research and set up the Christopher and Dana Reeve Foundation (n.d).

3.2. Wheelchair design history

The wheelchair designs most commonly seen today is based on a design from the 1930s known as ‘Model 8’ (Nias, 2019), a design that has not changed much in its ninety years of existence resulting a design that looks particularly dated in comparison with prosthesis. Prosthesis have seen huge advances over the decades in the same time span. This is especially evident when viewing the history of prosthesis, an artificial hand produced in the 1930s is a world away from the designs of today (Lawrence, 2019). Contemporary prosthesis features a wide variety of technologies, customisation and materials that are far more advanced than those used in currently available wheelchair designs.

4. STATE OF THE ART

Current solutions vary widely in function and price. At the highest end, designs now include standing functions, to the lowest end; carers periodically moving the patient's position. This chapter will examine the range of solutions available to users for pressure ulcer risk reduction.

The highest level of wheelchairs features an expanded range of position adjustability over the average. The position options can range from fully prone to standing upright. This works by the chair straightening out and upwards into a flatter angle which lifts the occupant into a standing position. There are two immediately obvious benefits to this function. Firstly, the ability to reach higher places and pressure relief. Standing avoids putting pressure on the body for extended periods. One current product that includes this technology is the Quickie Q700-UP (Millercare, n.d.) but at prices upwards of £10 000, it may often prove inaccessible for the average user.

Image 1: Quickie Q700-UP fully extended in its standing position.

More commonly, chairs at lower price points feature a more limited range of position options and most exclude standing options. When the user wants to adjust the pressure on their body, the chair can be tilted backwards and forwards dependent on its current positioning. The leg rest and back rest can also be raised or lowered to lift the legs up or lay back into a prone position. These functions are achieved using mechanically or electronically actuated hydraulics. The user has a number of buttons available at the end of one arm rest in order to electronically actuate the chair. This system is found in chairs such as the Ottobock B500 (n.d). Some position adjustable wheelchairs without mechanical actuation are the Ottobock A200 (n.d) and ID Soft (Sheen Mobility, n.d). Although a mechanically actuated system retains the same positioning capabilities, a motorised approach allows the user a greater degree of freedom by relieving the need to rely entirely on a caregiver to change the users position. Products with mechanically actuated tilting are more affordable.

The Kirton Duo (Premier, n.d) features the highest level of adjustability and posture support out of all products reviewed here. Likewise, with some of the precedingly reviewed products, it features an enhanced level of position adjustability whilst introducing some other key features. These features include a backrest divided into individually adjustable sections that pivot and rotate to properly support the sitter's posture. Rotating brackets at the end of these backrest sections can be bent forwards to effectively alter the width of the chair providing a base for *"prop"* sitting (Minkel, 2000); additional support for the compensatory positions that persons with neuromuscular impairments or spinal cord injuries often show, such as kyphosis, pelvic obliquity and scoliosis.

Although the Kirton Duo features the highest level of support, it comes at the cost of increased unwieldiness. The inclusion of extra adjustability and extensive gel padding through the entirety of the sitting surface means that the total width of the chair can be as much as 830mm, 250mm wider than the ID Soft (Sheen Mobility, n.d). Therefore, the Kirton Duo and others chairs of with similar extensive postural care technologies are largely relegated to indoor, mainly stationary use, but reviewing their designs is still of interest for this project.

Image 2: Kirton Duo (Premier, n.d).

The next stage of the state-of-the-art review looks exclusively at pressure relief cushions designed for the avoidance of pressure ulcers. There are two main technologies commonly found in pressure relief cushions; static or dynamic. Static solutions rely primarily on soft gels, foams and air. They are often available at lower price points than dynamic types. Pressure from the user is spread evenly across the surface to enhance comfort and relieve pressure. They often come in a range of sizes and depths such as the Harley Pressure-Tex cushion (Harley, n.d) and the Jay Balance Wheelchair Cushion (Jay, n.d) which is available in thicknesses of up to 600mm. These dimensions should be selected depending on the level of relief required and the size of the surface they will be placed on. Persons at a higher risk of developing or already have pressure ulcers would require thicker cushion. Although with improved health benefits there is a compromise that deeper cushions do not provide as much stability when sitting (Aissaoui et al., 2001). Thinner cushions will provide a more stable sitting surface and would normally be recommended for those who are not at such a high risk of pressure ulcers.

The other cushion-based solution is described within this review as *dynamic* meaning that they are capable of moving and changing their structure under their own power. The inner cavity of the cushion is divided into hollow sections filled with air. These sections are then alternately varied in pressure in a cyclical pattern to create a sitting surface tension that is constantly varying, therefore no single area on the sitter's body undergoes pressure for a prolonged period. Dynamic air-filled cushions would normally be recommended to those most at risk of developing pressure ulcers.

5. DESIGN INSPIRATION

A secondary aim of this project is to examine the aesthetic qualities of tetraplegia focused wheelchairs in comparison to more aesthetically considered mobility aids like prostheses. The impetus behind this being the belief that an objects aesthetic quality compliments a designs usability and subsequently enhances said objects usability. This is especially relevant for vital aids such as a wheelchair. This aspect of the project will be informed by current prosthesis as well as furniture designed not with paralysis care as primary intent. This chapter will inform the reader on the influences that informed this project.

Prosthesis, despite being highly specified and therefore not as ubiquitous as wheelchairs, appear on initial examination, to be designed with more consideration of their aesthetic qualities than is currently afforded to wheelchairs. One such example is Naked Prostheses (n.d), whose products are highly specialised yet utilise a beautiful design that can even be customised according to the user's discretion, there is a range of colours and patterns to choose from. During the review stage in the preceding section, no existing powered wheelchair featured a similar concern for the product's aesthetic qualities nor ability to extensively customise said aesthetic quality.

Image 3: An example of a Naked Prostheses (n.d) device. The colours around the wrist and fingertips can be chosen by the customer.

There is some improvement in this area with self-propelled wheelchairs. Küschall (n.d.) is a company that creates visually exciting designs with sports style influence. The customer has a limited range of colours to choose and some optional graphics. Where Küschall's designs are especially interesting is in their materials choice and finishing. Carbon fibre composites and aluminium features prominently, giving their products both aesthetic and performance advantages. Entire wheelchairs can be as light as 6.8kg improving their functionality and the finishing gives the chair a prestigious feel. It is these types of materials that help to enhance the aesthetic qualities of prosthesis and are just as effective in the instances they are used in wheelchairs. If this material choice can be expanded to include powered wheelchairs, their usability will be greatly enhanced.

Image 4: The KSL produced by Küschall (n.d). Produced from high-performance materials.

The design of mobility aids should be informed by design as a whole. There are design studios producing ergonomically functional designs whilst maintaining aesthetic qualities. One of the most prominent studios that influenced the visual as well as the physical aspects of this project is de Sede (n.d). de Sede creates sculptural furniture that incorporates the human form into design decisions to produce intriguing yet functional designs; some products even being reminiscent of the human spine. Designs such as the DS-2100 and DS-414 were of special interest to this project. The seating surfaces of the products are split into sections that can flex or rotate independent of each other thus conforming to the body to provide enhanced postural support, the result being that more of the chairs surface is in contact with the sitter's body. This is an idea that could be replicated to improve seating for persons with tetraplegia. Another product of interest is the DS-

142. All three of its postural support appendages are flexible and can be contorted into any desired position whilst still remaining solid enough to adequately support a person's weight. As a person with paralysis is unable to support their own body, a chair that can form around and support them in the way that the preceding three products, could. A mechanism such as this is of interest for this project. It could be replicated using torque or friction hinges that arrest the movement of the object in a chosen position, a mechanism type that is commonly featured in airline headrests such as those produced by Reinhold (n.d). Airline headrests are capable of holding their position for hours at a time under persistent pressure over their operational lifetime with minimal maintenance.

Image 5: From top to bottom: DS-2100, DS-414, DS-142 produce by de Sede (n.d). Note the segmented quality of all three designs.

6. ANTHROPOMETRICS

Before formulating designs, it is necessary to settle on fixed dimensions that will be referenced throughout the design. The first measurement methods this project will reference is *Ergonomics and Design: A Reference Guide* (Openshaw & Taylor, 2006) from furniture manufacturers, Allsteel. It details useful anthropometric data for both sitting and standing positions as well as data that is focused on wheelchair users. This document references several anthropometric databases. It would be beneficial if access to these databases were currently possible but they are unfortunately inaccessible with a significant cost. The one that is currently fully accessible is the ANSUR II (U.S. Army anthropometric survey II) (Gordon et al., 2014) database. A comprehensive collection of measurements from 4082 male participants and 1986 female participants. Using the diagrams from *Ergonomics and Design: A Reference Guide* as reference to understand the measurements from the ANSUR II database, this project will list appropriate anthropometric measurements.

Table 1: Averages from ANSUR II dataset.

ANSUR II results			
Measurement (Mean)	No.	Female (mm)	Male (mm)
Abdominal Extension Depth	12	230	255
Bideltoid Breadth	10	450	510
Cervicale Height		624	679
Chest Height (distance between sitting surface and chest point)		400	453
Elbow Rest Height (distance from sitting surface to olecranon)	17	232	245
Eye Height	15	748	805
Forearm Length (elbow – centre of grip)	18	318	349
Forearm - Forearm Breadth		495	579
Head Breadth		148	154

Hip Breadth (whilst sitting)	13	399	379
Knee Height (whilst sitting)		511	554
Leg Length	22	1044	1130
Popliteal height (back of knee to sole of feet)	23	388	430
Seat Depth (Buttock-Popliteal length)	20	485	503
Sitting height	14	857	918
Suprasternale – Waist length	16	350	382
Thigh Clearance	11	168	180
Waist Back length		425	478
Waist Breadth		299	326
Weight (kg)		67.8	85.5

Using this dataset rises one issue being that it is populated by individuals employed by the US Army. This data may not be representative of the wider, general population. This concern is alleviated when reading that Openshaw and Taylor (2006) review both ANSUR (and earlier, smaller iteration of ANSUR II) and CAESAR when approaching ergonomic design and share that many ergonomic textbooks reference these two datasets.

The measurements above are applicable when designing a chair although all of them may not be entirely necessary during design phases. A number of measurements have been portrayed on a anthropometric illustration below. This data is vital for proceeding onto preceding steps; deciding chair dimensions.

