ME450 Fall 06
Redesigning High-End Office Chair

FINAL REPORT

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Date: 12/15/06

EXECUTIVE SUMMARY

The Knoll Life Chair Series 400 is a high-end office chair with a mechanism that couples the motion of the seat with the recline angle of the chair's back which is a well-liked feature among customers. However, the current mechanism is relatively heavy, complicated, and difficult to assemble. Due to the high cost associated with these characteristics, the Knoll Life Chair Series 400 office chair is not as price competitive and as profitable as it can be in the market. Thus we were asked by the Knoll Furniture Company to modify the current chair design such that the chair's 1) current functions are maintained, 2) number of parts is reduced, 3) the overall cost of the chair is reduced, 4) modified mechanisms can be easily integrated onto the current chair, and 5) reliability is maintained.

Based on the customer's requirement, we obtained a list of general engineering specifications for our design which are 1) simplification of synchronized recline and upright tilt locking mechanism, 2) maintenance of all current functions, 3) capable of entering full-scale production, 4) easy to assemble, 5) high reliability. Using QFD analysis, we ranked the importance of the customer requirements and the general engineering specifications.

Based on the engineering specifications identified, we generated a total of nine design concepts focused on redesign of 1) the synchronized recline mechanism, 2) complicated upright tilt locking mechanism and 3) the back casting to allow for ease of assembly. Based on results obtained from our Pugh chart study, for the synchronized recline mechanism, we chose a concept which transforms the current four-bar linkage system of the synchronized recline mechanism into a 4-link compliant mechanism with Small Linkage Flexural Pivot (SLFP) replacing the original pin joints as the final concept for our alpha design. The torsion bar in the current chair design that stored energy during recline movement of the chair was eliminated and replaced by the compliant mechanism. Using this final concept we were able to develop an initial design that was optimized to support a weight of 200 lb and allow for a back inclination angle of ±16 degrees. We determined that E-glass SLFP segments and Aluminum rigid links would provide the highest safety factor for our design among the materials that we analyzed. For the upright tilt lock system, we chose to redesign it to a one-piece compliant mechanism using High Density Poly Ethylene (HDPE). Using this method, we would be able to reduce the parts dramatically while sustaining the current function.

Based on the CAD drawings for both designs, the manufacturing plan was generated. According to the plan, we built two versions of the compliant synchronized recline mechanism using water jetting. Prototype One is a one-piece aluminum mechanism which has partial functionality. Prototype Two is a fully functional compliant synchronized recline mechanism based on our E-glass and Aluminum dual-material design which has allows for a full range of chair motion. We built the compliant upright tilt lock mechanism based on our CAD drawing using High Density Polyethylene (HDPE) from the laser cutter.

Compared to the original product, we reduced the synchronized recline and the upright tilt-lock mechanisms' part counts from 30 to 21 parts and 9 to 3 parts, respectively. The four-bar linkage mechanism on the current chair has a vertical displacement of 1.55 cm and the current upright tilt-lock mechanism has horizontal displacements of 1.2 cm at its ends. Prototype Two, the compliant synchronized recline prototype with E-Glass SLFP segments, had a vertical displacement of 1.2 cm and the compliant upright tilt-lock prototype had horizontal displacements of 0.7 cm on each side. Based on these results, we have achieved the goals of the project because we reduced the number of parts which will in turn reduce the cost of the current chair. We also maintained the current functions of the chair because the results we received from our prototype were similar to the current chair's attributes.

However, our design for the synchronized recline mechanism is not a one-piece compliant mechanism due to the high cost of manufacturing the entire system using E-glass. Therefore, this may cause some potential problems for full-scale manufacturing of the product. In the future, the development of a distributed compliant one-piece mechanism should be explored. We also recommend the future teams to try and integrate the designs onto the chair. To integrate the designs, 3-D force and stress analysis based on the current chair should be developed

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INTRODUCTION

Figure 1: Current Knoll Life Chair

Knoll is internationally renowned for creating innovative and modern office furnishings. Started in 1938, there are over 300 Knoll dealerships and 100 showrooms and regional offices in North America alone. Knoll also has showrooms and dealers located in Europe, Asia, and Latin America. Knoll's best selling product is the Knoll Life Chair Series 400 office chair, as shown in Figure 1. Although the chair is its best seller, the company continues to explore options to enhance the profitability on the chair. The primary objective of the "Complaint Seat-Recline Mechanism for a high-end Office Chair" project is to minimize the cost of the chair to improve its profitability and market position. Currently the chair retails for $1086 to $3192 depending on the customer specified features. Lowering the manufacturing costs and other associated costs would significantly increase the profits generated by the chair and make the chair more competitive in the overall market.

Knolls Furniture Company communicated to us that they would like us to provide them with a new design of their office chair based on the current chair's functions. They would like the chair to cost less to manufacture and contain fewer parts. At the same time they would also want the new chair design to maintain all the major functions the current chair design possesses. These functions primarily include the back upright tilt lock, movable seat pan, and synchronized recline. The major customer requirements of our series 400 office chair redesign as dictated by our sponsor are listed below:

1. Low cost
2. Fewer parts.
3. Reliable
4. Maintain synchronized recline feature
5. Maintain back upright tilt lock
6. Maintain sliding seat pan
7. Easy to integrate into the current chair design

The main direction for the redesign of the office chair is to convert the current synchronized recline and upright tilt lock mechanisms composed of conventional multipart mechanisms into a single piece compliant mechanisms. The complaint mechanisms will result in significant reduction of the number of parts needed for the assembly of the chair which would in turn simplify the assembly process. The project is aimed at creating a successful integration of the new synchronized recline compliant mechanism, upright tilt-lock compliant mechanism, and other redesigned subsystems onto the existing chair to drastically reduce the production cost of the chair.

CORRESPONDING ENGINEERING SPECIFICATIONS

General Engineering Specifications for Concept Generation

Based on the analysis of the original customer requirements from Knoll Furniture Company and our study of the current chair's mechanisms, we derived several major engineering specifications for our new office chair design.

Simpler Synchronized Recline Mechanism: In order to significantly reduce the cost of the chair from a manufacturing perspective, the chair's synchronized recline mechanism for raising and lowering the seat pan in response to the inclination angle of the back seat has to be simplified. The reduction in the number of parts from this mechanism through compliant design will significant cut the fabrication and assembly cost for the chair.

Simpler Upright Tilt-Lock Mechanism: The customer has expressed concerns with the current upright tilt-lock system for the chair's back. It is currently a complicated system containing many moving parts. Replacing this mechanism using compliant system would reduce the number of parts and lead to a significant cost reduction while improving the reliability of the locking system as required by the customer.

Simple Assembly: The new chair design should be simple and quick to assemble even for the most mediocre operator. Redesign of the chair for simple assembly would lead to a reduction in the production cost of the chair through reduced labor and savings from the reduction of part inventory. Simple assembly would also make repairing defective chairs faster and cheaper.

Maintenance of Functionality: While adequately meeting the improvement requirements that the customer want, the design must also maintain the major functions that the current chair possess. Some of the major functions are the synchronized recline, upright tilt-lock, and movable seat pan. Thus the new chair design must be able to maintain the ±16 degrees back rotation, perform the same synchronized recline motion as the current chair does, and have the ability of being locked in the upright position.

Capable of Entering Full-scale Production: The current product is one of our customer's best selling products in the high-end office chair market. There is a significant demand that our customer must meet and as result, the redesigned product must be capable of being produced at the same scale of production as the current product. The customer required us to provide a redesign of the chair that can be easily implemented onto the current chair. Thus our redesigned office chair must be able to enter full-scale production at a relatively low product introduction cost.

High Reliability and Safety: The new chair design must be able to support the 200 lb weight with little possibility of failure, like the current chair.

Specific Design Characteristics
Through analyzing the general engineering specifications that were translated from the original customer demand, we derived a set of specific part characteristics that can fully satisfy the needs of our customer.

Quality Function Deployment for Specific Design Characteristics: Based on our new QFD analysis, shown in Figure 2 on p. 6, we determined the key design characteristics that will meet the engineering specifications to satisfy the original requirements of our customer. They are ranked in order of importance below:

1. Feasible to manufacture at a low cost
2. Compliant synchronized recline mechanism
3. Compliant upright tilt-lock mechanism
4. High safety factor

Feasible for Manufacturing at a Low Cost: The key issue surrounding the parts in our new design is cost. The customer's primary requirement is the reduction of the chair's production cost. As a result, it is most critical that every part of our design has a low overall manufacturing cost and product introduction cost (manufacturing cost encompasses value-adding operation, logistics, overhead, setup, material, and labor cost.)

Compliant Synchronized Recline System: Having a compliant synchronized recline system is the second most important characteristic for our design. This feature would reduce the 4-bar linkage system composed of 4 parts in the original design down to 1 part composed of a fully compliant 4-bar mechanism. This would drastically simplify the synchronized recline mechanism, reduce assembly time, reduce the number of main parts in the chair, provide the same reliability as the current design, and provide for exactly the same range of motion as the original design. This new compliant mechanism can also be feasibly produced on a large scale with relatively low production introduction cost.

Compliant Upright Tilt-Lock system: Having a compliant upright tilt-lock system is the third most important characteristic for our design. This feature would significantly reduce the complexity of the locking mechanism currently in place. The redesign will lead to a shorter assembly time, fewer parts, and easy initiation of production. The reliability of the system will not be affected.

High Safety Factor: To maintain reliability, our design must provide for the advised weight limit on the current chair. As result, each system or component must have a high safety factor.

Figure 2: QFD for Office Chair Redesign

1	Not related
3	Weakly related
5	Neutral
7	Moderately related
9	Strongly Related

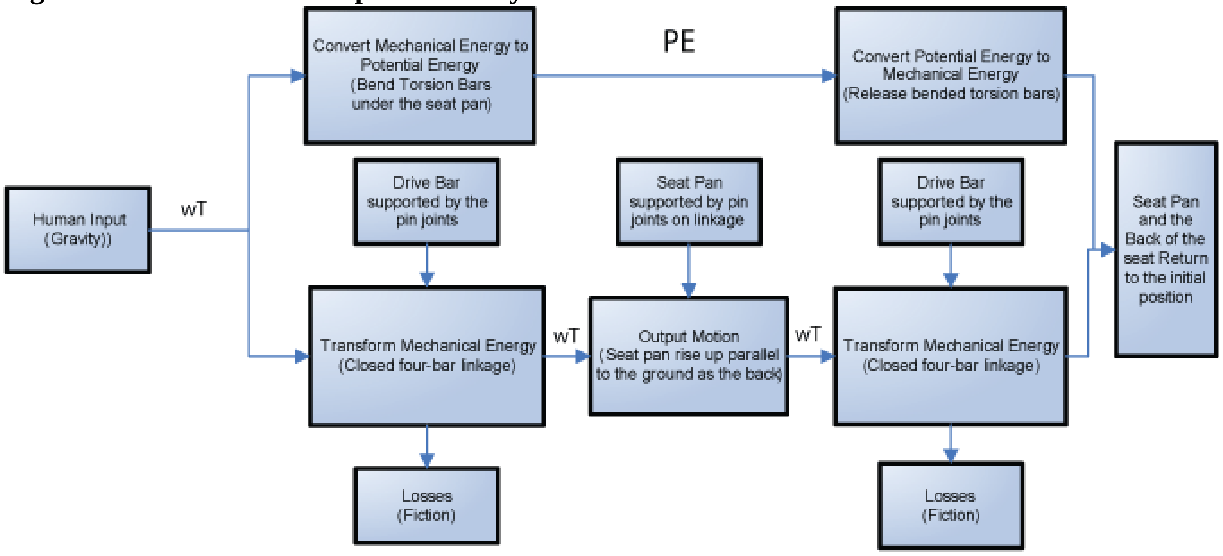
	Customer Requirements / Part Characteristics	Normalized Importance to Customer (Relative Weight)	Compliant Uptight Tilt Locky Mechanism	Compliant Synchronized Reclined Mechanism	Feasible to Manufacture at Low Cost	High Safety Factor and Fatigue Life	TOTAL - CUSTOMER REQUIREMENTS	RANK	Importance
USER-PERCEIVED QUALITY	Simplier Back Upright Tilt lock Mechanism	0.9	9	5	9	7	27	3	0.19
	Simpler Synchronzied Recline Mechanism	1.0	5	9	9	9	32	1	0.22
	Maintain Current Functions	1.0	9	9	7	7	32	1	0.22
	Capable of Entering Full-scale Production	0.9	9	9	9	5	28.8	2	0.20
	Short Assembly Time	0.8	9	9	9	5	25.6	4	0.18
	High Reliability	1.0	9	9	5	9	32	1	0.22
	Total		37.4	37.8	39.4	30.8			
	Rating (%)		26%	26%	27%	21%			
	Ranked Importance		3	2	1	4			

FUNCTIONAL DECOMPOSITION

Synchronized Recline Mechanism

The synchronized recline mechanism is activated when a force is applied onto the back-rest of the chair causing the mechanical energy to transform and transfer. The transferred mechanical energy moves throughout the four-bar linkage as torque and rotational velocity. The energy displaces the seat pan into a raised parallel position with the ground. The transformed mechanical energy turns into potential energy that is stored in the torsion bars. Once the force on the back-rest is released then the stored potential energy will transform back into mechanical energy and return the four-bar linkage into its original position. Functional decomposition of synchronized recline mechanism is shown in Figure 3 on page 7.