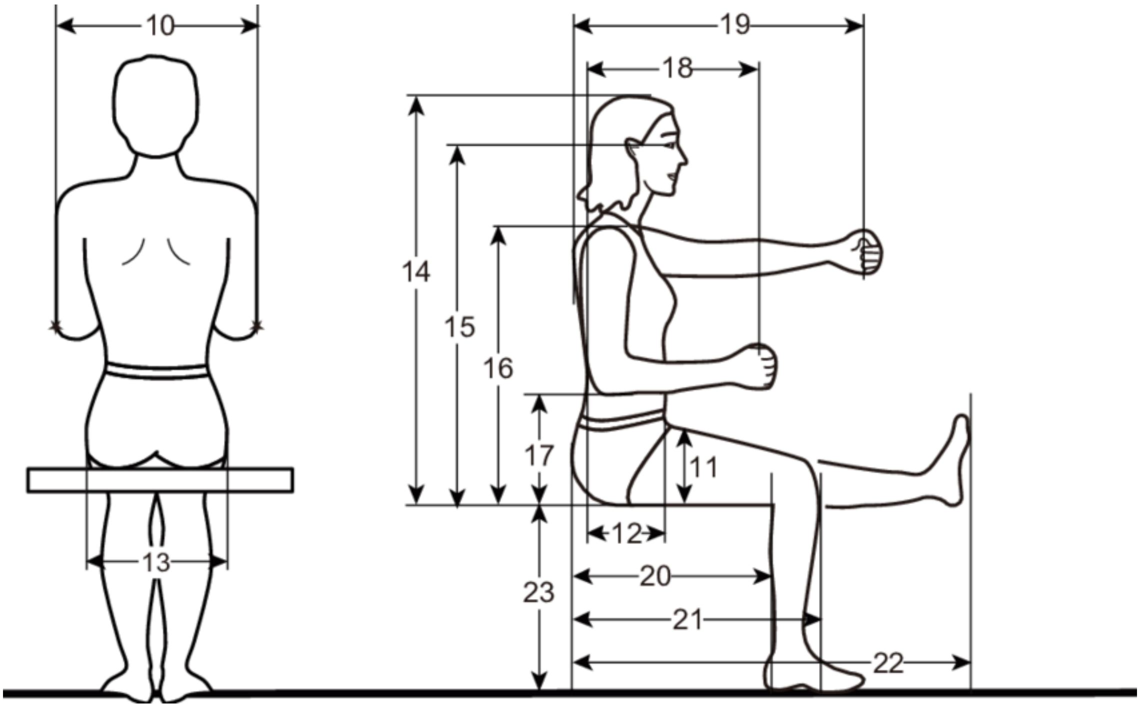

Image 6 courtesy of Karuppiah et al., 2011.

6.1. Profile of Individual

To simplify the design process, this project will focus on one particular person's profile, i.e. deciding on their dimension and condition. Tetraplegia can affect any individual but according to the National (US) Spinal Cord Injury Statistical Center (NSCISC, 2020), 78% of new spinal cord injuries cases are male. Men are therefore at a higher risk of tetraplegia. Furthermore, available datasets have much larger male sample sizes. For these reasons the chosen individual profile will be male. All required measurements will be taken from the averages in the male column from table 1.

The level of paralysis that will be focused on is C5 tetraplegia. This specific category was chosen as patients' mobility is severely reduced yet they do not often require a chair that is highly adapted. Patients with more complete paralysis often require apparatus in conjunction with mobility aids, a respirator is one such device. If focusing on higher paralysis levels it is then necessary to examine how a chair can incorporate these devices, something that is beyond the scope of this project.

7. IMPLEMENTATION

To fully visualise some of the chosen concepts that will be developed, it is necessary to implement them into a working design. This will be undertaken in a number of ways: CAD (Computer Aided Design) models, FEA (Force Element Analysis) with optimisation and actuation circuitry. Firstly, the process of producing a CAD model will be explained before subsequently documenting the process of using FEA technologies to optimise parts for both weight, strength and cost. Finally, an overview of the components and circuitry required to actuate a chair with a human sitter.

7.1. Product Design Specification

Before the project continues, it is necessary to formulate a Product Design Specification (PDS) to inform the design process and grade its success. Table 2 shows the ten requirements that constitute the PDS. The second column shows either *D* or *W*, Demand or Want, a demand is a fundamental design whereas a want is secondary to the main goals but would be advisable to achieve.

Table 2: Product Design Specification

No.	D/W	Requirements	Description
Performance			
1	D	Sufficiently support posture of someone with tetraplegia	Apply ergonomic principles. Recognise needs of tetraplegic body.
2	W	Extended degree of flexibility	User requirements often vary.
3	D	Adaptive and responsive according to stimuli.	Adapt to prolonged use to reduce health risks.
Environment			
4	D	Weather resistant	Chair may be used outside.
Life expectancy			

5	D	High durability	Device will be used extensively. Must withstand this.
Maintenance			
6	W	Washable	Should be easy to clean without removing parts.
7	W	Simple maintenance	Any routine maintenance (adjustments) shouldbe easy to undertake.
Size and weight			
8	D	Design must not exceed 10kg.	
9	D	Maximum width of 650mm	Chair may be used in narrow spaces.
Aesthetic			
10	W	Improve visually upon exiting wheelchair designs.	

7.2. Computer Aided Design and Modelling

Computer based modelling will be accomplished using Solidworks, a Computer Aided Design (CAD) software for accurately sketching and forming complex shapes with the added benefit that it contains options for simulating forces applied to the component (known as FEA, Force Element Analysis), which will be used in the proceeding section, and animations that can aid in visualising how the solution will operate.

The first stage of the CAD modelling process will conceptualise the general design of the chair. At this stage, the dimensions necessary to properly seat the individual profile specified by the anthropometric data in section six are incorporated into the design as well as the designs explored in section five.

Image 7: Preliminary render of chair in its initial conception stage.

Image 6 displays a preliminary rendering of the chair at this stage. The metallic textured sections will be aluminium (6061-T6) and the black sections are intended to represent the general layout of the chairs cushioning. Although the positioning of the cushioning is portrayed within this project, the composition of the cushions themselves will not be covered by this project so will be considered for display purposes only.

Now that the general design of the chair is now specified, the next stage is to start optimising each part. This is a process of removing or adding material to minimise weight and cost whilst retaining the parts strength. The central column is the largest component of the design that bears the entirety of the load, therefore it is the most important component to be properly optimised.

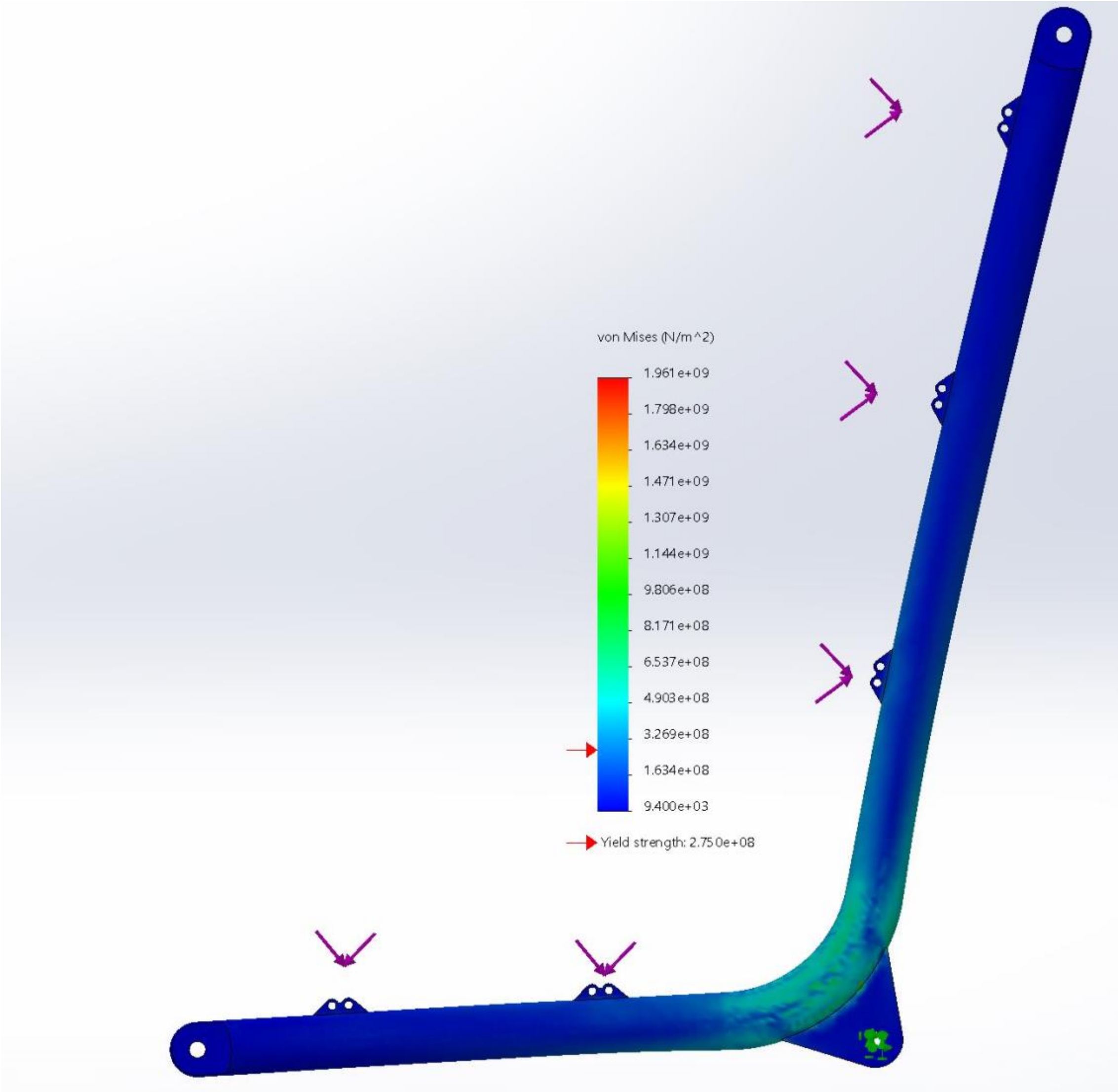

Image 8: Initial Force Element Analysis with 1mm thick outer walls.

Image 7 shows the results of the initial FEA study. The green ring on the bracket in the bottom right is where the component is fixed, meaning this area cannot move. The two sets of purple arrows along the bottom extension denote a force of 834N (85kg) and 400N for each set of arrows along the right-side extensions. These force values are intended to replicate the expected forces the chair would experience when in use. These values do not account for the weight of the user being evenly distributed across the chairs sitting surface area primarily due to the nature of the design as well as the potential for unexpectedly high forces such as using the chair when going down a curb or use by another, heavier user. Therefore, the chair will be optimised to withstand forces in excess of what would normally be expected.

For the first stage of optimisation, the length of the tube section was shelled to create a wall thickness of 1mm as a general starting point for and to examine how a particularly light configuration would cope. The coloured chart in the centre of image 7 shows the rang of stress the component experiences. The red arrow points to the yield strength of the chosen material, 6061-T6 aluminium, the point at which the material experiences permanent plastic deformation. The coloured areas of the studied component correspond to the chart.

As shown by this study, a small area of the component (depicted as red) experiences high stress, 1.96e + 09 N/m^2, 85.8% greater than the materials yield strength. At this small stress point the component would be likely to experience plastic deformation which would be unfeasible. Despite this high stress the majority of the component experiences particularly low stress; between 9.40e + 03 and 1.63e + 08 N/m^2, 0.0016% and 59.3% of the material yield strength 2.75e + 08 N/m^2. This indicates that there is plenty of material that can be removed further away from the fixed geometry, but more will need to be added around it. At 166.7 grams the component is currently very light.