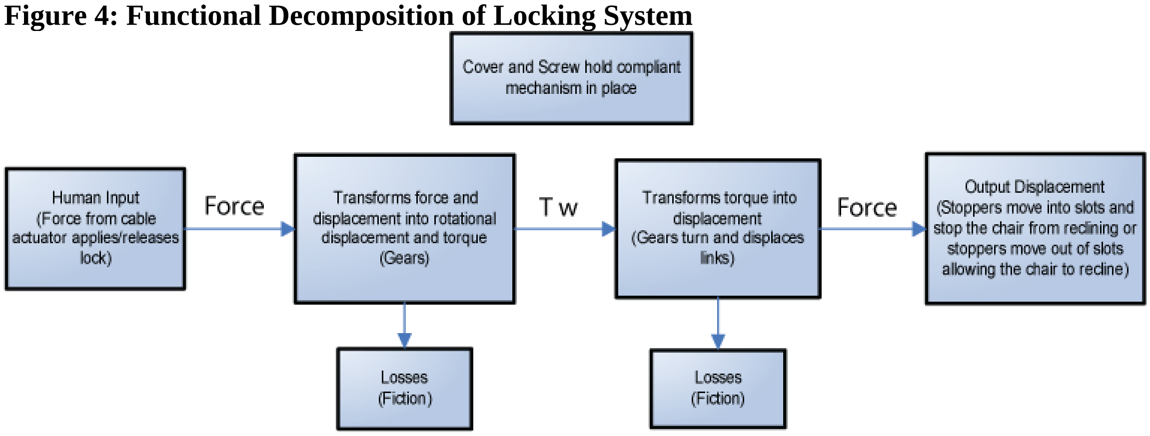
Figure 3: Functional Decomposition of Synchronized Recline Mechanism



Upright Tilt Lock Mechanism

To control the upright tilt lock mechanism a force is applied from the cable actuator which in turn causes a displacement at the end of the cable. The end of the cable is a block with teeth that is in sync with gears. The displacement causes the gears to rotate and the rotation causes links that are attached onto the gears to displace. The links are attached to stoppers that move in and out of slots. Depending on the position of the stoppers the chair will either be locked or free to recline. Functional decomposition of the locking system is shown in Figure 4 below.

Figure 4: Functional Decomposition of Locking System



CONCEPT GENERATION & CONCEPT SELECTION

Concepts for Synchronized Recline Mechanism

Based on the customer requirements and our general engineering specifications, we generated a total of 7 concepts. Using the Pugh chart analysis shown in Table 1 on page 8, with the current design as the baseline, we selected the top 3 concepts to explore further for our design. The concepts selected were numbers 3, 5, and 7, each with its individual advantages and drawbacks.

Table 1: Pugh Chart Analysis for Preliminary Concept Selection

	Concepts						
selection criteria	1	2	3	4	5	6	7
Low Cost	+	+	+	+	+	0	+
Maintain Synchronized Recline	-	0	0	0	0	0	0
Maintain Sliding Seat Depth	0	0	0	0	0	0	0
Fewer Parts	+	+	+	+	+	+	+
Maintain Back Upright Tilt Lock	0	-	0	-	0	0	0
Reliability	-	-	0	0	0	0	0
Easy to integrate	+	+	+	-	+	-	+
Sum +'s	3	3	3	2	3	1	3
Sum 0's	2	2	4	3	4	5	4
Sum -'s	2	2	0	2	0	1	0
Net SCORE	1	1	3	0	3	0	3
Rank	4	4	1	4	1	4	1
Continue?	No	No	Yes	No	Yes	No	Yes

Concept 3: Concept 3 is a partially-compliant linkage system that only has 3 links connected by thin flexural pivots. The input link is activated by the reclining motion of the chair's back. Acting as a lever, the downward force on the input link forces the whole mechanism to rotate with the fulcrum at point A in Figure 5 below. This in turn achieves the parallel upward movement desired for the seat pan. The links of this compliant linkage mechanism are attached to the seat pan and pinned to the seat base (ground) at points A and D in Figure 5.

Figure 5: Design Concept 3

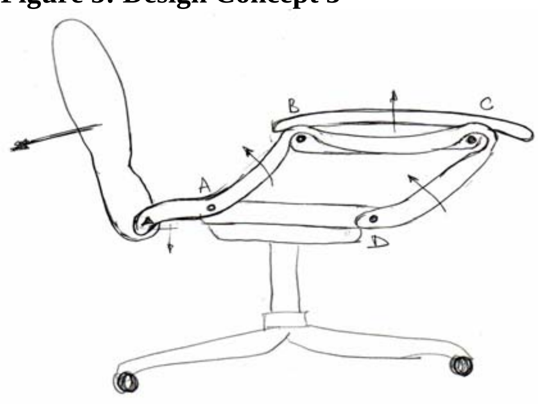
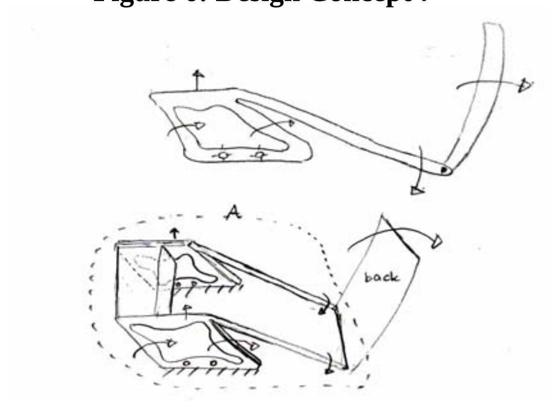
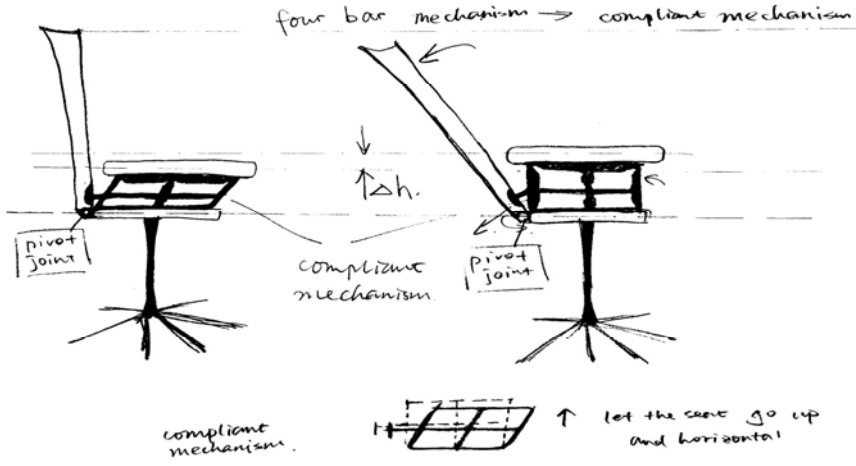


Figure 6: Design Concept 7



<u>Concept 5:</u> In this concept, the back-rest is connected to the base of the seat by a pivot joint in order to go back and forth. Once force is applied to the back-rest to push it backwards, the compliant mechanism connected to the back-rest will change from a parallelogram shape to a rectangle shape. This will in turn cause the seat pan fixed on the mechanism to rise and be horizontal to the ground, as shown in Figure 7 on page 9. The range of motion that this concept can create is questionable and the extra size and cost associated with the extra supporting links may pose a problem for this design concept.

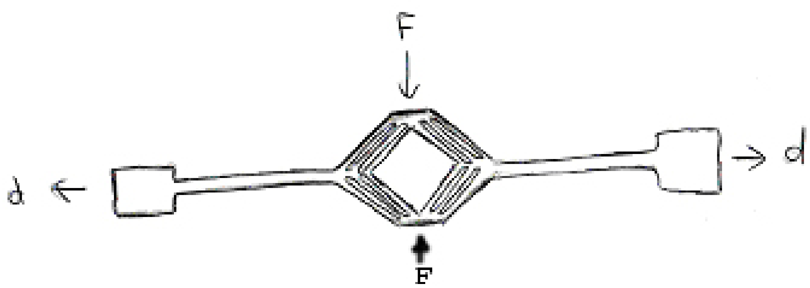
Figure 7: Design Concept 5



Concept 7: This concept uses a compliant mechanism to replace the four-bar linkage while maintaining the synchronized recline function of the current chair. Part A, shown in Figure 6 on page 8, is attached to the seat base using four bolts. When the ground attached back is reclined, it pushes down the two bars of part A. Then, the rest of linkages follow their own paths and eventually lift up the front part of the seat. This design has the advantage of full compliancy and full functionality (in terms of the range of motion it is capable of). However, this design concept could be further simplified if the drive link between the chair's back-rest and the mechanism is improved.

Concepts for Upright Tilt-Lock Mechanism

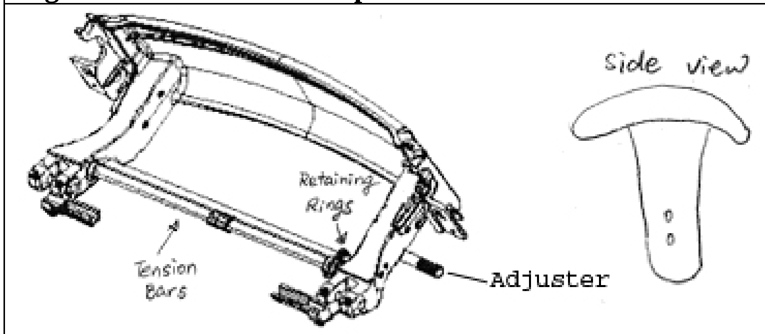
Figure 8: Locking System Design Concept



The current upright tilt lock system consists of six plastic parts that can easily fall apart. The new concept, shown in Figure 8, will replace the current mechanism with a compliant one-piece mechanism. The new compliant system will work by compressing the middle of the mechanism with a cable actuator. The actuator will be connected through the areas where the forces are shown in Figure 8. When the actuator compresses the middle, this will displace the sides of the mechanism outward and into locking slots, thus keeping the chair in one position. The only problem with the new compliant mechanism is the repositioning of the cable actuator. Currently the cable actuator is positioned parallel to the displacement of the mechanism, but in order to compress the middle of the mechanism the cable will have to be positioned perpendicularly. The compliant mechanism will reduce the number of parts from nine to three, since the blockers on both ends will be kept due to its complex shape. The compliant mechanism will be beneficial in the assembly of the chair because it will reduce the number of parts which reduces overhead and assembly time.

Design for Easy Assembly

Figure 9: Back Cast Concept



Knoll, our sponsor, has asked us to simplify the assembly process for the torsion spring bars. Therefore, the concept shown in Figure 9 reduces not only the number of parts but also the assembly time. There are two holes on one side of the part, so that the two spring bars can be slid into place. Then the spring bars will be locked in by retaining rings. There should not be any problems from the adjustable torsion bar by implementing this manufacturing process. The adjuster, shown in Figure 10 on page 11, will also have a hole drilled through the area for the bar to be inserted.

FINAL CONCEPT SELECTION

When choosing the best concept design, each concept was scored and ranked from the criteria based on customer requirements as shown in Table 1 on page 8. Concepts 3, 5, and 7 have advantages of low cost due to fewer parts and being easy to integrate onto the existing chair. These designs also do not have significant negative effects to the current chair. All three designs have the same net score and similar concept which is replacing four-bar linkage by compliant mechanism. Therefore, we optimized our final design by combining the above concepts (3, 5, and 7) together as shown in Figure 10 on page 11. Since compliant mechanism can store the energy required to move back to an upright position, the torsion bars can be removed from the back cast. After calculating the energy stored in the torsion bars we can design our α-design to duplicate this feature. The α-design reduces 17 parts, which decreases the manufacturing cost and simplifies assembly process, and the design can be easily integrated onto the current chair. The drawback in our final design is that the thicknesses of the segments are relatively small, so that those segments have a relatively high likelihood of failure. This makes the compliant mechanism relatively less reliable than the conventional steel casted 4-bar linkage system.

Final Concept Description

The "Alpha Design" shown in Figure 10 on page 11 is a combined redesign of concepts 3 and 7. It is called a pseudo-rigid-body model. Theoretically, the pseudo-rigid-body model concept is used to model the deflection of flexible members using rigid-body components that have equivalent force-deflection characteristics. Thus, the design uses the rigid links from the original four-bar linkage system of the current chair while the joints in the current chair are replaced by the Small Linkage Flexural Pivot (SLFP) at the same position. This will allow a full range of motion for the SLFP segments so it will not be inhibited by the rigid links. The complaint mechanism will only work if the SLFP segments are in tension and should not experience bending moment at the initial position. Therefore, the segment orientations have to be the same with that of force on the current four-bar linkages.

Another advantage of using SLFP segments is it can discard the torsion bars by storing the same amount of energy needed to retain the original position of the current chair. By doing so, the torsion bars can be replaced and there would be no need to implement design concept 9.

Figure 10: Final Concept for Compliant Synchronized Reclined System

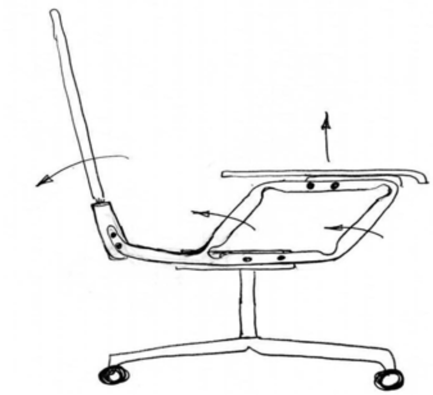
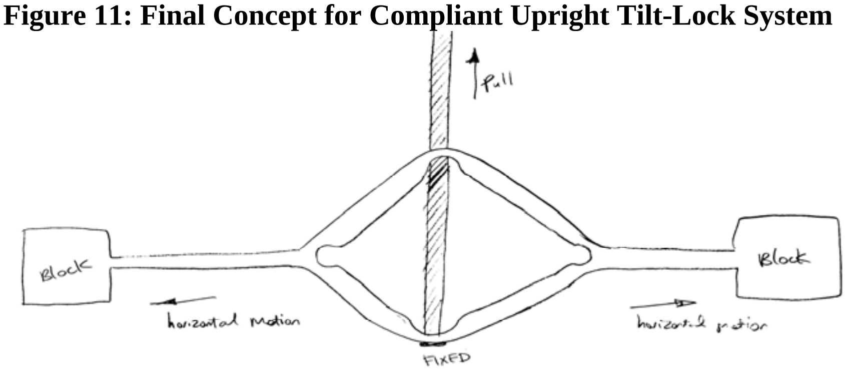


Figure 11 shows the final design for the compliant upright tilt lock system. This final design will work by compressing the middle of the mechanism with the cable actuator. The cable goes through the holes of the mechanism. The initial position of the mechanism is unlocked position, when the cable actuator is pulled the compliant mechanism will be compressed so that the link connected to the mechanism will be extended. This will displace the blocks on each side and lock the chair from reclining.