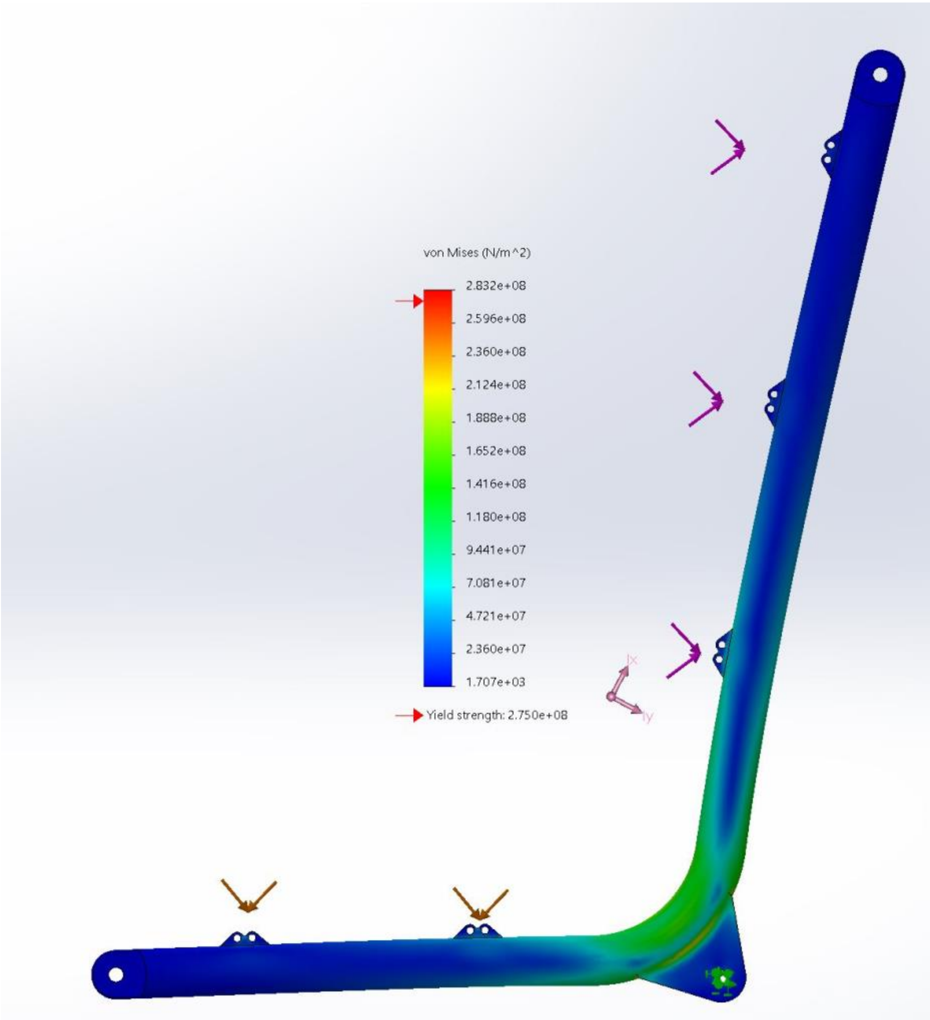

Image 9: second stage FEA with 5.5mm wall thickness.

The next stage implemented Solidworks' Design Studies feature in which variable ranges can be specified with sensors acting as constraints. Solidworks cycles through the predetermined range in steps comparing the results to the chosen sensor before recommending an optimal scenario. In this stage the inner diameter was chosen as the variable to be tested and the yield strength of 6061-T6 aluminium as the sensor. From this, Solidworks recommended a wall thickness of 5.5mm; image 8 shows the FEA results of this outcome. The chart shows that material stress is now within tolerable levels although the greatest stress now peaks in a single location, this is known as a stress singularity which is shown in image 9 below.

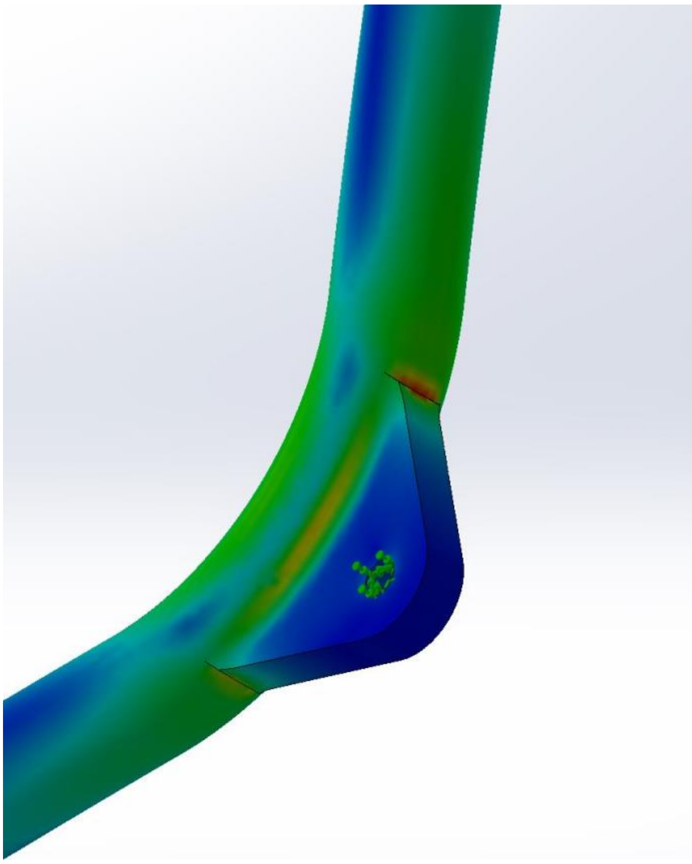

Image 10: a stress singularity occurring just above where the bracket joins the tube, a small area highlighted by red.

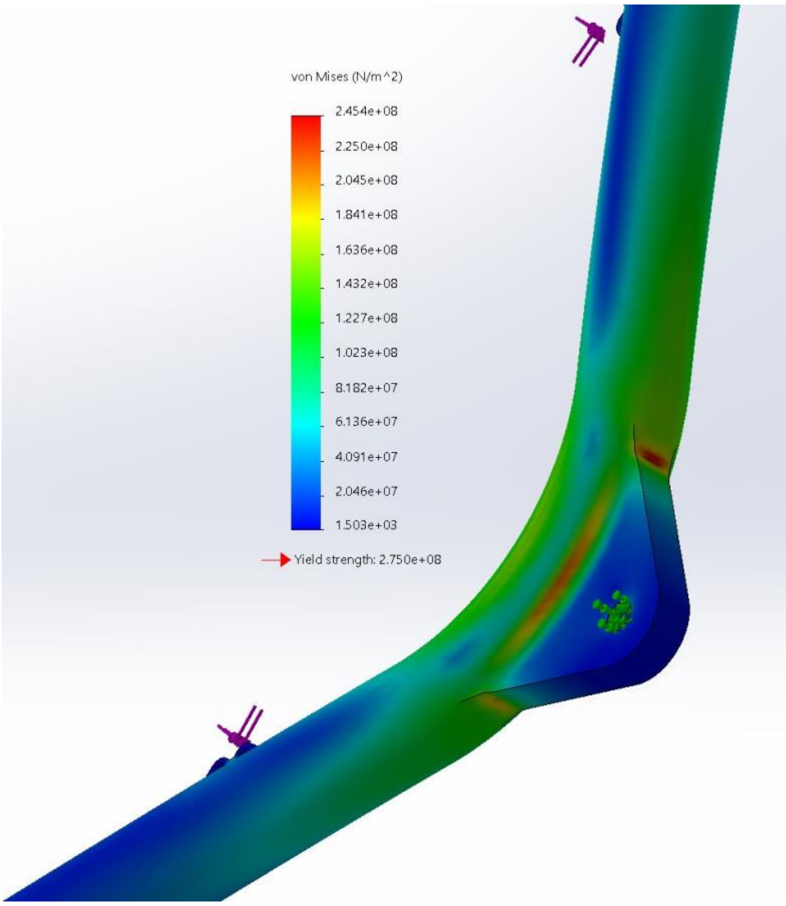

Image 11: redesigned bracket with the addition of fillets.

By redesigning how this bracket section combines with the rest of the component this stress singularity can be dissipated as shown in image 10. With this redesign there is a 13.4% decrease in overall stress. Upon running the same Design Study again, the software now recommends a wall thickness of 5.2mm resulting in a peak stress of 2.68e + 08 N/m^2 and 4% weight decrease. This configuration is optimal for two reasons: cost and strength. Although the weight of the component could be further reduced by varying the wall thickness throughout tits length, by keeping the thickness uniform the manufacturing process is kept simple and therefore cheaper.

With further Design Studies and alterations, it is possible to create an even lighter component that still maintains an appropriate strength. The inner wall thickness was split into three different widths as shown in image 11. This configuration results in a 67% weight decrease over a consistent wall thickness of 5.2mm. The stress analysis results are shown in image 12.

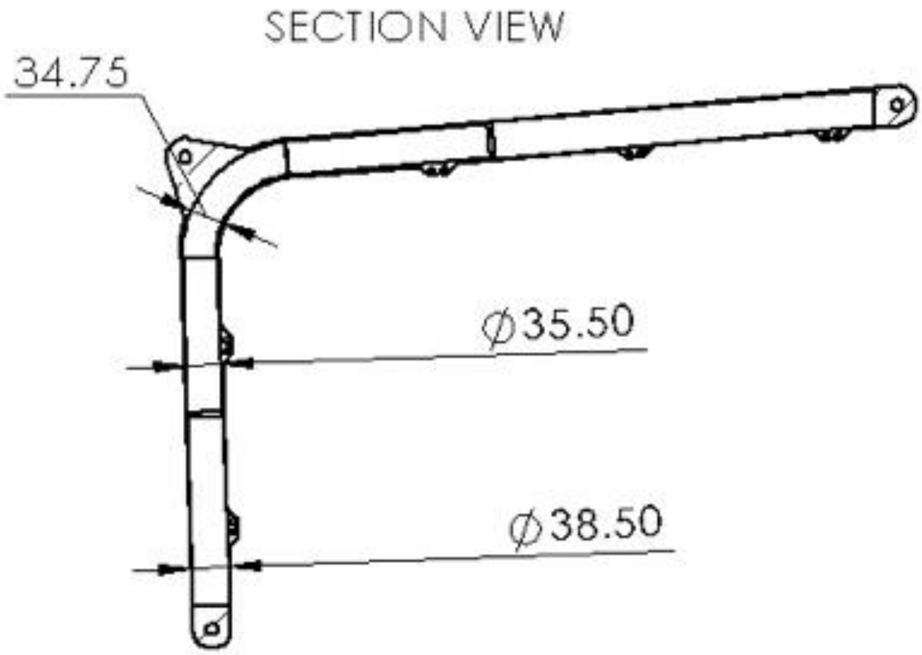

Image 12: side section view of centre component.