Figure 11: Final Concept for Compliant Upright Tilt-Lock System



ENGINEERING DESIGN PARAMETER ANALYSIS

Compliant Synchronized Recline Mechanism Parameter Analysis

Determination of Dimensions and Materials of SLFP Segments and Rigid Links: Using ADAMS software, we built the original model and compliant model as shown in Figure C1 and C2 in Appendix C. To determine the dimensions of the SLFP segments, based on the theory of solid mechanics and compliant mechanisms, we computed the bending and tension stress using

$$\sigma_{bending} = \frac{E\theta h}{2l} \qquad \text{Eqn(1)}$$

$$\sigma_{tension} = \frac{F}{hd} \qquad \text{Eqn(2)}$$

where E is young's modulus of the selected material, θ is angular motion range, h and l is the thickness and length of SLFP segment, F is the applied force, d is the width of SLFP segment.

To compute the energy required to be stored on SLFP segments, we calculated the energy stored on the torsion bars in the current chair with an assumption that the behavior of torsion bars is the same as a linear spring. The following equations were used to calculate the spring constant k.

$$y_{\max} = \frac{Fl^3}{48EI} \qquad \text{Eqn(3)}$$

$$F = ky_{\max} \qquad \text{Eqn(4)}$$

where y_{max} is the maximum deflection of each end of the torsion bars, F is the applied force transferred to the center of the torsion bars, E is the young's modulus of steel, I is the second moment of area, l is the length of the torsion bars. From equation (3) and (4), k was determined to be following:

$$k = \frac{48EI}{l^3} \qquad \text{Eqn(5)}$$

Then, the energy stored on the torsion bars, E_{bars}, was determined by:

$$E_{bars} = \frac{1}{2}ky_{\max}{}^2 = \frac{24EIy_{\max}{}^2}{l^3} \qquad \text{Eqn(6)}$$

Based on the theorem of compliant mechanism, the energy stored by the SLFP segments, E_{SLFP}, is determined by:

$$E_{SLFP} = \sum_{i=4}^{4}\frac{1}{2}\frac{EI_i}{l_i}\theta_i{}^2 \qquad \text{Eqn(7)}$$

We constraint that the energy stored on the torsion bars equals to that on the SLFP segments and the safety factor is to be two. Then, based on material properties, such as yield strength and Young's modulus, the width, thickness, and length of the SLFP segments were determined from using Equations 1,2, and 7 above. We ran the same calculations using different materials, shown in Table 3 on page 13, to find a feasible material for the compliant design. The only material that can be used for our design is E-glass. Microsoft Excel Solver ™ was used to calculate all the dimensions of SLFP segments with the given constraints. The constraints are as follows

1. The total energy stored on the SLFP segments should be equal to that on the torsion bars.
2. The length of the SLFP segments should be no longer than 20% of the adjacent rigid bars.

3. The thickness of each SLFP segment should be no more than 10% of the thickness of rigid links

The determined dimensions of SLFP segments using E-glass are shown in Table 2 below.

Table 2: Determined SLFP Segments Dimensions

SLFP dimensions	Length (m)	Thickness (m)	Width (m)	Length Ratio (Rigid bar to SLFP)	Safety Factor
Segment 1(pivot 1)	0.020	0.002	0.025	3.80	2.09
Segment 2(pivot 2)	0.015	0.002	0.025	6.67	2.08
Segment 3(pivot 3)	0.020	0.003	0.025	6.55	3.90
Segment 4(pivot 4)	0.024	0.003	0.025	5.46	2.29

The thickness and width of the rigid links were determined based on the current chair dimensions, but the length of the rigid links changed because of the length and orientation of the SLFP segments. Although the rigid link lengths were changed, the motion of the compliant mechanism is the same as that of four-bar linkage on the current chair because the pivots of the four-bar linkage remained at the same locations, which is the midpoint of SLFP segment. The material for the rigid links was chosen to be Aluminum 7075 since manufacturing rigid links using E-glass is more expensive than the manufacturing cost for the current four-bar linkages. Aluminum 7075 has relatively low density and high machining performance, and it is relatively cheaper than other Aluminum alloys. The disadvantage of manufacturing our design using two different pieces is that we cannot reduce 17 parts, as previously expected. We still managed to reduce nine parts by replacing the four-bar linkage with our design.

Based on the application and the function of the compliant system, materials for SLFP segments were chosen to maximize both flexibility and stiffness. According to the theory of compliant mechanism, one criterion for us to choose the material for SLFP segments was to maximize the strength-to-modulus ratio. The material with the highest strength-to-modulus ratio allows a larger deflection before failure. Since a large load (human body weight) needs to be supported while the compliant mechanism is functioning, the material for the design needs to be strong enough to support the large force. Materials with high yield strength were considered and are listed in Table 3 with their material properties and the strength-to-modulus ratio.

Table 3: Ratio of yield strength to Young's Modulus of materials for SLFP

Material	E (GPa)	Sy(MPa)	(Sy/E)×1000
steel (4140Q&T@400	207	1641	7.9
aluminum (7075 heat treated)	71.4	503	7
Titanium (Ti-13 heat treated)	114	1170	10
Beryllium copper (CA170)	128	1170	9.2
Kevlar (82vol%) in epoxy	86	1517	18
E-glass (73.3vol%) in epoxy	56	1640	29

Determination of Orientations of SLFP Segments: To apply SLFP segments, it is crucial that every SLFP segments remain in tension during the entire motion. This implies that the segments will have to be oriented in the same direction as the force acting on each of them. Therefore, we determined the joint segment orientation through the use of force analysis of the compliant mechanism.

The preliminary orientations of the four SLFP segments are determined by building the pseudo-rigid-body model from ADAMS. The SLFP segments are simulated by the combination of pin joints and torsion springs. The stiffness constants of torsion springs are determined by the maximum rotation angle of each segment, the dimensions, and the material properties determined above. With assumptions that a total gravity force with the magnitude of 444 N acting on the middle of the seat pan (rigid bar in the model) and the static motion to run the model , the forces acting on each joints are conducted from the software as shown in Figure D1 to D8 in Appendix D.

Based on the static analysis from ADAMS, we were able to determine angles of the orientation of each SLFP segment shown in Table 4.

Table 4: Force Analysis and Optimized Orientation of SLFP

	Initial Force			Final Force			Optimized
	F_x (N)	F_y (N)	Angle (◦)	F_x (N)	F_y (N)	Angle (◦)	orientation
SLFP1	-274.80	-164.00	30.83	-445.60	-336.50	37.06	33.95
SLFP2	-340.40	153.70	24.30	595.00	283.40	25.47	24.89
SLFP3	345.90	-287.70	140.25	600.60	-158.10	165.25	152.75
SLFP4	-345.90	288.50	140.25	-600.60	158.90	165.25	152.75

Compliant Upright Tilt Lock System Parameter Analysis

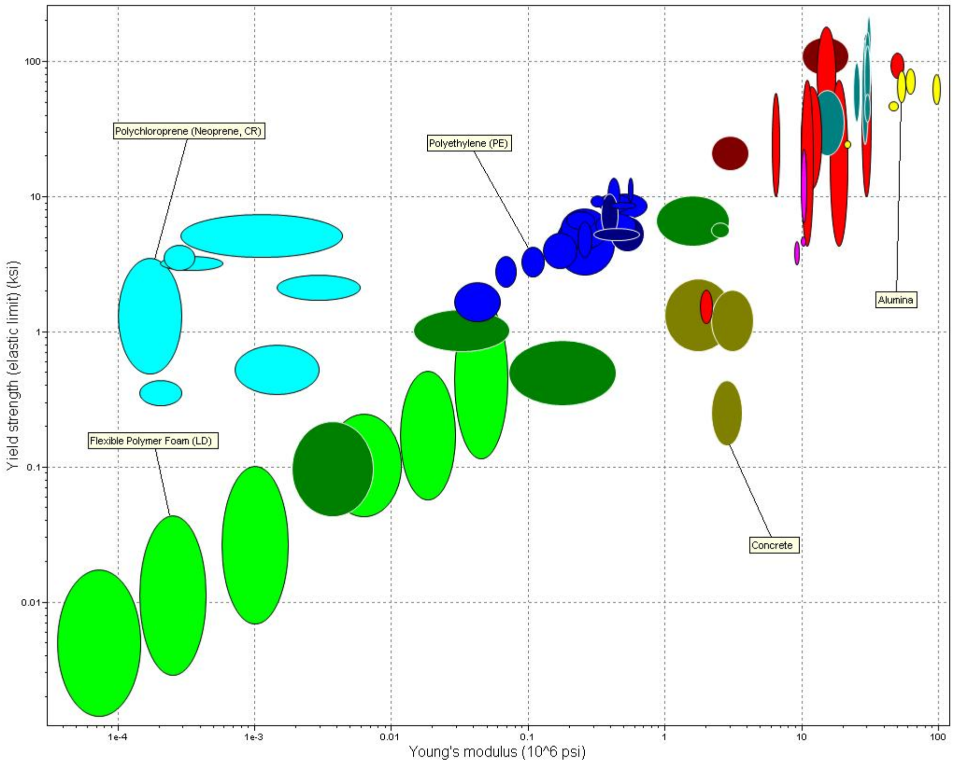
Determination of dimensions and materials: Before we determined the dimensions and shape of the locking compliant mechanism, the dimensional constraints were decided based on the available space of the current chair. The width and the height should be less than 50 mm and 75mm, respectively. At the final position of the mechanism, the movement of each side tip has to be 12 mm to properly function as a lock system. The possible shape of the locking compliant mechanism was a circular or a diamond shape. Since the compliant mechanism should have flexure joints, a diamond shape was chosen as our locking mechanism shape: there are four flexure joints at each side for the diamond shape, which will make the lock mechanism have two positions (unlock and lock). Compliant mechanism stores energy inside the mechanism, but we have to reduce the stored energy as small as possible because the human force required to operate the current locking mechanism is less than 10N. Thus, the thickness of the body should be the smallest without any failures when functioning as a lock system. The thickness of flexure joints should be less than that of body to generate bending motion on the flexure joints. Based on the constraints, we designed the locking compliant mechanism using Pro-Engineering and simulated it using AnSys to test whether there are any failures and if the deformation of the body is acceptable.

Based on Table 5 on page 15, we determined that the upright tilt lock system should be made with Polyethylene. The reason for this is three fold. First, it has a very high ratio of strength to modulus. Second, it is readily available, inexpensive, easy to process, and has a low density. Third, it is also very ductile. This makes it well suited for living hinges because the material must undergo large strains for millions of cycles.

Table 5: Ratio of yield strength to Young's modulus of materials for Lock System

Material	E (Gpa)	Sy(Mpa)	(Sy/E) ×1000
Polyethylene(HDPE)	1.4	28	20
Nylon (Type66)	2.8	55	20
Polyethylene	1.4	34	25

Figure 12: CES Selector Result for Material Using for Compliant Lock System



Finite Element Analysis Using ANSYS

Stress Analysis for Compliant Synchronized Recline Mechanism: Figures 13 and 14 show the deformation analysis and the stress analysis, respectively.

Figure 13: Deformation analysis for the final design of the Compliant Synchronized Recline Mechanism shows that the final design meets the displacement requirement in the seat pan area (an upward displacement of approximately 15 mm).

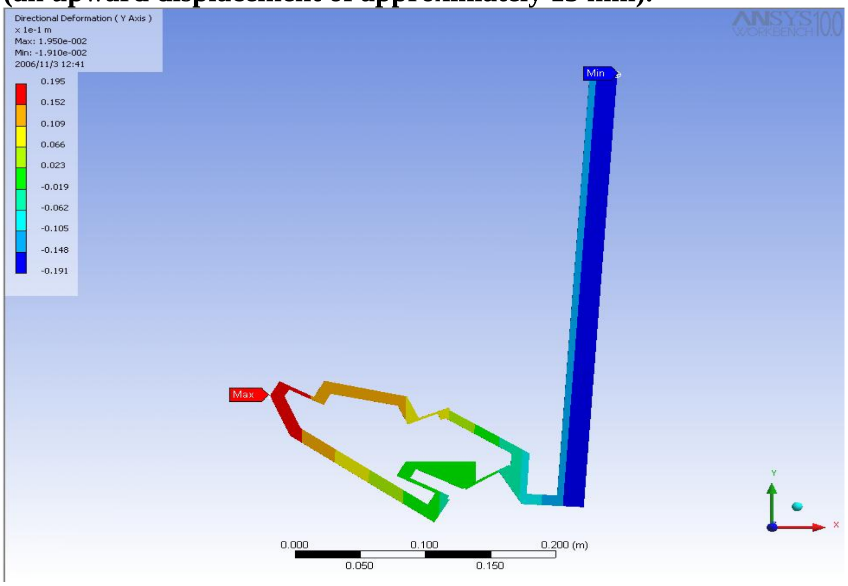
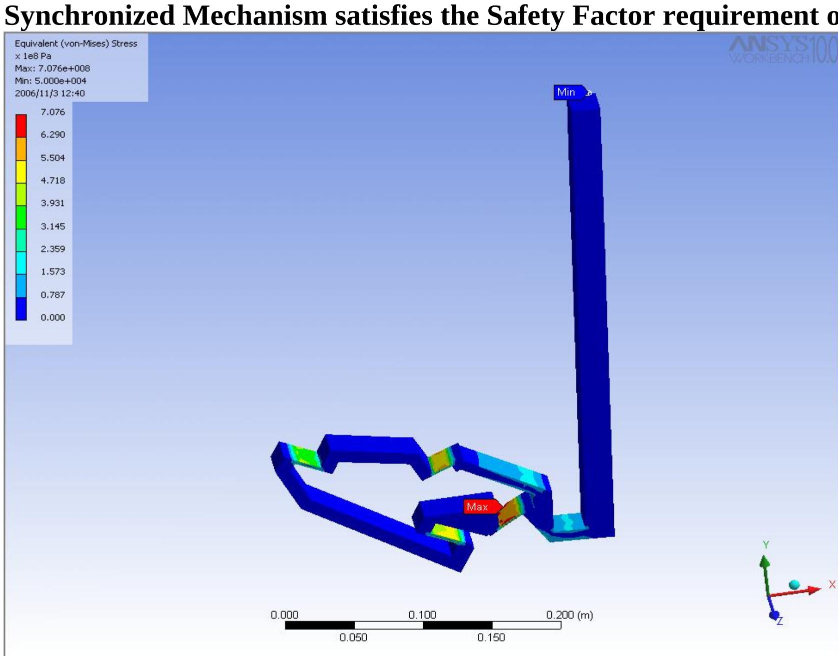


Figure 14: Stress Simulation shows maximum stress experienced on the Compliant Synchronized Mechanism satisfies the Safety Factor requirement of the design.