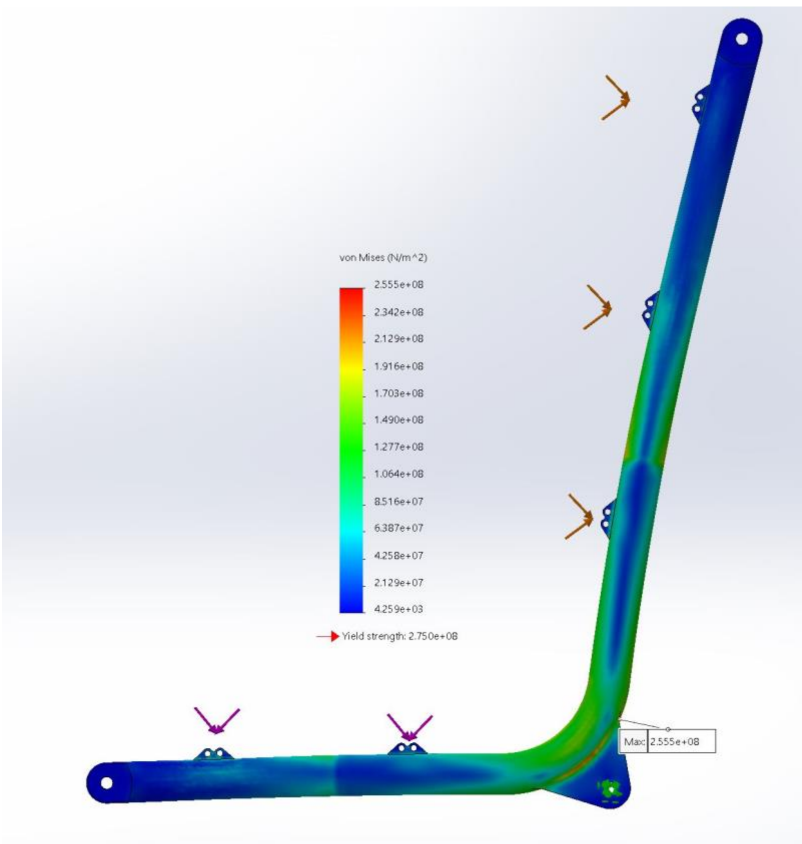

Image 13: stress analysis results from component with stepped wall thickness.

The next component to undergo analysis and optimisation will be the panels that combine together to form the seating surface itself. As these panels can force in excess of what could be expected from the previously stated 85kg individual. Image 13 displays stress analysis results from the initial design without any optimisation with the central part fixed via a bracket on the componenets underside.

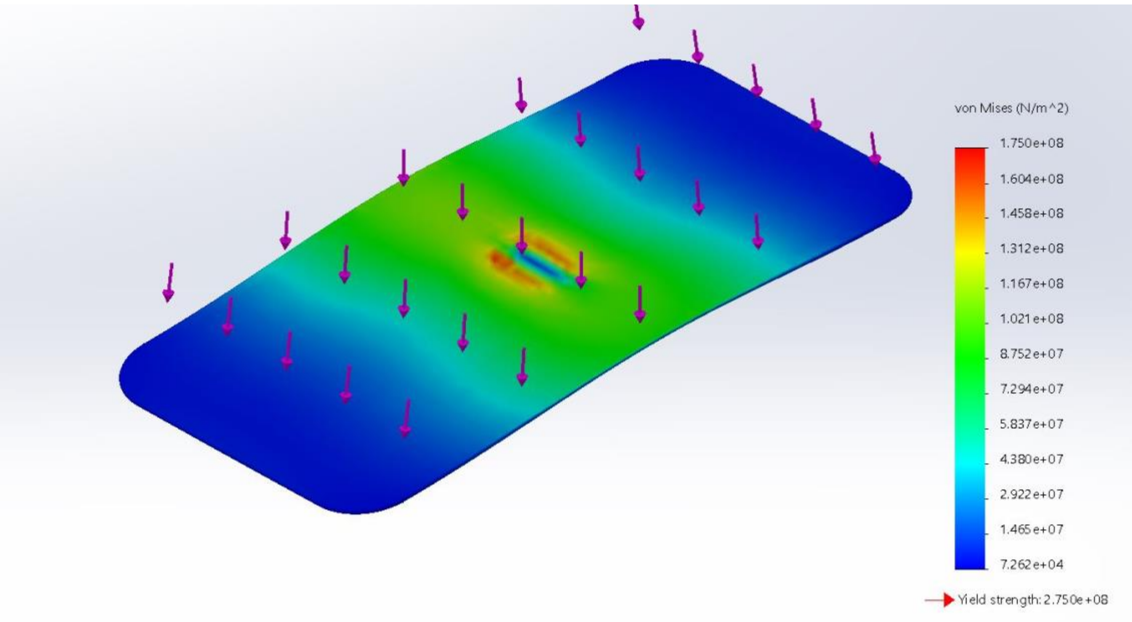

Image 14: before optimisation with 3mm thick aluminium 6061-T6.

Stress levels are within tolerance so there is no immediate concern for material failure, although the displacement of the two extreme ends is of particular concern. Although the materials yield strength has not been exceeded, this relatively thin piece which is fixed in the centre is likely to experience deformation that is difficult to predict. This becomes especially pronounced when conducting a Design Study on this component. Once the thickness of the panel has been reduced to 2.5mm to suit the optimisation criteria as shown in image 14, the deformation becomes too extreme requiring remedial action as shown in image 15.

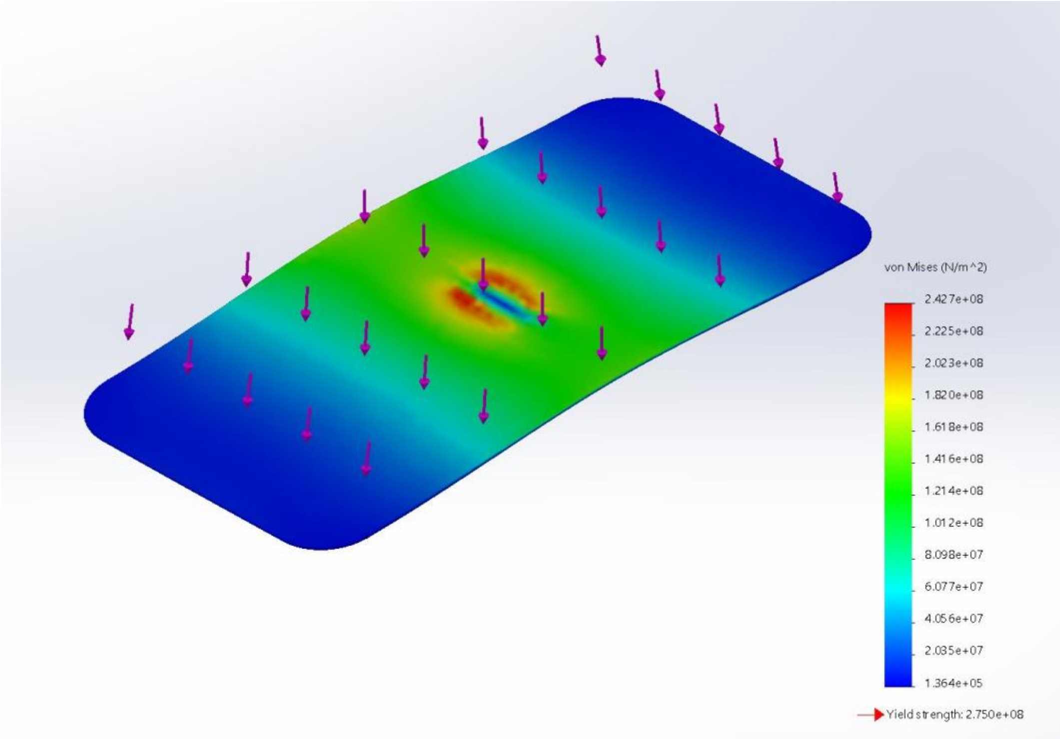

Image 15: Design Study has determined 2.5mm to be the optimal panel thickness.

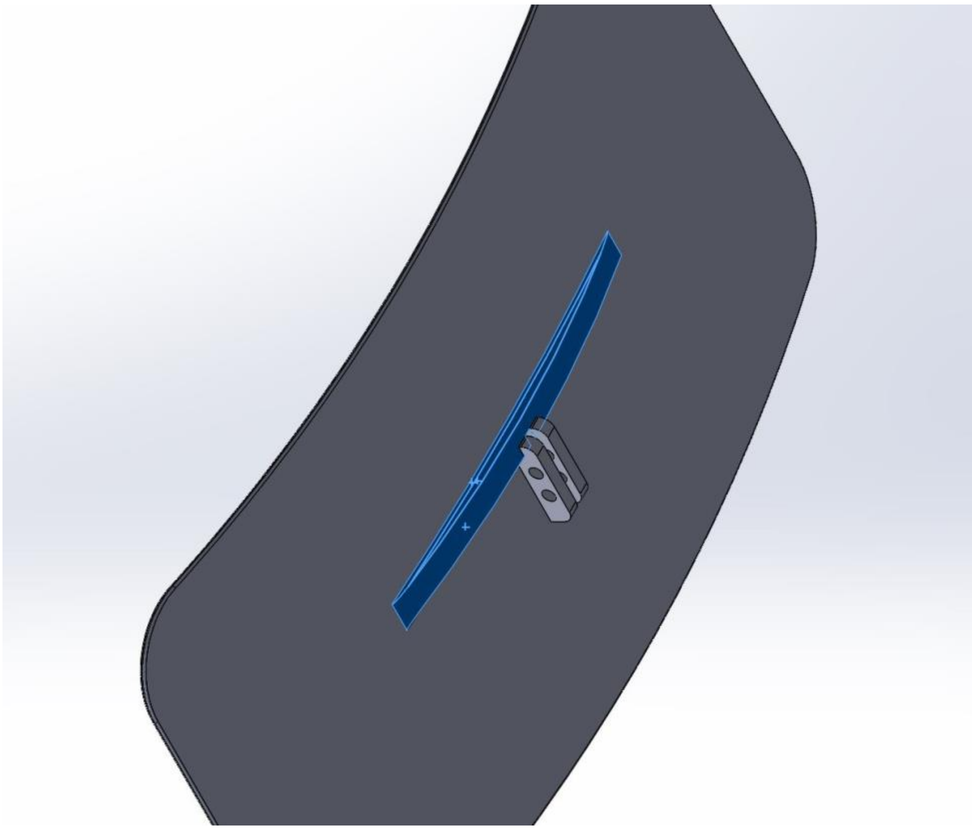

Image 16: addition of supporting beam on the panel's underside is highlighted in blue.

Image 15 shows how material has been added to prevent the panel from deforming so drastically. Design Study calculated the appropriate positioning and width of the additional material to determine the optimal scenario. The stress analysis results can be seen in image 16. The reduction of stress singularities has been greatly reduced and is now evenly distributed. Component mass is now 250.52g, 2.7% heavier than previous component iteration. A similar principle will be applied to the headrest which is a similar design, just on a smaller scale.