Stress Analysis for Compliant Upright Tilt Lock system: Figures15 and 16 show the deformation analysis and the stress analysis, respectively.

Figure 15: Deformation analysis for the final design of the Compliant Upright-tilt Lock Mechanism shows that the final design meets the displacement requirement for Each Side to Lock the Chair (a horizontal displacement of approximately 7 mm)

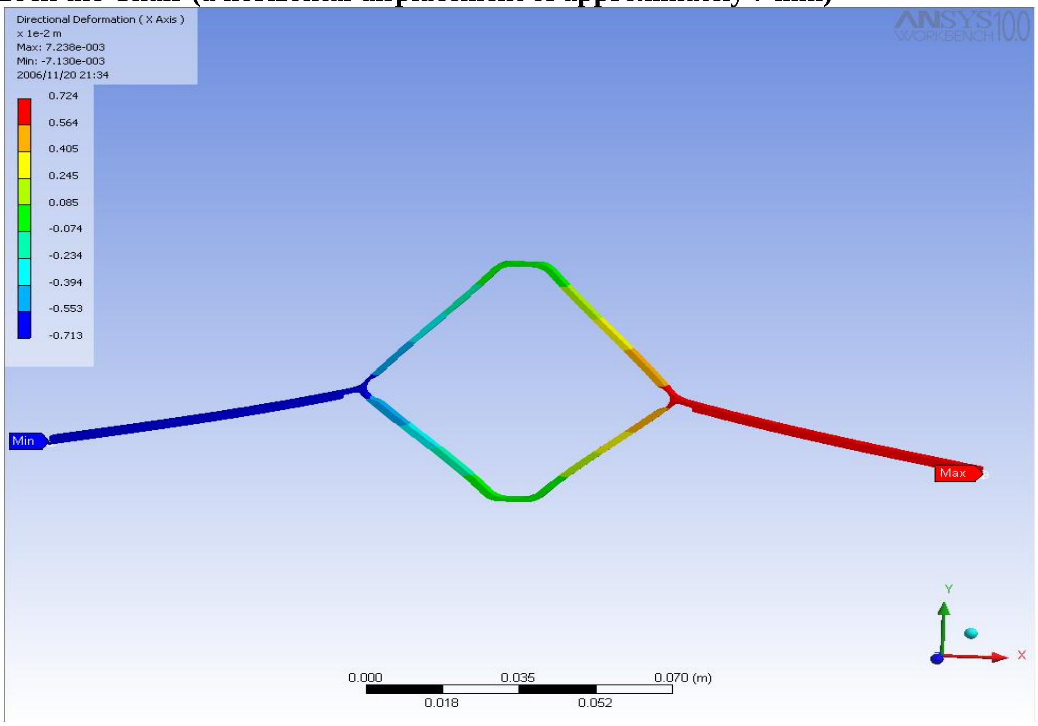
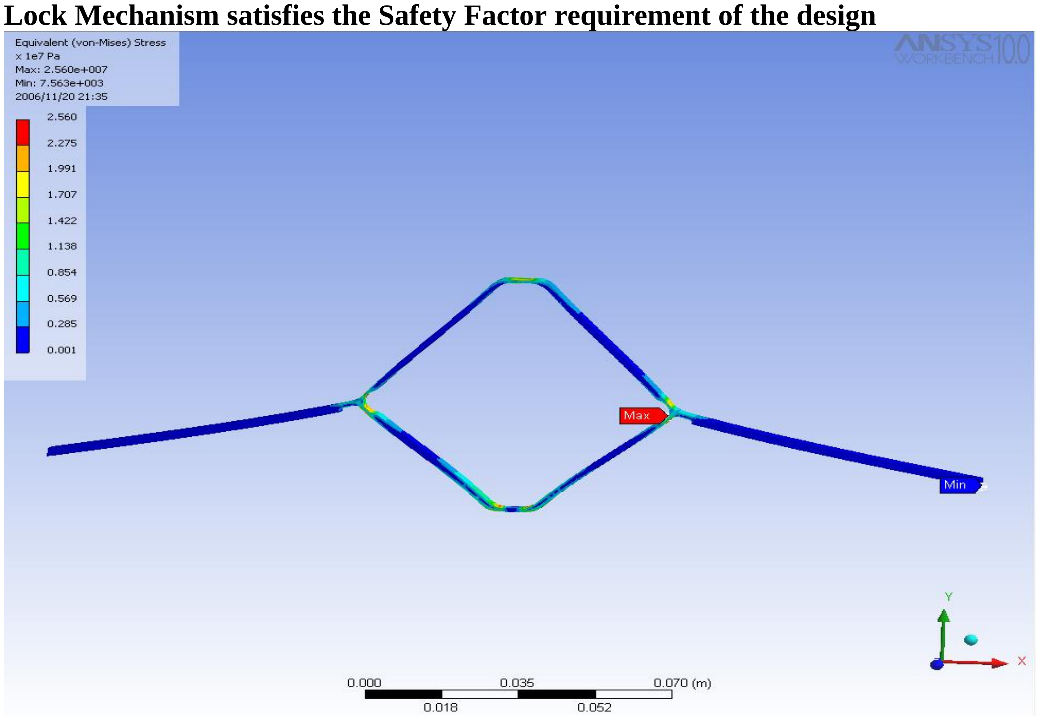
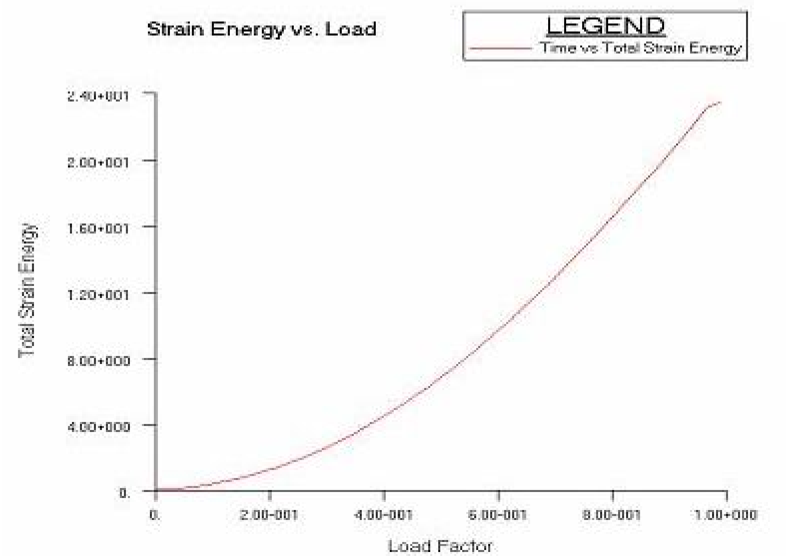


Figure 16: **Stress Simulation shows maximum stress experienced on the Compliant Upright-tilt Lock Mechanism satisfies the Safety Factor requirement of the design**



Buckling Analysis for SLFP Segments of the Compliant Synchronized Recline Mechanism
We had a buckling test done on our synchronized compliant mechanism to make sure that the SLFP segments remained in tension. If there is any compression in the SLFP segments, they will buckle so we performed this test to validate that our design is correct and all the segments were in tension. The resulting graph can be seen in Figure 17. There is no buckling because strain energy increases up to the maximum load.

Figure 17: Buckling Test for Synchronized Recline Mechanism



FINAL DESIGN DESCRIPTION

Prototype Description

Compliant Synchronized Recline Mechanism: There will be two prototypes built for the complaint synchronized recline mechanism. The first one will be a one-piece aluminum prototype and the second one will have e-glass SLFPs with aluminum rigid bars. These two will be the same size as the current four-bar recline mechanism. The positions of the joints of the synchronized recline mechanism will also be the same as the current four-bar recline mechanism. The main difference between the prototype and the final design is the prototype only has planar forces and motions while the final design should be designed for integration onto the existing chair. While the input force for the final design and our prototypes will have different orientations in space, the output displacements should be the same. This is because the motion of the current four-bar mechanism is planar and since the prototype is planar the motion can be replicated.

Another difference between the prototype and the final design is in manufacturing. The aluminum with E-Glass SLFPs prototype will have the E-glass bolted onto the rigid aluminum links. In the final design, the E-Glass inserts should be press fitted in the aluminum links thus having one solid piece instead of multiple pieces. Although the manufacturing of the prototype will be with multiple pieces, if the final design is manufactured then it should be a one-piece compliant mechanism. This will reduce the number of parts needed for the office chair and thus reduce the costs associated with the chair.

The entirely aluminum prototype will be used to demonstrate a one-piece compliant mechanism. Although it may not be fully-functional as the other prototype, its purpose is to display that the motion of the system is still maintained with only one piece. The drawbacks with this prototype are that the output displacement will not be as large as the other prototype and the SLFP segments have a smaller safety factor.

Upright Tilt-Lock Mechanism: The prototype of the upright tilt-lock mechanism will be manufactured by Robert Coury in the ME 450 Manufacturing Lab. The prototype will be a full-scale model and should be able to fit into the size constraints of the chair. The prototype will be made out of delrin and should displace the same amount as the final design.

There are two differences between the final design and the prototype of the upright tilt-lock mechanism. The first difference is that the prototype will not be shaped at the ends. The final design should have some sort of ball form at its ends. The difference is due to the difficulty of manufacturing rounding in 3D.

The other difference between the prototype and the final design is the placement of the cable actuator. In the prototype the cable comes from the bottom of the prototype and pulls on the top to compress it. In the final design, the cable actuator should push down on the top of the mechanism to cause an outward displacement by the ends.

Since the current locking mechanism is planar the prototype should be able to replicate the motions because it is also planar. The way the force is applied from the cable is arbitrary compared with the final results. As long as the prototype displaces its ends a certain amount then the way the force is applied should not matter. The prototype shows that given a specific force it will displace a certain amount regardless of how the force was applied. The unshaped ends on the prototype can also be disregarded because its only use is for displaying how the prototype works in comparison with the current locking mechanism.

FINAL DESIGN

Compliant Synchronized Recline Mechanism

Prototype Design: Based on our analysis and design synthesis, we developed a detailed prototype design for a compliant synchronized recline mechanism with E-glass small length flexural pivots. The major components of this design are shown in Table 6 on page 20. The complete bill of material for this design is shown in Table E1 of the Appendix E. As shown, our prototype design is composed of 2 different materials. The rigid main bodies' (1-4) material is Aluminum 2024 whereas the small length flexural pivots' (1-4) material is E-glass. The detailed assembly drawing and engineering drawing for the prototype are shown on the following pages.

In addition to the prototype described above, we manufactured a one piece prototype made completely of Al 2024 by water jet cutting using the same design as the E-glass prototype. This prototype was meant to demonstrate the idea of design for no-assembly for our application with limited reliability, safety, and functionality.

Table 6: Part list for Compliant Synchronized Recline Mechanism Prototype with E-glass SLFP

Part ID	Quantity	Part Description
P01	1	Al 2024 Rigid Main Body Component 1
P02	1	Al 2024 Rigid Main Body Component 2
P03	1	Al 2024 Rigid Main Body Component 3
P04	1	Al 2024 Rigid Main Body Component 4
P05	1	E-Glass SLFP Insert 1 - 2mm(thickness) x 25.4mm(width) x 41.13mm(length)
P06	1	E-Glass SLFP Insert 2 - 2mm(thickness) x 25.4mm(width) x 34.93mm(length)
P07	1	E-Glass SLFP Insert 3 - 3mm(thickness) x 25.4mm(width) x 40.00mm(length)
P08	1	E-Glass SLFP Insert 4 - 3mm(thickness) x 25.4mm(width) x 43.74mm(length)

Figure 18: 3-D Drawing of the Prototype Compliant Synchronized Recline Mechanism

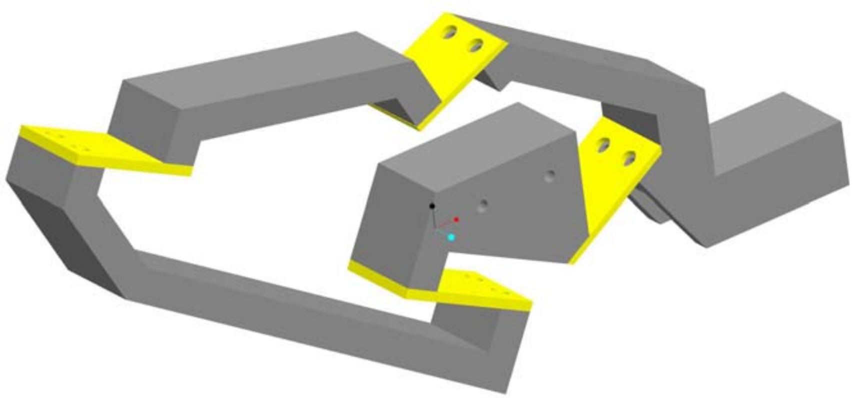


Figure 19: Exploded Assembly Drawing of Prototype Compliant Synchronized Recline

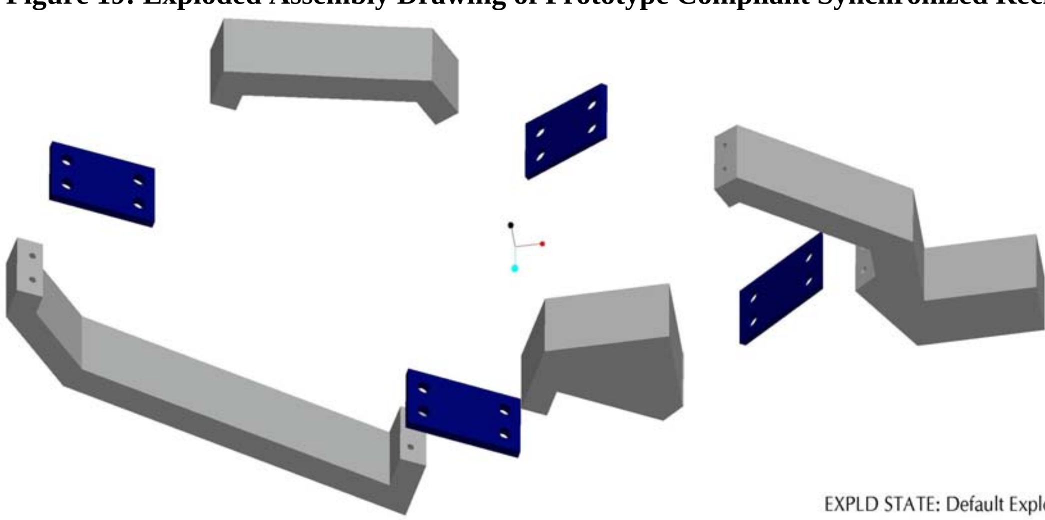


Figure 20: Synchronized Recline Mechanism Engineering Prototype Drawing

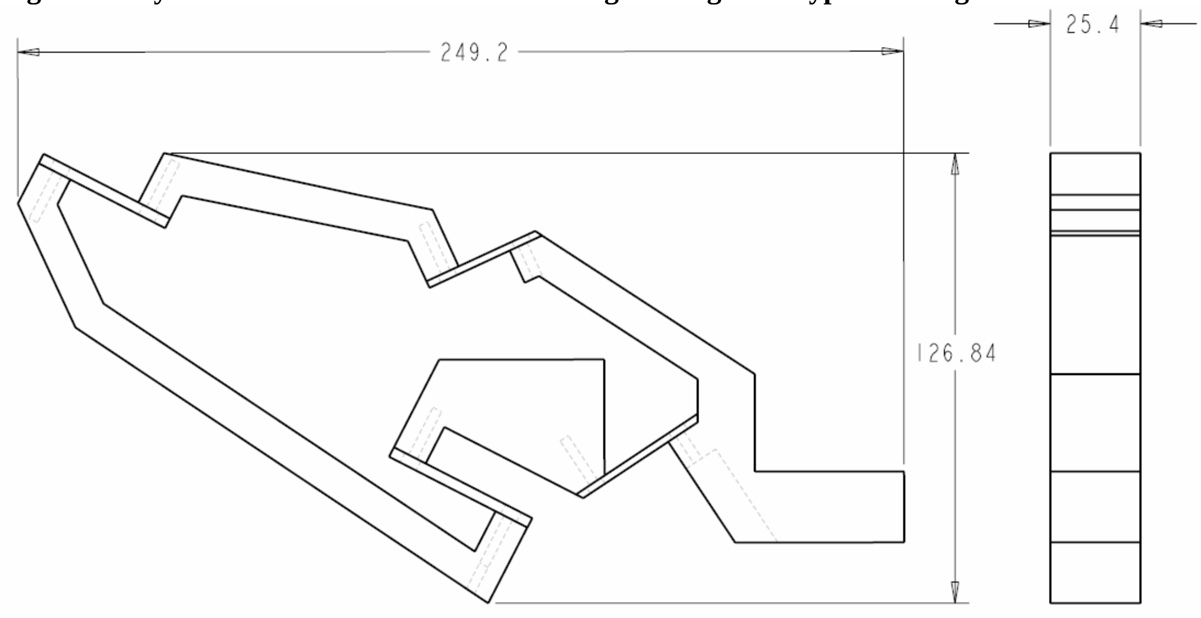


Figure 21: Al 2024 Rigid Main Body Prototype Manufacturing Component 1

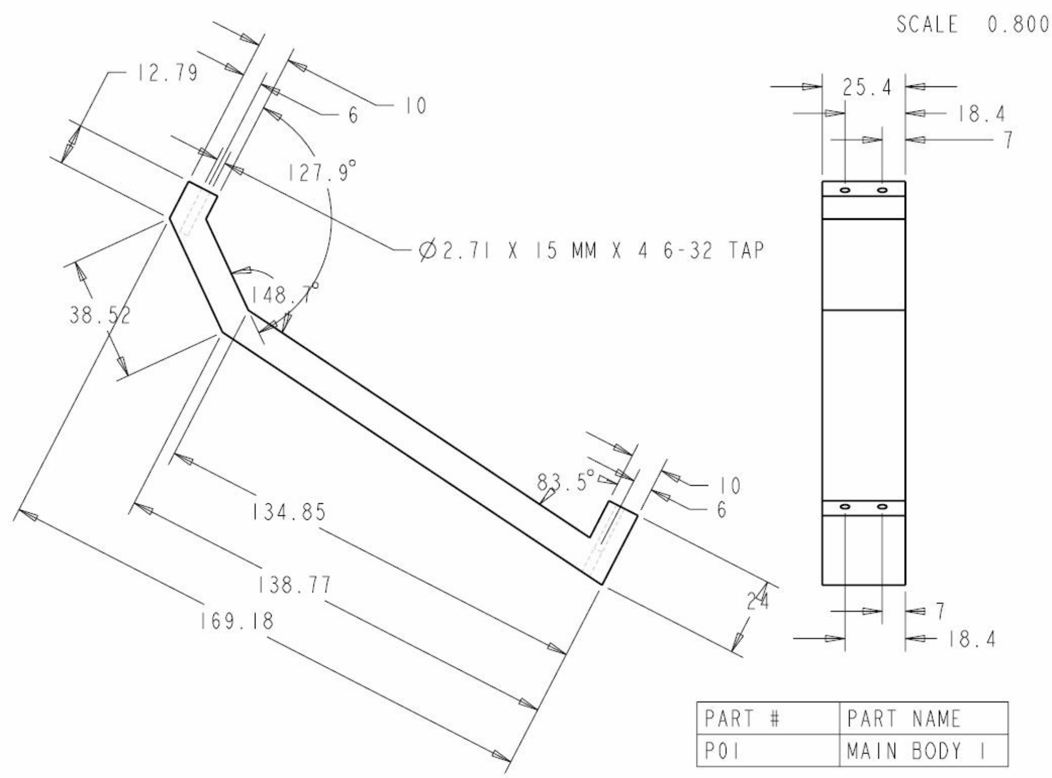
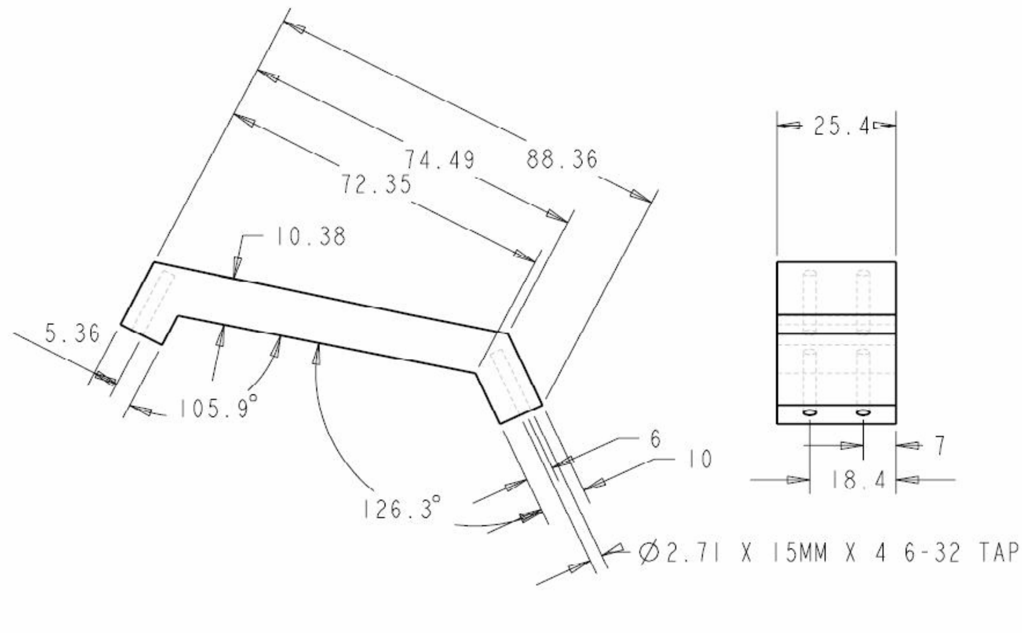
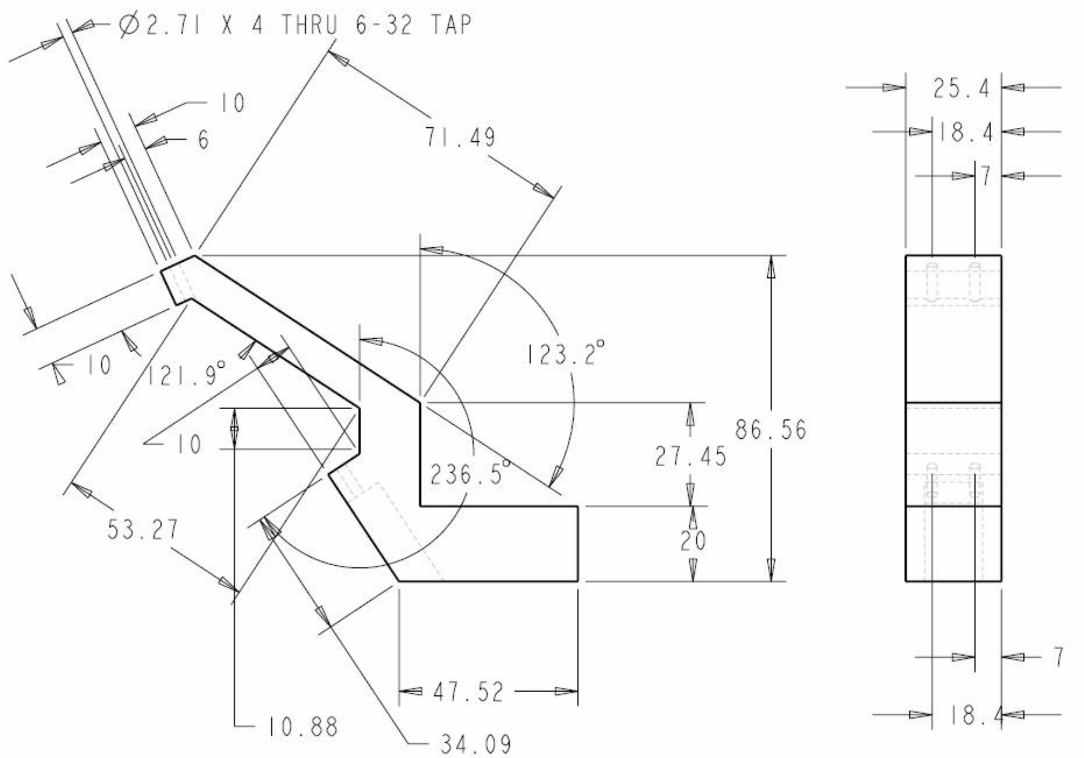