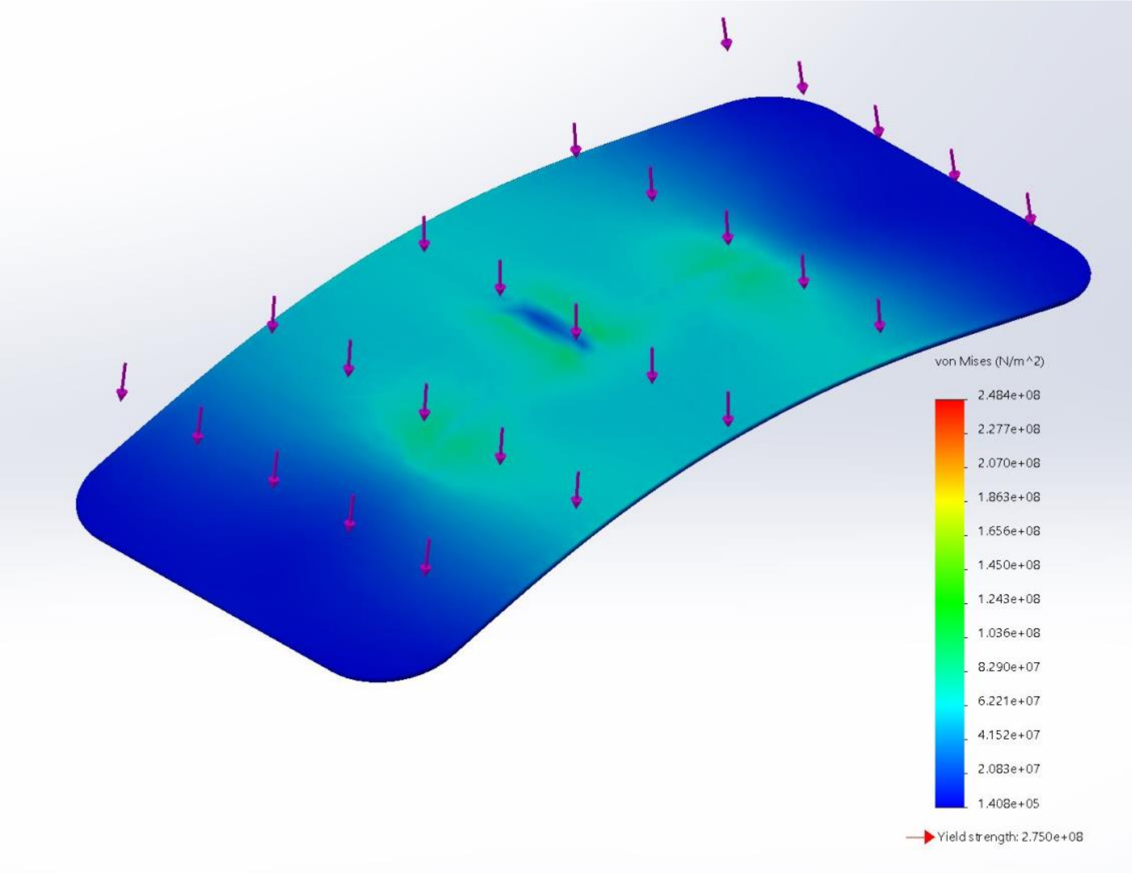

Image 17: panel with supporting beam. Final optimisation stage.

The next component to be optimised will be the armrest structure. As it is unlikely to experience force as significant as the previous components. For the tube section, the Design Study software recommended a wall thickness of 26.8mm, the stress analysis of which can be seen in image 17. As shown in this diagram, the highest stress levels are present near the fixed geometry where it connects to the central column whereas the armrest section itself experiences little stress, there is material that can be removed from this section.

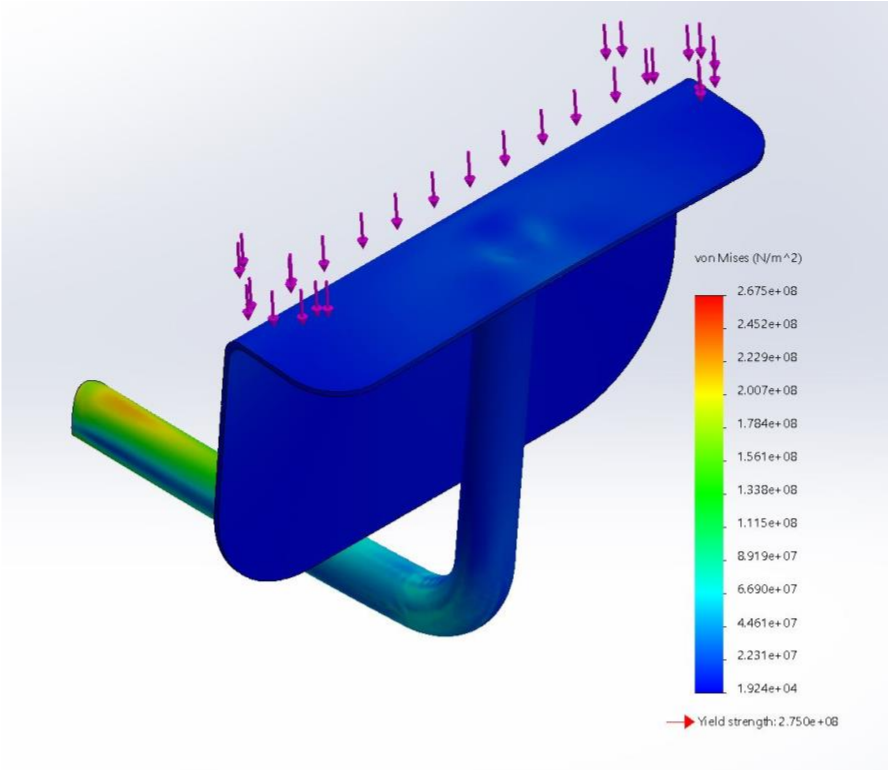

Image 18: initial optimisation stage.

A mesh structure was created throughout the arm rest section visible in image 18. By removing this material, simulation data shows that the maximum stress has been reduced by 2.8% with a 15.8% decrease in weight, from 266.9g to 230.6g.

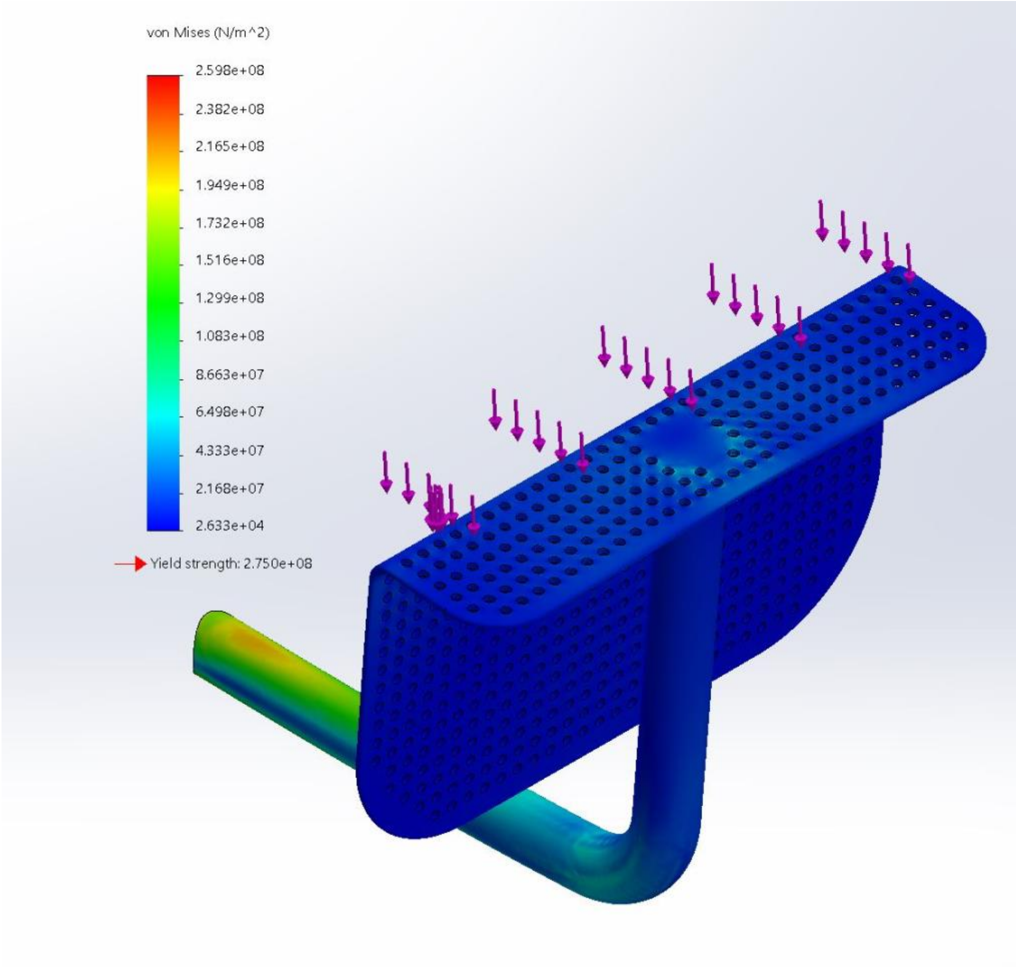

Image 19: armrest components with material removed.

Now the components that connect the headrest to the chair will be optimised. Five of them will be connected in a row using friction hinges meaning they must be optimised to reduce the likelihood of wearing out the friction hinges. These components will not experience as high forces so therefore have been studied with reduced levels at 400N represented by the purple images in the two proceeding images. As this component is relatively short, it is difficult to shell. Therefore, a central hole will be cut in the centre. Image 20 shows the component before any optimisation has taken place and image 21 shows the component after with a large part of its centre removed. The post optimisation component weighs 4.7% less than the previous iteration at 60.03g.

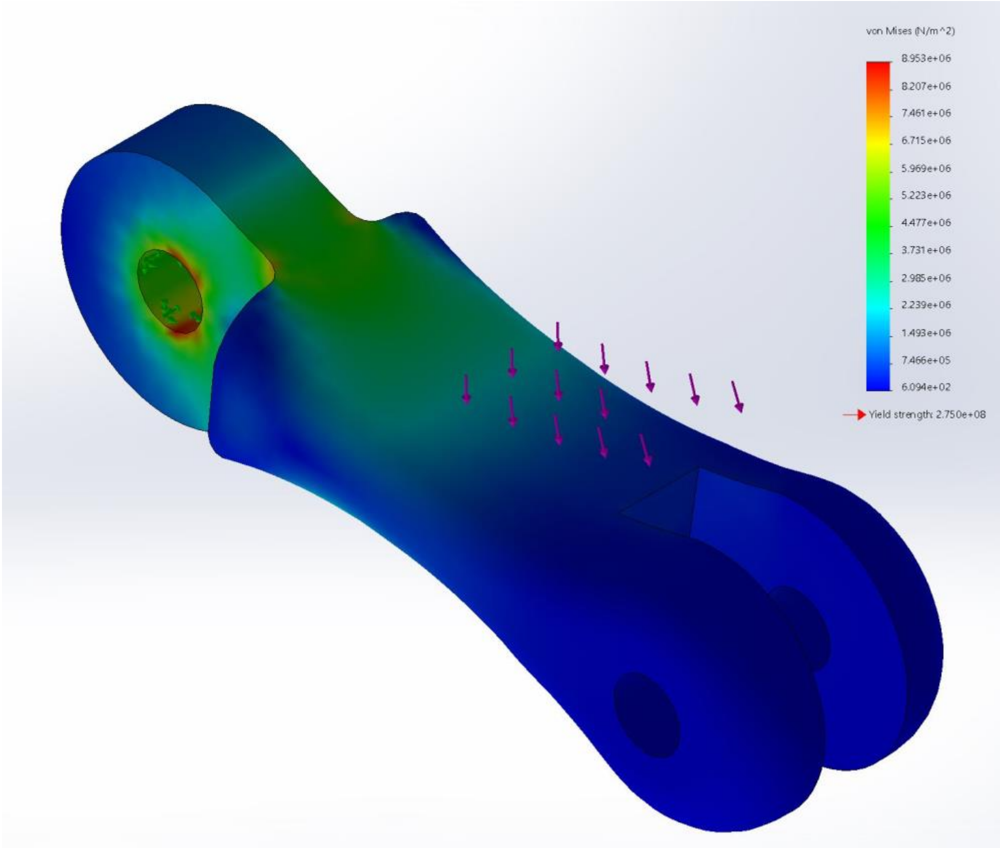

Image 20: headrest segment before any optimisation.

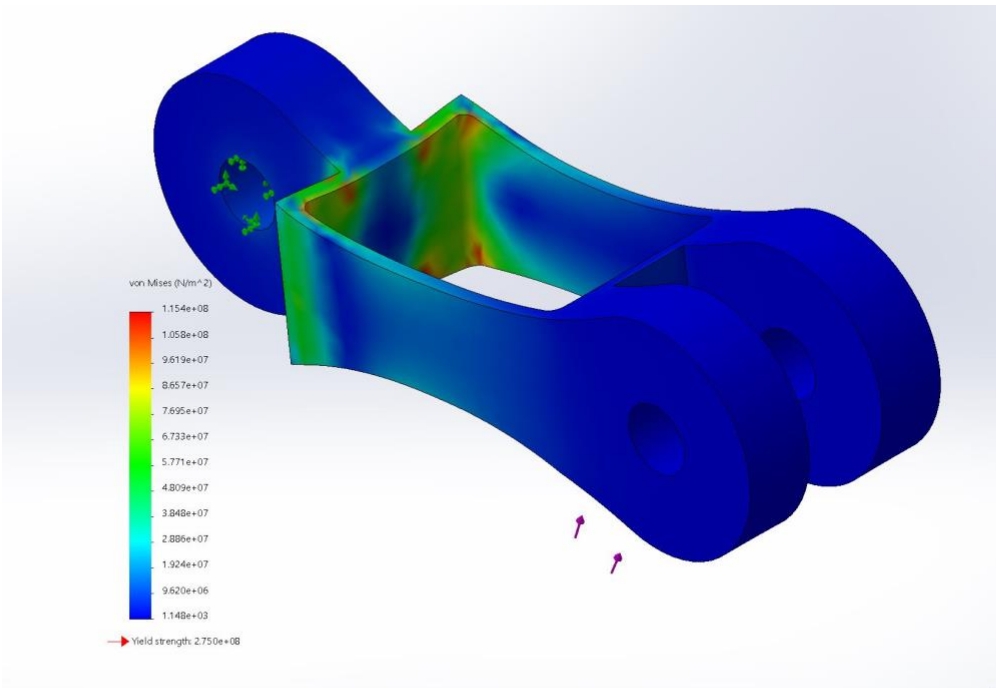

Image 21: headrest segment post optimisation. Solidworks does not display small fillet features in simulation studies.

The final part that will be optimised is the foot rest. As this section is likely to be stepped on it must withstand the mass of the specified individual, 85kg. Therefore, the stress analysis simulations undergo a force of 833N represented by the purple arrows in image 22. Design Study initially recommended a wall thickness of 4.5mm for the down tub section but as shown below, there is still an instance of stress singularity where the tube connects to the bottom plate. To counteract this, a beam was added as shown in image 23.

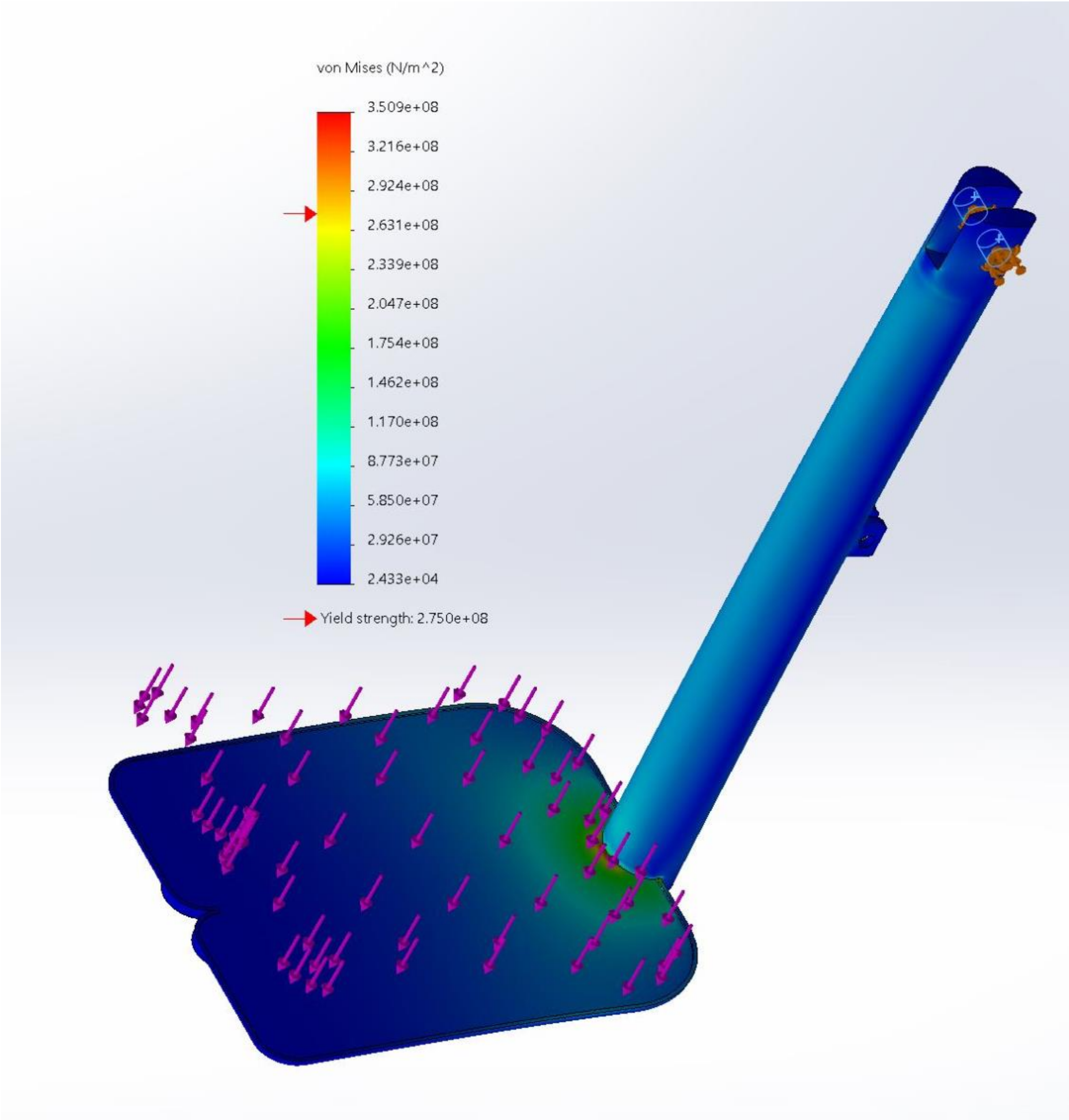

Image 22: initial stage of footrest optimisation.

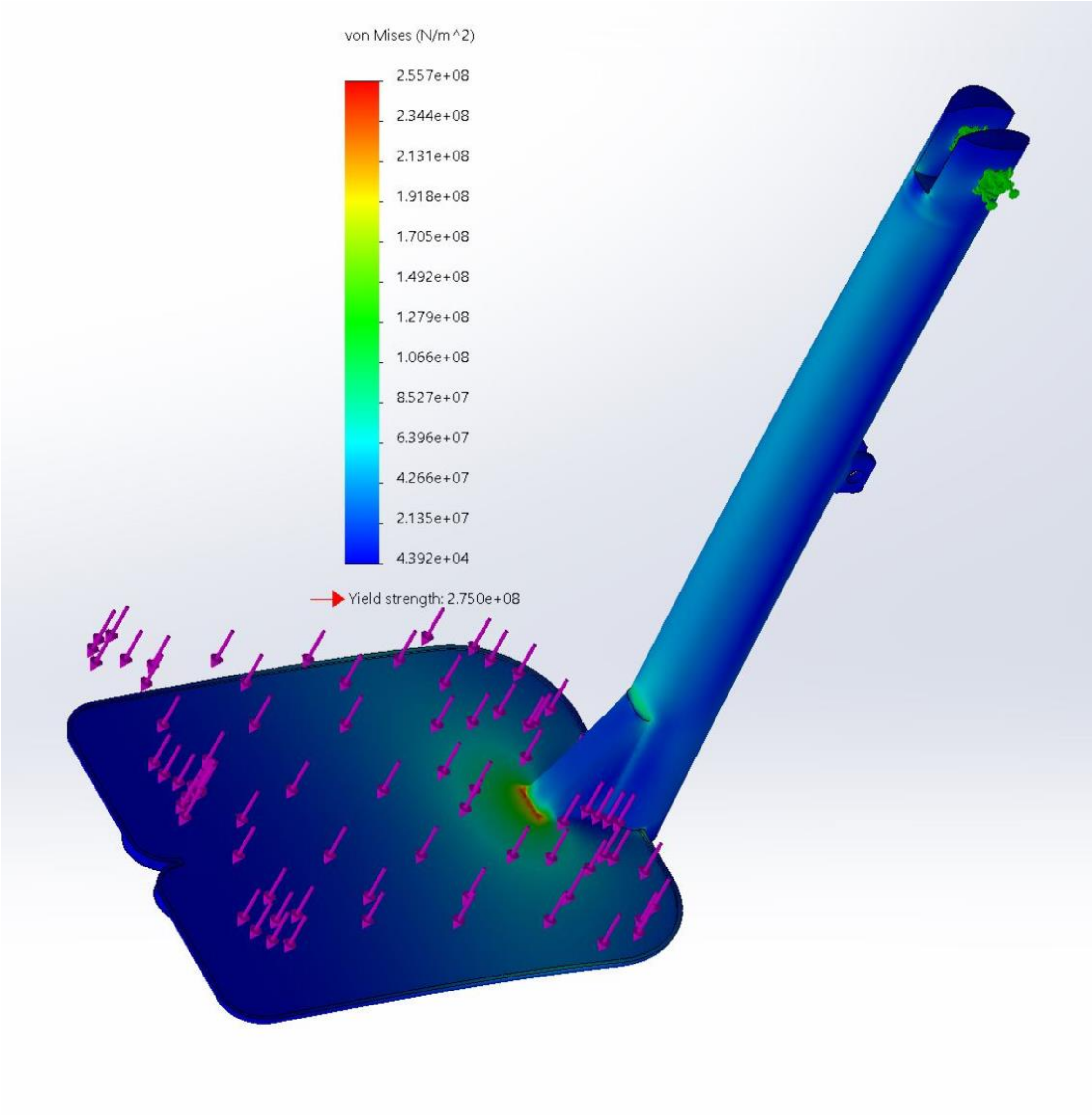

Image 23: final stage of footrest optimisation. Beam added between tube and bottom plate.

Design Study determined the optimal width of the additional beam to be 20.5mm. As a result, the peak stress level has decreased by 37.2% concluding the optimisation of the chairs components.

During the design's implementation, there were many articles in the aforementioned that were met such as: maximum weight and width limit, the use of simple, adjustment and maintenance mechanisms. But others are more difficult to determine such whether the chair supports somebody properly, or whether its visual aspect is an improvement. These requirements are subjective and therefore require more testing.