Figure 22: Al 2024 Rigid Main Body Full Scale Manufacturing Component 2



PART #	PART NAME
P02	MAIN BODY 2

Figure 23: Al 2024 Rigid Main Body Full Scale Manufacturing Component 3



PART	PART NAME
P03	MAIN BODY3

Figure 24: Al 2024 Rigid Main Body Full Scale Manufacturing Component 4

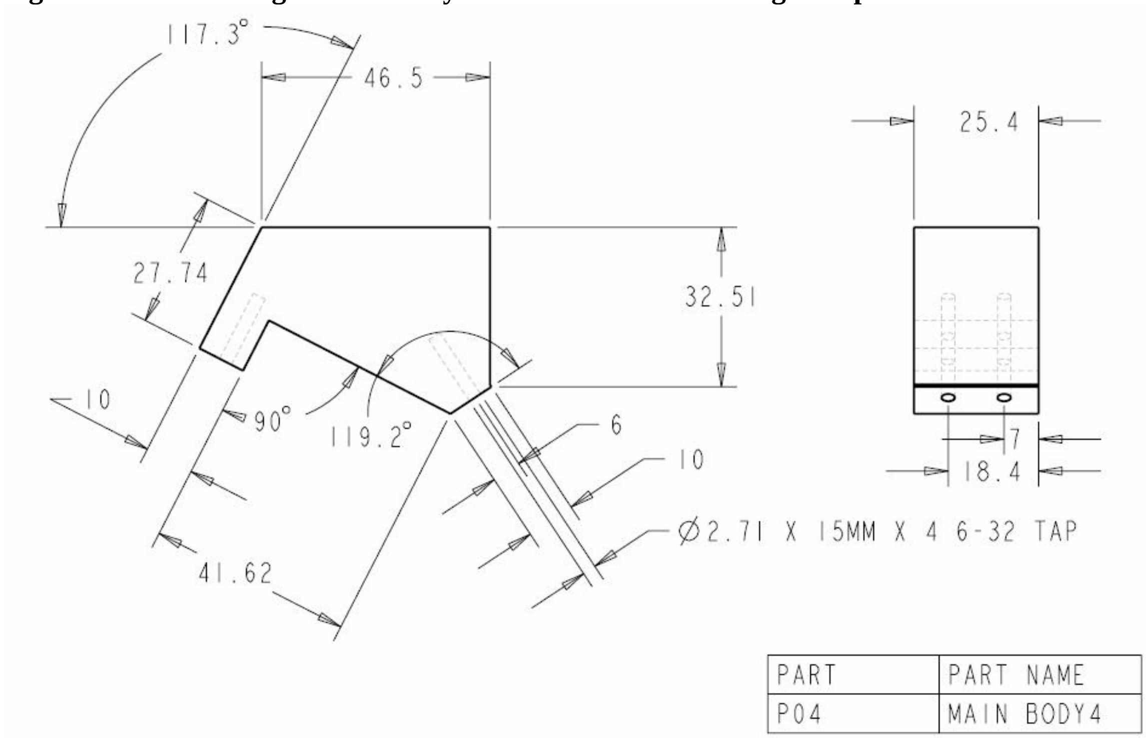


Figure 25: E-Glass SLFP Segment Insert 1

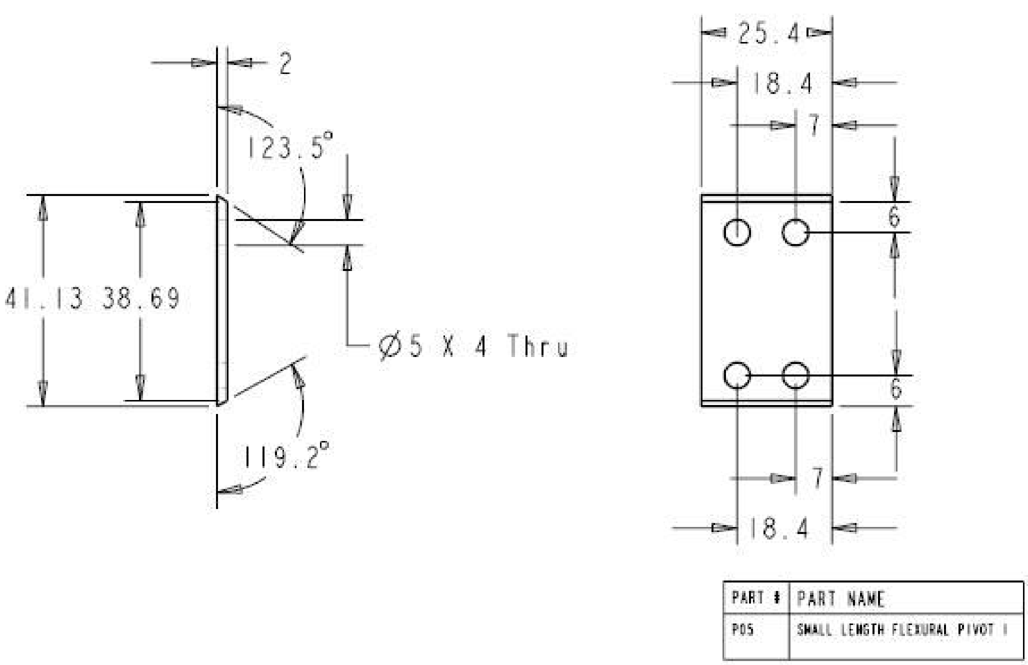


Figure 26: E-Glass SLFP Segment Insert 2

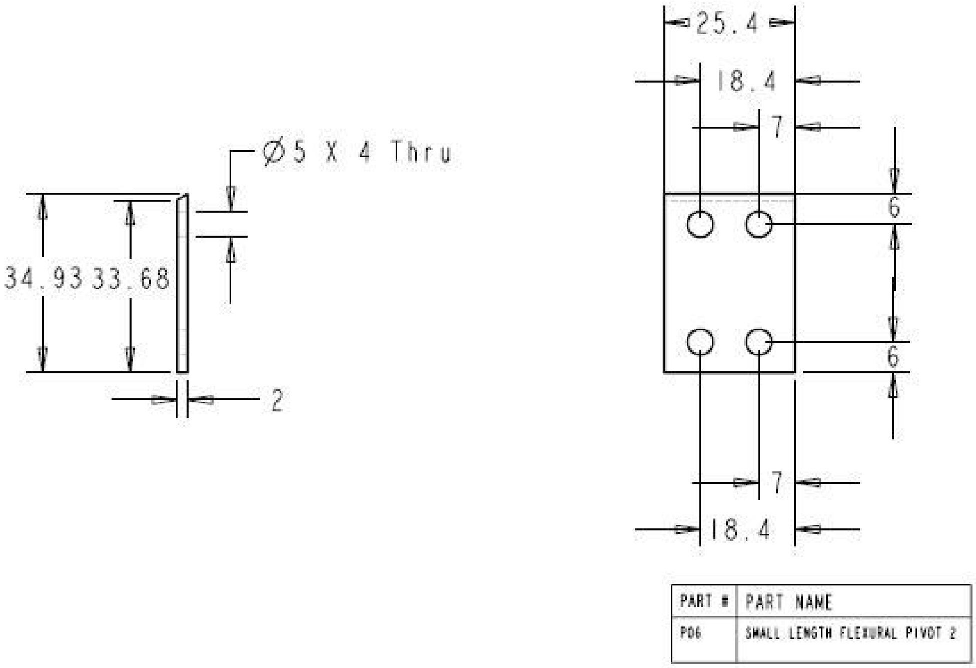


Figure 27: E-Glass SLFP Segment Insert 3

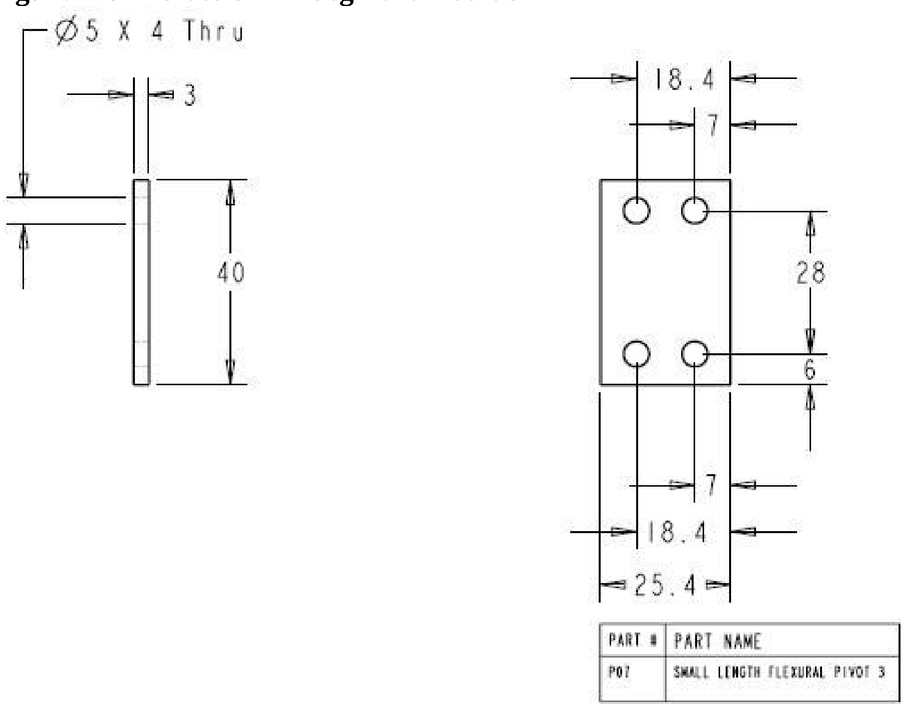
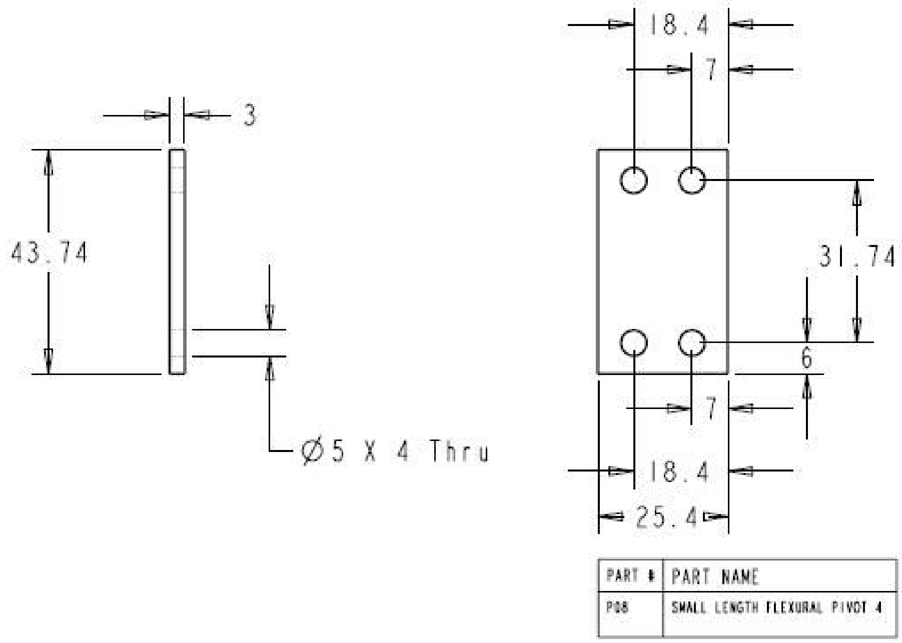


Figure 28: E-Glass SLFP Segment Insert 4



Full Scale Production Design: Based on our prototype design, we developed a variant of the complaint synchronized recline mechanism with E-glass small length flexural pivots that eliminates the need for the screws and nuts. This design variant added tight slots onto parts P01, P02, P03, and P04 that allow the E-glass SLFP inserts to be press fitted in during the assembly. The part list of the design is shown in Table 7 below and the detailed engineering drawings are shown in the following pages.

Table 7: Part list for Full Scale Production Design Variant of Compliant Synchronized Recline Mechanism with E-glass SLFP

Part ID	Quantity	Part Description
F01	1	Al 2024 Rigid Main Body Component 1
F02	1	Al 2024 Rigid Main Body Component 2
F03	1	Al 2024 Rigid Main Body Component 3
F04	1	Al 2024 Rigid Main Body Component 4
F05	1	E-Glass SLFP Insert 1 - 2mm(thickness) x 25.4mm(width) x 31.13mm(length)
F06	1	E-Glass SLFP Insert 2 - 2mm(thickness) x 25.4mm(width) x 24.93mm(length)
F07	1	E-Glass SLFP Insert 3 - 3mm(thickness) x 25.4mm(width) x 30.00mm(length)
F08	1	E-Glass SLFP Insert 4 - 3mm(thickness) x 25.4mm(width) x 33.74mm(length)

Figure 29: 3-D Drawing of the Full Scale Compliant Synchronized Recline Mechanism

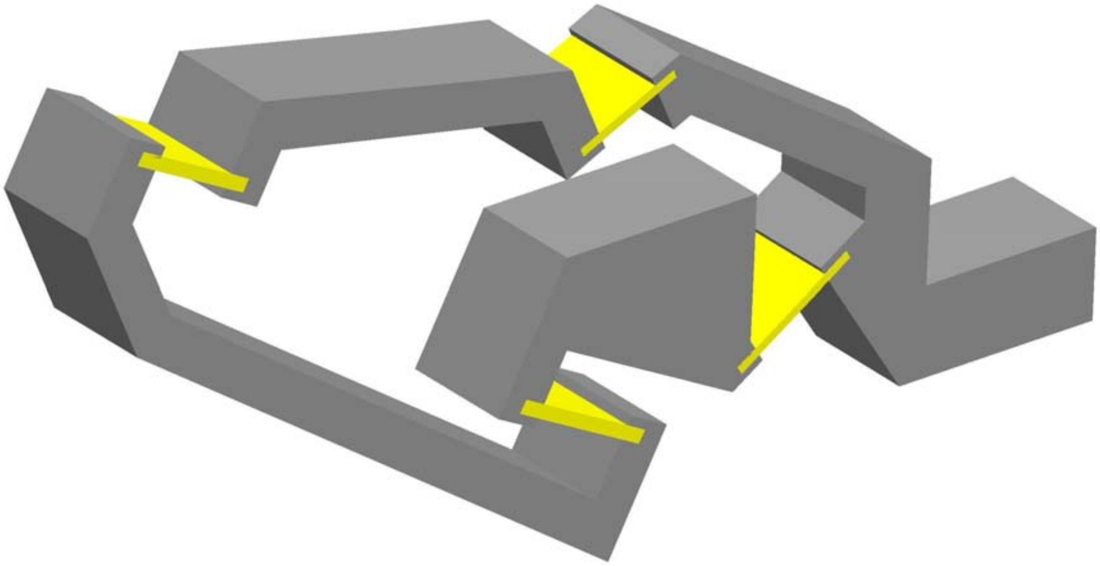


Figure 30: Exploded Assembly Drawing of Full Scale Compliant Synchronized Recline

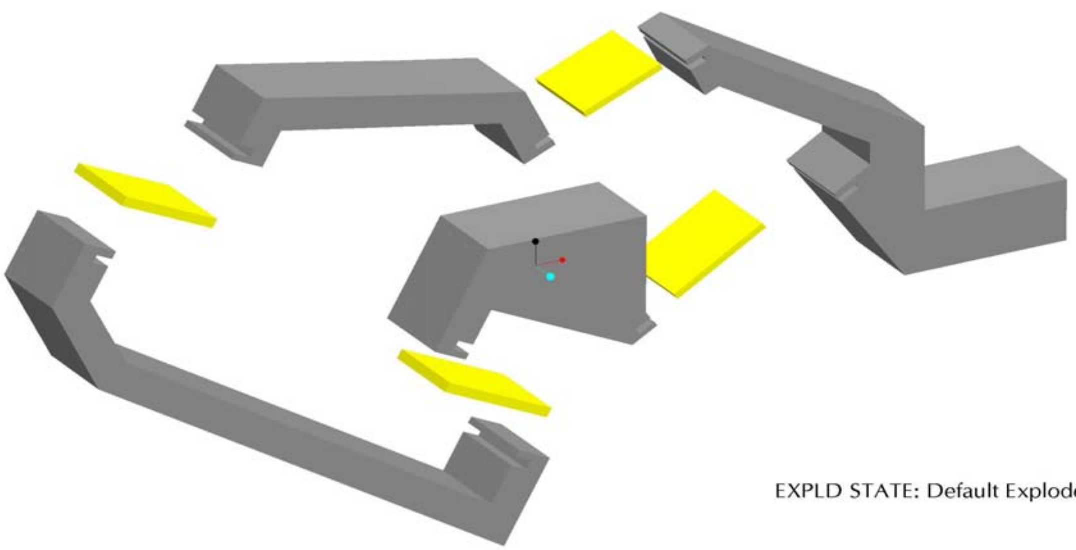


Figure 31: Al 2024 Rigid Main Body Full Scale Manufacturing Component 1

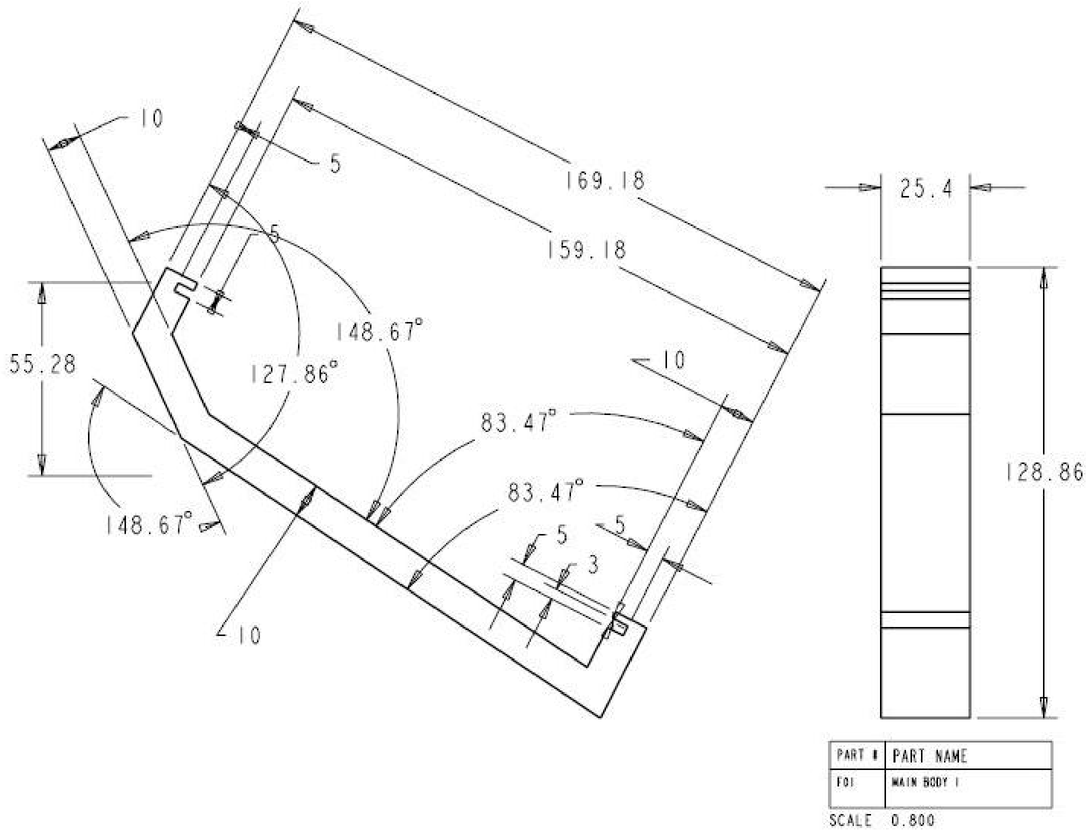


Figure 32: Al 2024 Rigid Main Body Full Scale Manufacturing Component 2

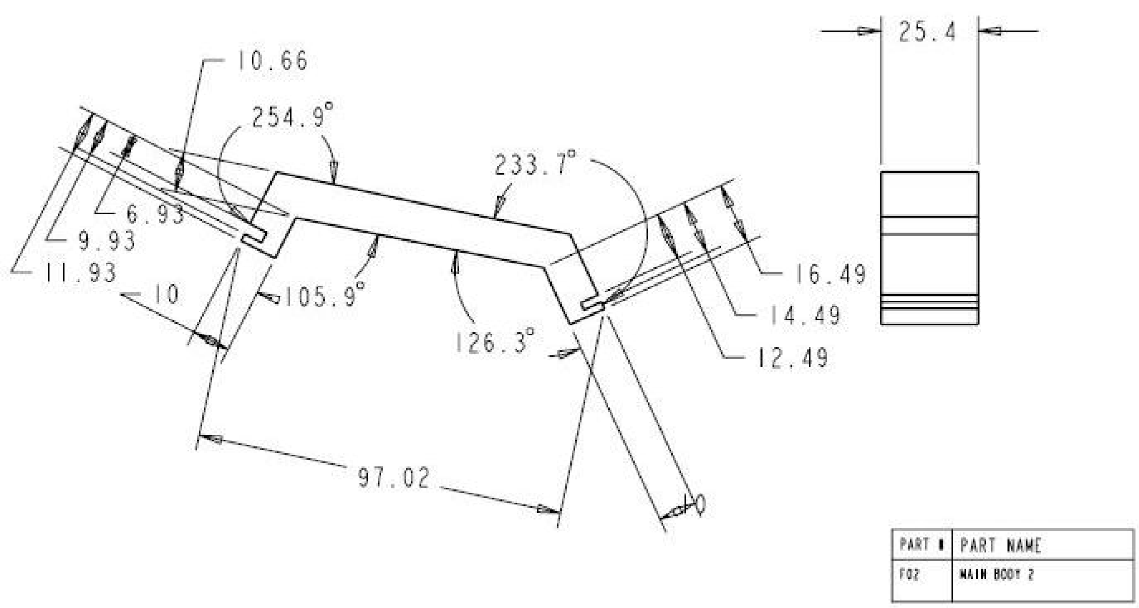


Figure 33: Al 2024 Rigid Main Body Full Scale Manufacturing Component 3

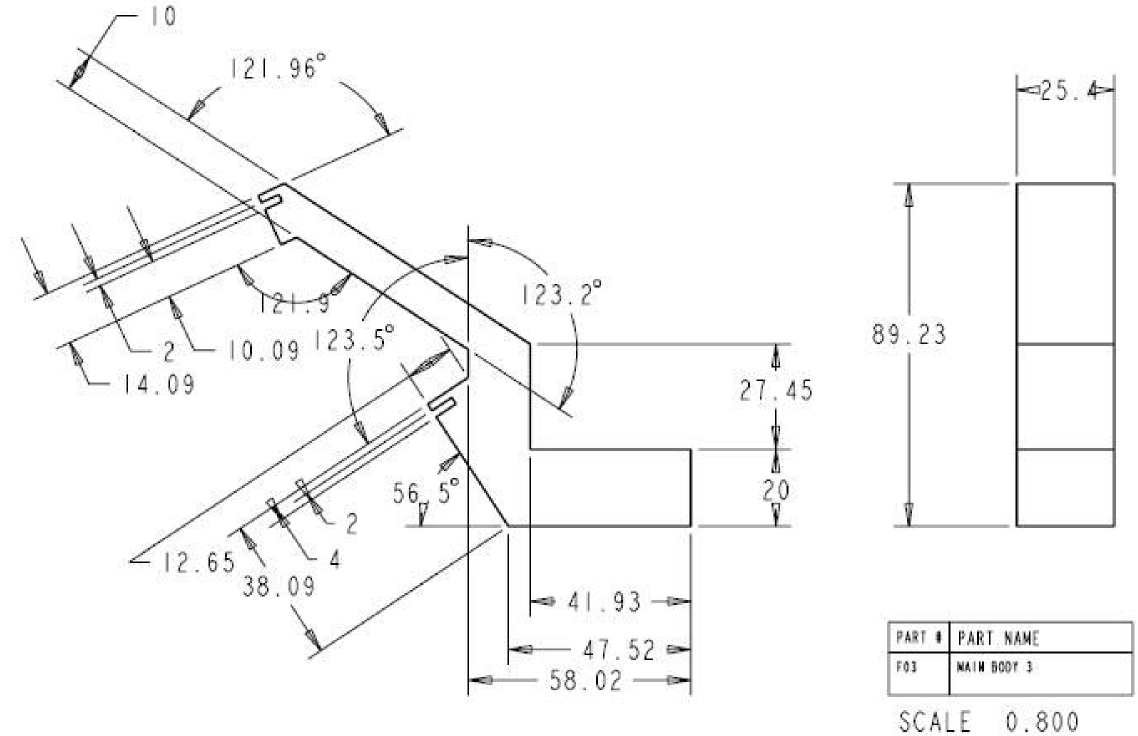


Figure 34: Al 2024 Rigid Main Body Full Scale Manufacturing Component 4

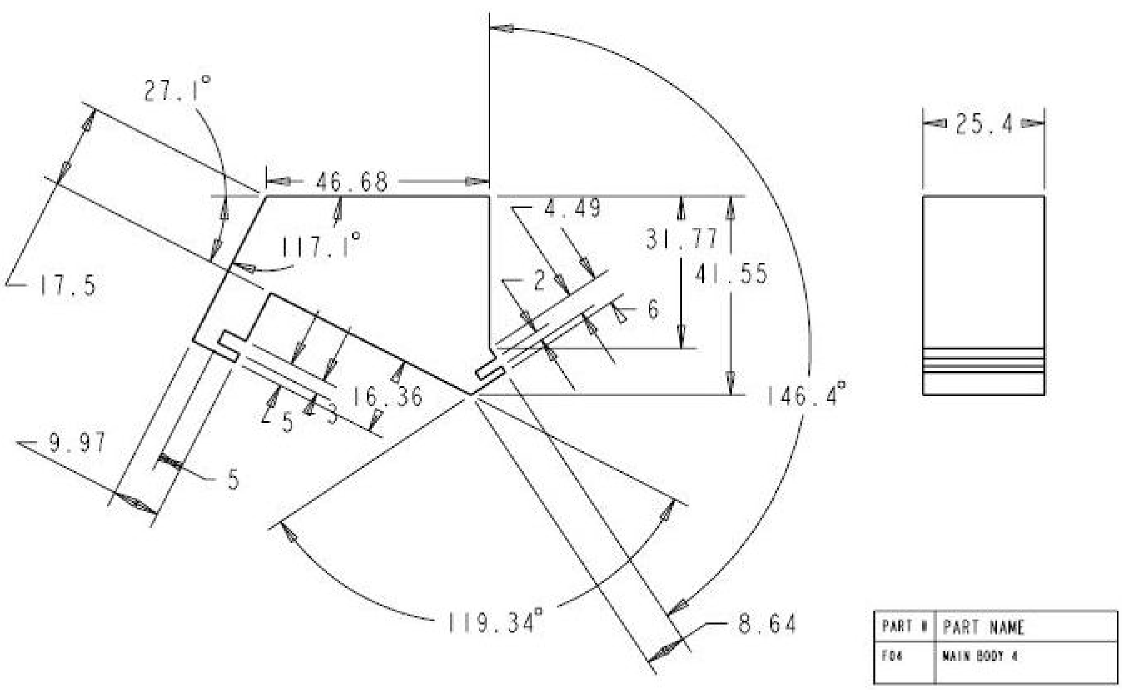
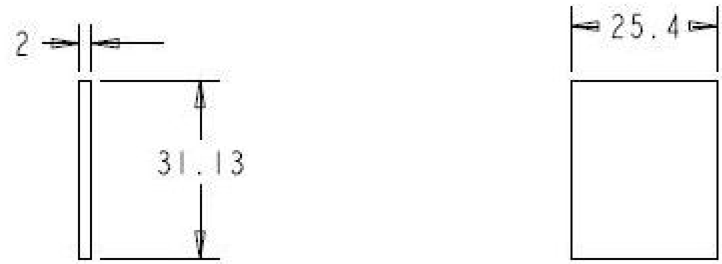
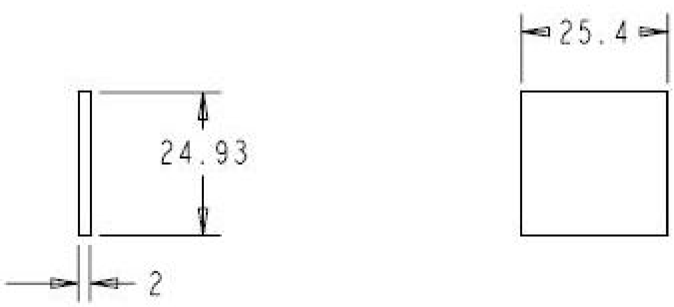