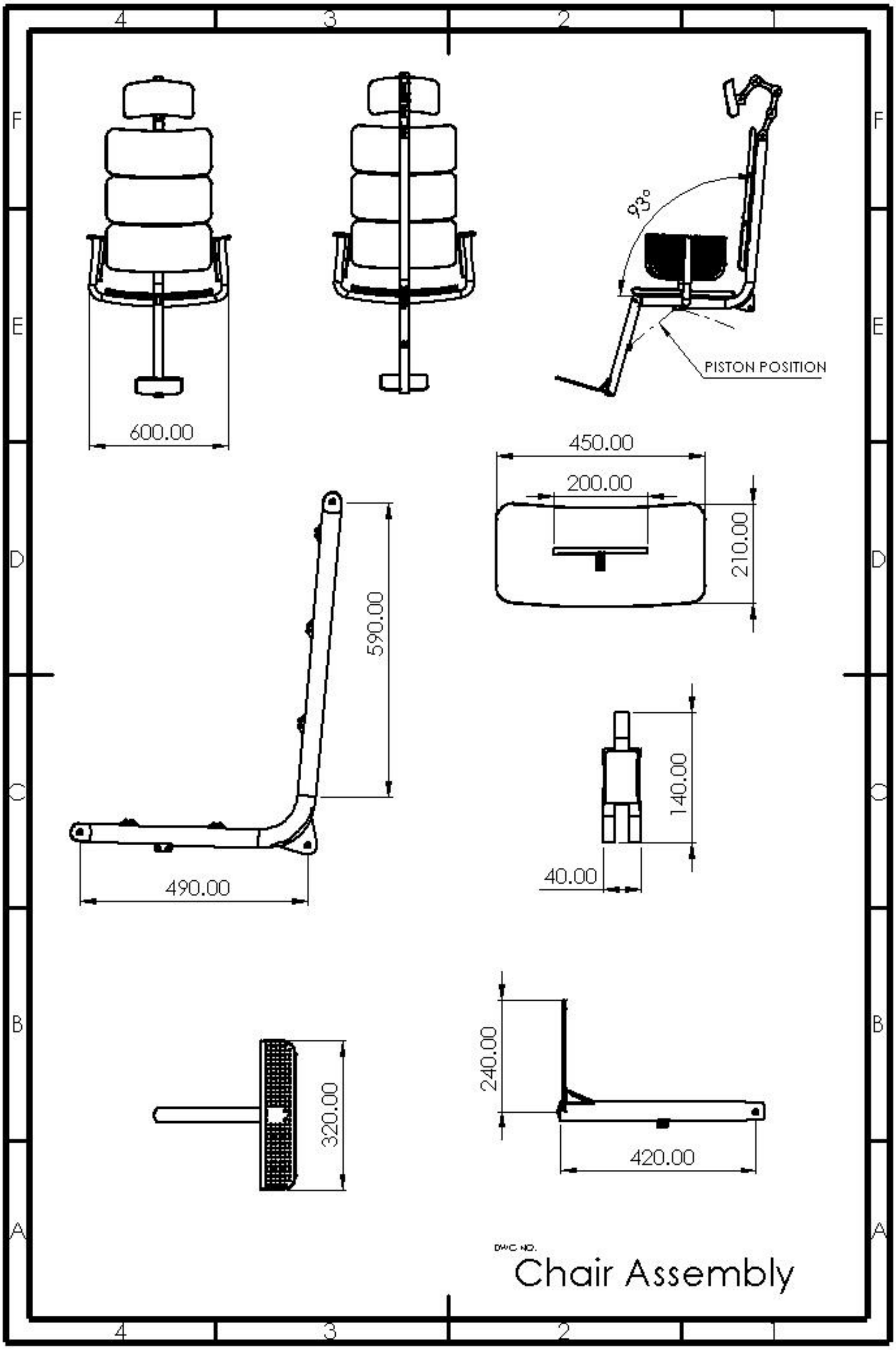

Image 24: isometric display of chair components as well as full assembly.

Image 25: rendered image of assembled components in their optimised form.

8. AUTOMATION

With the physical aspects of the initial model finalised, this report will now move on to development of actuation programming. To combat the onset of pressure ulcers it is vital that the patient is able to periodically relieve pressure on vulnerable areas of the body. Often a carer would lift up and move the patients to promote blood flow to compressed areas. With a chair that can move the sitter automatically, a greater degree of independence and quality of life is afforded. This chapter will develop a system for a chair to do this.

8.1. Pressure Sensing

To accomplish this task automatically requires some form of pressure sensing. Preliminary reviews of related literature highlight pressure 'mapping' products such as the XSENSOR X3 (n.d.) used in pressure-oriented studies such as *Pressure Mapping Comparison of Four OR Surfaces* (Kirkland-Walsh et al., 2015). Readily available similar products are offered by companies Tekscan (n.d.), Pressure Profile Systems (PPS, n.d.) and there are others being developed such as those described by Lee et al. (2015) and Saenz-Cogollo et al. (2016). These products are only available at significant cost. The *Foresite* system produced by XSENSOR starts at £17 600 and can be as much as £30 600 (SUMED, n.d.). This cost would largely increase the overall cost of a chair making them unfeasible for the average user. The goal of this section is to develop another method of pressure sensing using readily available resources.

Many pressure mapping mats generations consist of an array of sensors of varying densities. Increased densities of sensors are capable of producing a more detailed map. The user interface end of the product usually comprises of software that depicts the map, pressure location and severity.

A more rudimentary system that reflects the functioning of these advanced systems is possible using an Arduino Uno, a microcontroller used in a wide range of applications. Servo motor based applications are simple to set up as shown in the *'Examples'* tab on the Arduino IDE (Integrated Development Environment). The example code *'knob'* demonstrates how a servo motor can be positioned using a potentiometer that produces a variable resistance. This is useful for determining how a Force Sensitive Resistor (FSR) can be attached to the Arduino Uno board to control a servo. The next example code named *'sweep'*, details how a servo can be moved to a predetermined positioned using loops. The prototype chair will need to be able to move in a similar fashion described within this code.

With these basic concepts understood it is now possible to continue developing a code for sensing pressure on the chair and controlling its movements. Initial coding will be undertaken using *'tinkercad.com',* an educational tool that features a fully programmable Arduino Uno simulator.

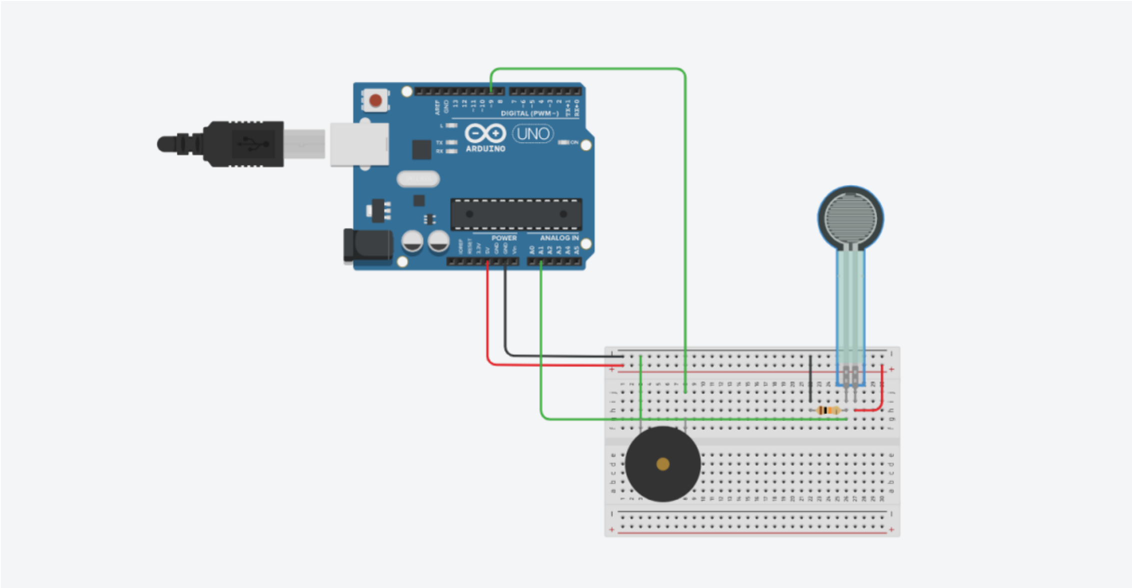

Image 26: initial experimental circuit simulation. FSR with resistor on left hand side. Black circle is the piezo buzzer.

The first prototyped circuit is shown above. The Arduino Uno is on the left connected to a breadboard on the right with a piezo buzzer, force sensitive resistor and static (non-variable) resistor. A servo has not yet been included within this circuit for simplicity. It is first necessary to finalise the force measurement functioning and timing of the code before moving on to the more complex servo positioning.

```
/* Code 1, initialising force measurements */
int Piezo = 9;
int ForceSensor = A1;
int ForceValue = 0;
int Threshold = 740;

void setup() {
    pinMode(ForceSensor, INPUT);
    pinMode(piezo, OUTPUT);
    Serial.begin(9600);
}

void loop() {
    ForceValue = analogRead(ForceSensor);
    Serial.println(ForceValue);
    if (ForceValue > Threshold){
        tone(Piezo, ForceValue);
    } else {
        noTone(Piezo);
    }
}
```

This code demonstrates a forcer sensitive resistor connected to a piezo buzzer. The code is continuously checking to see whether the pressure applied to the FSR exceeds 740. If the pressure applied does exceed this value, the piezo buzzer will activate. Once the applied pressure is back below the threshold value, the piezo buzzer will deactivate again.

The purpose of this code is to examine how a readily available FSR could be utilised in reducing the likelihood of pressure ulcers developing. The next portion of code development will look at timing. From the literature review, it can be ascertained that care givers will move the patient periodically in two instances; when the patient desires and when is required. Medical professional will determine the likelihood of the patient developing pressure ulcers and deduce the rate of how often the patients’ position should be altered to avoid reduce this likelihood. The code below involves a timing function to replicate the determined *rate.*

```
/* Code 2, initialising timing */
#include <Servo.h>

/* Servo */
Servo myservo; // servo object
int pos = 0;   // store servo position
int counter;   // count number of servo actions

double averageForce = 0;
int forceSensor = A1;
int forceValue;
int forceThreshold = 500;
int forceTotal = 0;
int timePeriod;

/* Timing Criteria. Currently 5000ms (5s)
This value could be determined by user */
const unsigned long eventInterval = 5000;
unsigned long previousTime = 0;

void setup() {
  pinMode(forceSensor, INPUT);
  myservo.attach(9);
  myservo.write(0);
  Serial.begin(9600);
}
```

After all variables and connective pins have been initialised the servo is set to its default position, zero, before the serial port is opened and its data rate is set. The serial monitor is a necessary component for code testing. Readings from the FSR will be displayed via it as well as the periodic average computation at the end of each time period. The continued code below displays the timing method. The area demarcated as *"Area for servo movement"* has not as of yet been developed fully. Once servo movements have been developed they can easily be inserted into this code.

A running total is kept of the force readings for *forceTotal* which is then used on line 45 with the chosen time period to determine an average force level. If that average force exceeds that of the chosen threshold force, the servo movements will be activated.

```
void loop() {

  /* Running Total */
  forceValue = analogRead(forceSensor);
  forceTotal += forceValue; // accumulate values
  Serial.println(forceTotal);

  /* Timing Indication */
  timePeriod++;
  Serial.print(timePeriod);
  Serial.print(": ");
  delay(1000);

  /* Event Timing (every 5 seconds) */
  unsigned long currentTime = millis();
  if (currentTime - previousTime >= eventInterval) {

    /* Average Force */
    averageForce = forceTotal / timePeriod;
    Serial.println("Average: ");
    Serial.print(averageForce);

    /* Event */
    if (averageForce >= forceThreshold) {
      /**********************
      Area for servo movement
      **********************/
    }
```

Finally, the time and force values will reset before beginning the loop again.

```
    /* Update for next event */
    previousTime = currentTime;
    averageForce = 0;
    forceTotal = 0;
    timePeriod = 0;
  }
}
```

With time functioning complete we will now examine servo movement. The initial concept is for the entire chair to tilt in multiple steps of a predetermined angle. For the purpose of prototyping, this will be three steps at 20 degrees each for a total tilt of 60 degrees.

The addition of the servo motor is shown in the diagram below. The servo motor is connected to the 5V, GND (ground) pins and a PWM (Pulse Width Modulation) pin that provides the control signal for the servo motor movements.

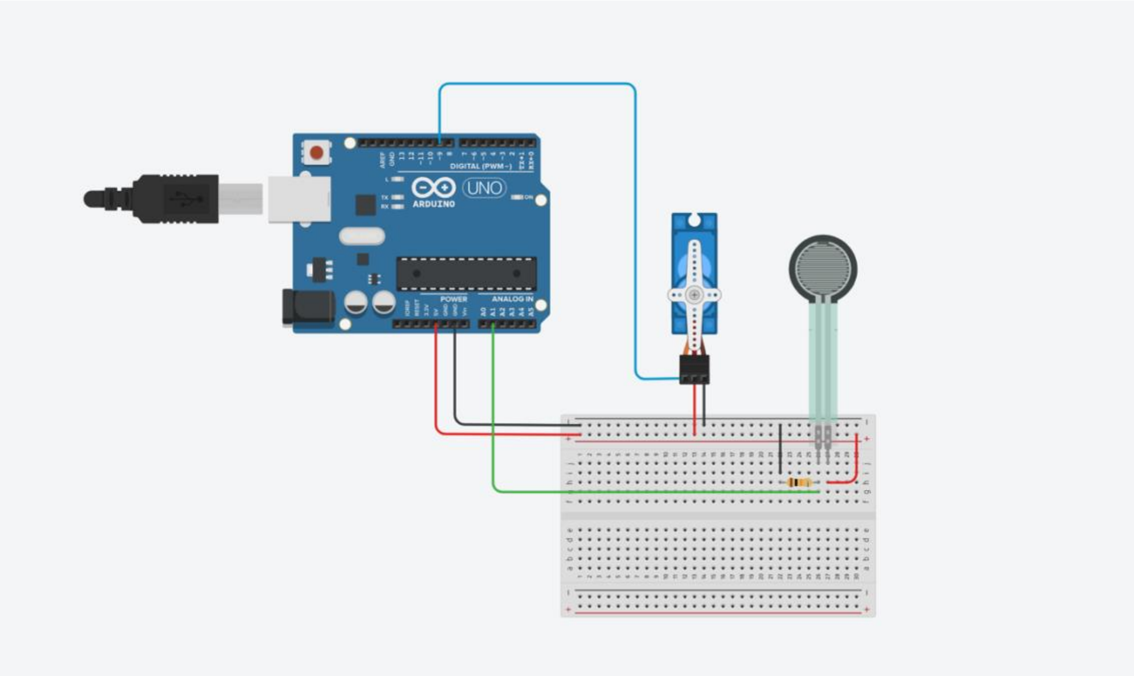

Image 27: final circuit design. Piezo buzzer has been replaced with a servo motor.

The initial code section for servo movement control is shown below. This section is an excert from the above code diagram 2 in place of *"Area for servo movement".* A counter is utilised to keep track of servo positioning. The initial loop activation will move the servo by 20 degrees in one direction and increment the counter by one and subsequently for two more steps in the same direction. Once the counter reaches values higher than three the servo will reverse direction and replicate the same steps as before. Once the servo has returned to its original position and the counter six, the counter and position both reset ready for the next loop.

```
  if (counter <= 2) {
    posCount += 20;
    for (pos = 0; pos <= posCount; pos += 1) {
        myservo.write(pos);
    }
    counter++;
  }
  else if (counter > 2) {
     posCount -= 20;
     for (pos = 60; pos >= posCount; pos -= 1) {
        myservo.write(pos);
     }
     counter++;

     } if (counter == 6) { // at end of event count, reset values
          counter = 0;
          pos = 0;
  }
```

This section of code conceptualises the “stepping” process of the chair. The system diagram in figure 1 shows the process of the entire code. Now that the prototyped code is in its final stages, a small prototype will be produced to visualise the workings of the code.

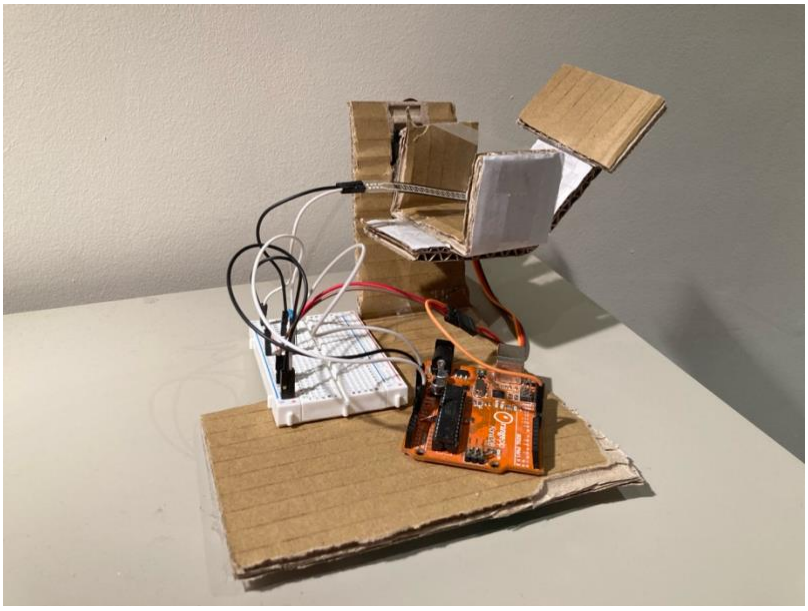

Image 28: protoype chair. Used to visualise the programming process. Consists of force sensitive resistor, servo motor, Arduino uno, breadboard, a resistor and cables.

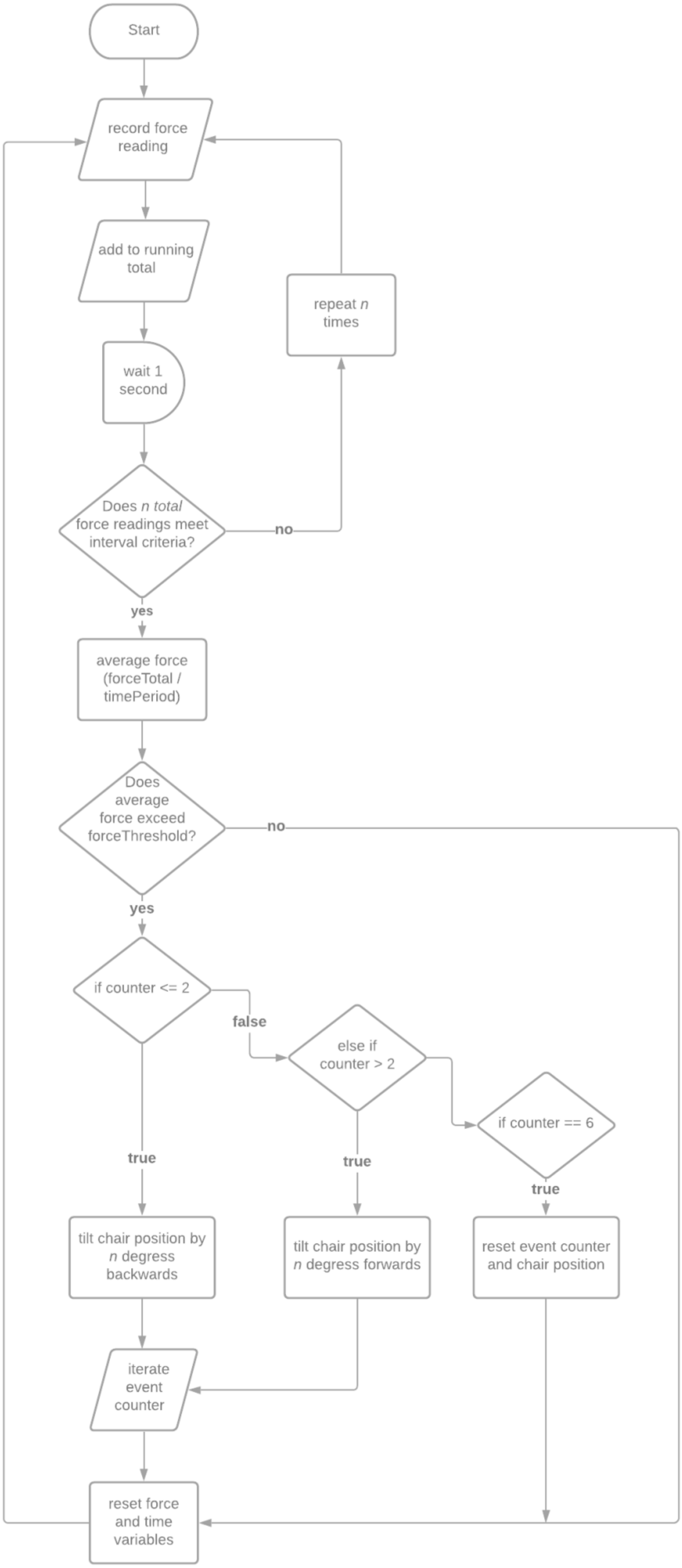
Start
record force reading
add to running total
wait 1 second
repeat n times
Does n total force readings meet interval criteria?
no
yes
average force (forceTotal / timePeriod)
Does average force exceed forceThreshold?
no
yes
if counter <= 2
false
else if counter > 2
if counter == 6
true
true
true
tilt chair position by n degress backwards
tilt chair position by n degress forwards
reset event counter and chair position
iterate event counter
reset force and time variables

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Figure 1: system diagram of chair functioning.

9. CONCLUSION

Some of these the more objective criteria for this project have been reached or even exceeded, such as maximum weight but others such as whether the developed design improves upon existing solutions and if it sufficiently supports someone with tetraplegia are harder to determine. To be able to properly determine whether these criteria have been met, it would be necessary to construct a full-size working prototype. By doing this, aspects such as positioning of force sensitive resistors, how supportive the chair is and how much it should tilt by to comfortably relieve pressure without feeling too intrusive.

Despite the need for further development, the chair designed should provide the framework for further analysis and implementation of design ideas to alleviate tetraplegia related problems and allow users to gain independence.

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