Figure 35: E-Glass SLFP Segment Full Scale Manufacturing Insert 1



PART #	PART NAME
F05	SMALL LENGTH FLEXURAL PIVOT 1

Figure 36: E-Glass SLFP Segment Full Scale Manufacturing Insert 2



PART #	PART NAME
F06	SMALL LENGTH FLEXURAL PIVOT 2

Figure 37: E-Glass SLFP Segment Full Scale Manufacturing Insert 3

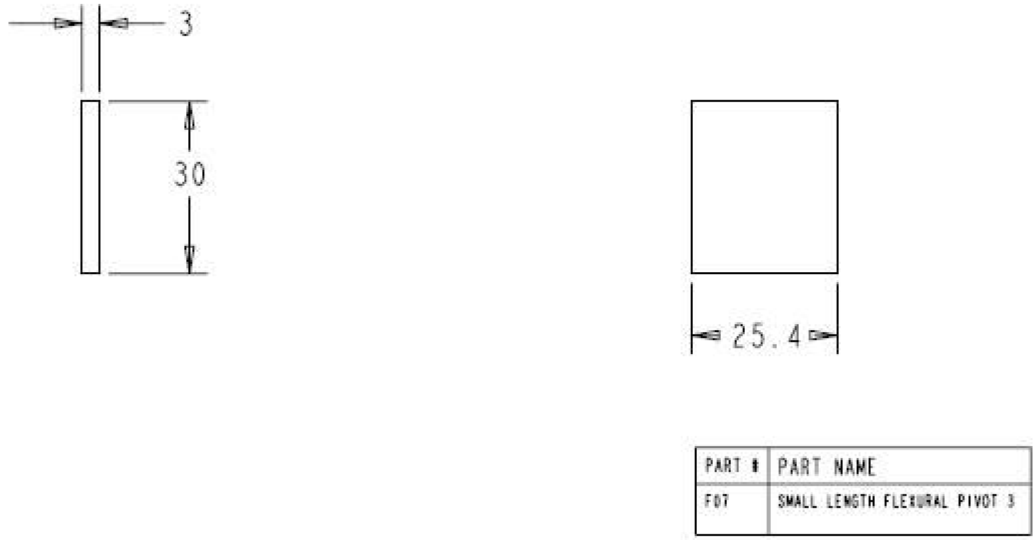
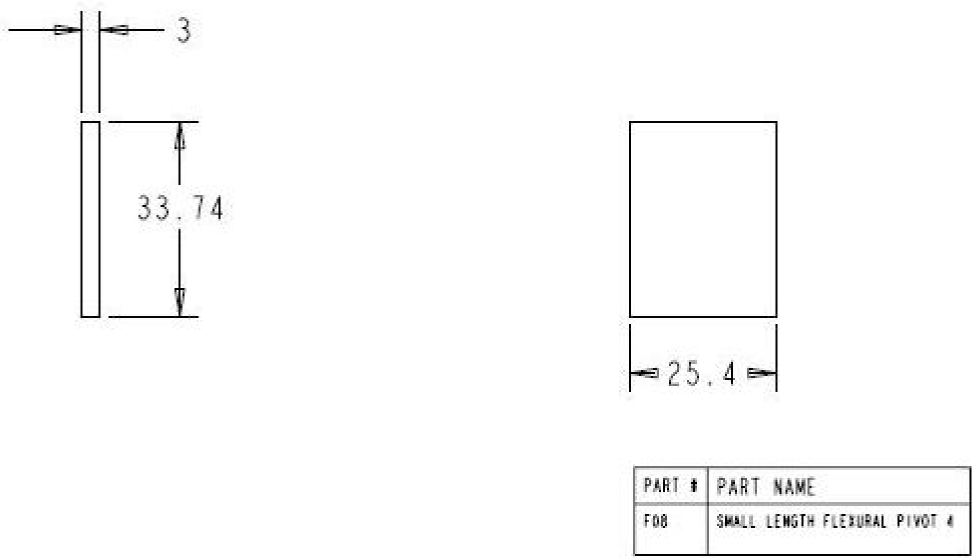


Figure 38: E-Glass SLFP Segment Full Scale Manufacturing Insert 4



Validation of Full-scale working Prototype: Our prototype will validate the general degree of rotational motion that the final design can achieve through physical testing. It will also validate the synchronized displacement level of the seat plan due to the rotation of the backrest. Finally, it will validate that the concept of applying compliant mechanism design in the synchronized recline mechanism of our current chair is feasible.

However since the prototype was not integrated onto the chair, we cannot be certain aside from the results of our FEA model that our final design will not fail in real use under the predicted maximum load. In addition, the reliability of the final design cannot be validated with the prototype.

Final Design Operation: The rigid main body component P04 of our final design is fixed to the base of the chair. When an input force is placed on the backrest of the chair, the backrest would rotate. As a result of this rotation, rigid main body part P03 would rotate correspondingly. This rotation is made possible by the small length flexural pivot component P05's deformation. As a result, the rigid main body part P02 pinned to the seat pan is displaced upward by the small length flexural pivot component P06's motion (induced by the motion of P03 that it is bonded to). The displacement of part P02 in turn forces rigid main body component P01 to rotate through both small length flexural pivot components P07 and P08. P07 is bonded on one end to P02 and on the other end bonded to P01. P08 is bonded on one end to P04 (fixed rigid main body component) and on the other end to P01. Hence as a result of the initial rotation of the backrest, the seat pan fixed to component P01 is displaced upward allowing for the desired synchronized motion.

Expected Level of Performance: We expect the prototype to be able to successfully achieve $\pm 16^{\circ}$ of rotational motion while achieving similar dynamic motion pattern as the current mechanism under various different loads without failing. We will test the prototype design through FEA simulation at different loads. In additional we will test the physical prototype to see the maximum achievable angle of rotation without yielding any of the E-glass components. These simulation and physical tests will ensure that our final design is accurate in meeting the functionality needs of our customer.

Compliant Upright Tilt Lock Mechanism

Prototype Design: Based on our analysis and design synthesis, we developed a detailed design for our compliant upright tilt lock mechanism. The design is composed of only 1 part whose material is high density polyethylene.

Deviation of Physical Prototype from Full Scale Design: Two full-scale working prototypes were made, one from HDPE and the other from Delrin. The HDPE working prototype was manufactured using laser cutter. As a result, the material was melted and the nominal material property of HDPE was altered. Thus, we made another working prototype from Delrin. Since there is a material property difference between Delrin and HDPE, the working prototype requires a larger input force to deform but offered improved energy storage.

Validation of Full-scale working prototype: We plan to validate the working prototype through FEA simulation and physical testing. In our FEA simulation we plan to apply a reasonable load that the current locking switch is capable of withstanding and determine the level of displacement at its ends. In our physical test, we plan to apply a reasonable load by hand through a metal cable attached to the working prototype to test for the level of displacement its ends.

Final Design Operation: Our final design will achieve displacement at its two ends which are attached to stopper blocks to lock the back-rest in place.

When the user attempts to lock the back-rest in the upright position, they will press down on the locking lever at the side of the chair. This lever with a bimodal spring inside will pull the cable connected to the upright tilt-lock mechanism in the forward direction compressing the compliant upright tilt-lock mechanism. As a result of this compression, our mechanism would change shape through its flexural joints and extend the two ends attached to the stopper blocks outward into slots. The locked position is maintained by a bimodal spring inside the lock lever.

When the lock lever is pull upward and released, the compression force on the upright tilt-lock mechanism will be released and the energy stored in the mechanism will return the mechanism to its original position.

Expected Level of Performance: The expected level of performance from a functionality point of view is quite high. Our final design should be able to achieve enough displacement at its ends to allow for the stopper blocks to fit into the slots with the reasonable amount of input force. However, there will be fatiguing issues as the material of the mechanism is a polymer. The fatigue life of the design maybe relatively low.

Figure 39: 3-D Drawing of the Compliant Upright Tilt-Lock Mechanism

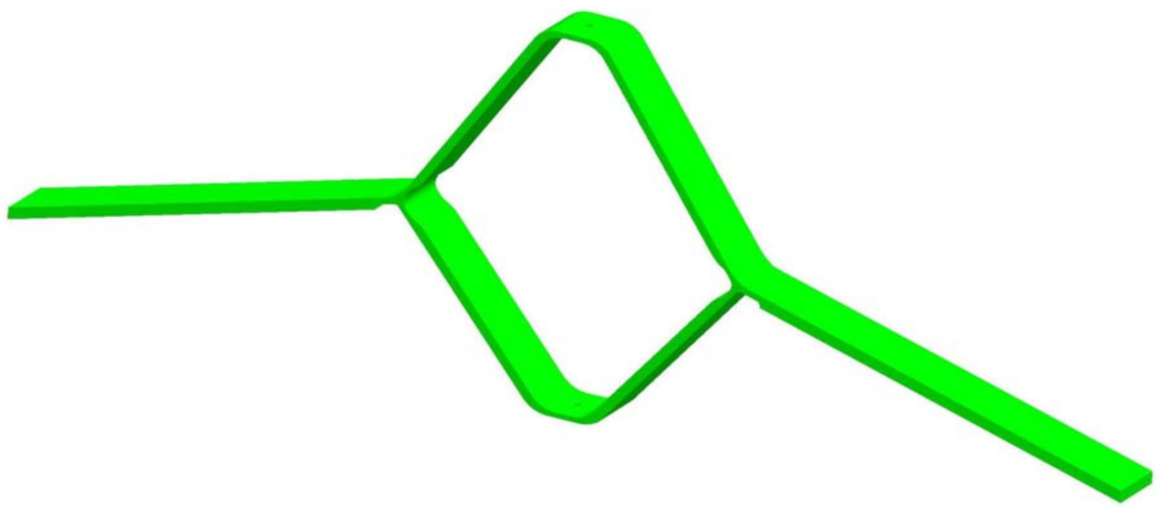
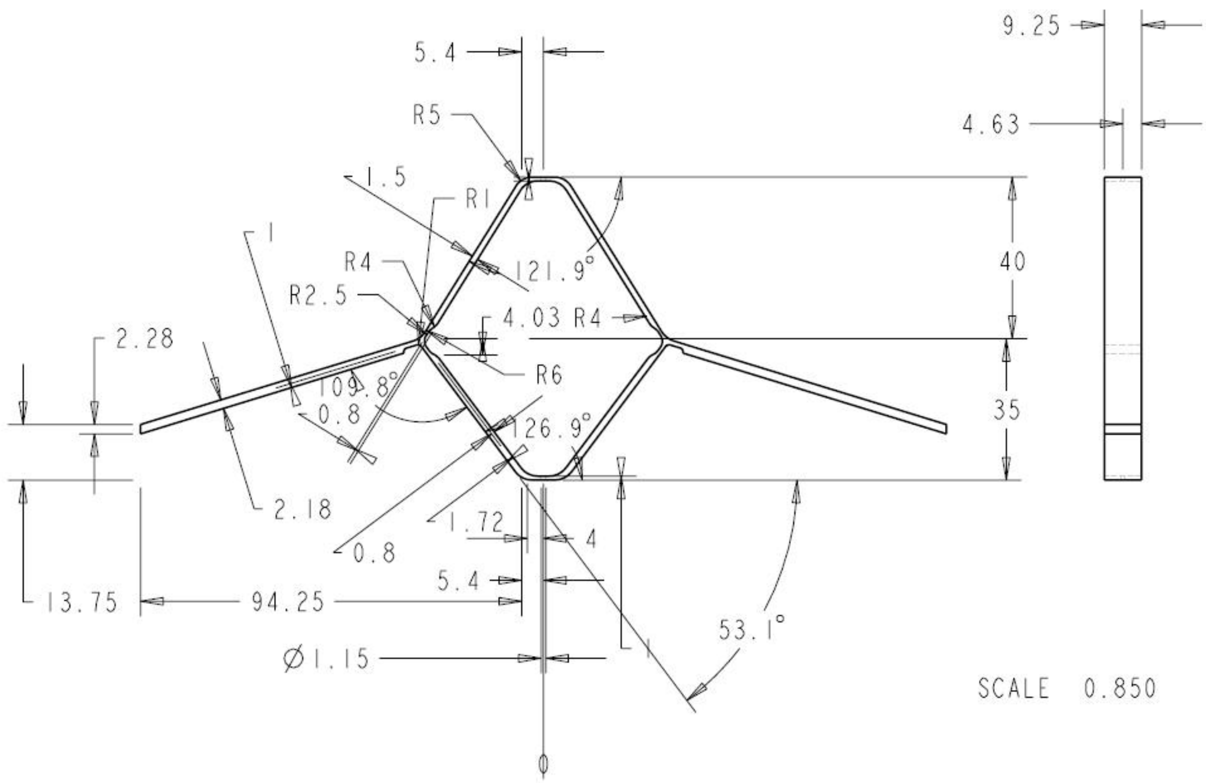


Figure 40: Engineering Drawing of the Compliant Upright Tilt-Lock Mechanism

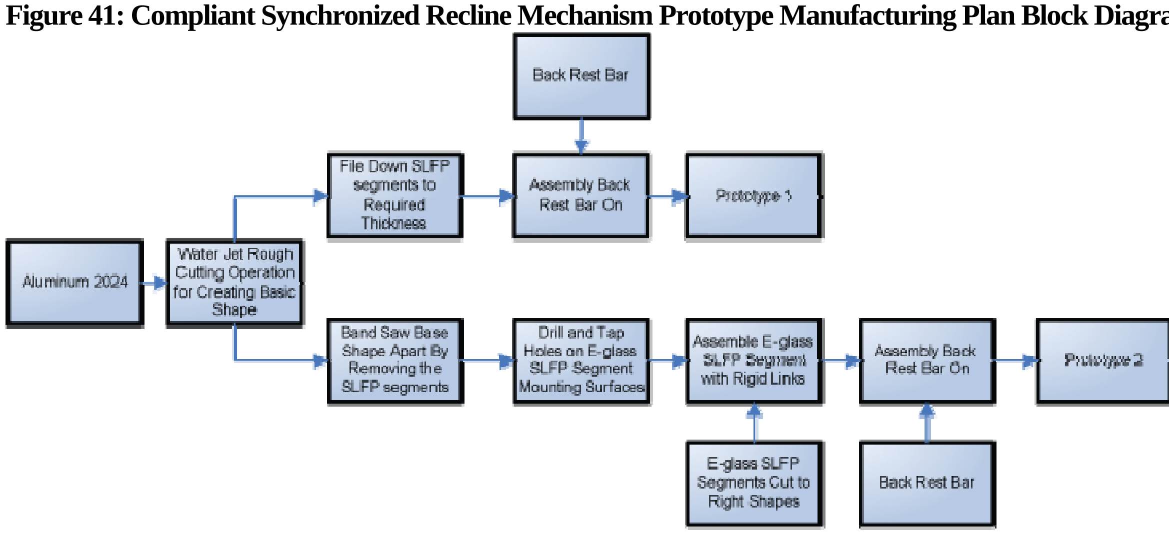


MANUFACTURING PLAN

Compliant Synchronized Recline Mechanism

Prototype Manufacturing Plan: Based on our prototype design, we developed a plan upon which our prototype was manufactured. The general process by which we manufactured our prototype is shown in the flow chart in the figure below.

Figure 41: Compliant Synchronized Recline Mechanism Prototype Manufacturing Plan Block Diagram



The detailed step by step manufacturing for our major components are shown in Table 8 below.

Table 8: Manufacturing Plan for Synchronized Recline Prototype with E-Glass

Part #	Part Name	Sequence #	Tool	Procedure
P01	Al 2024	1	Band Saw	Cut part out of the water jet cut base shape (300FPM)
	Rigid Main Body 1	2	Vise	Clamp part in vise on mill table with bonding surface 1 parallel to mill table
		3	3/8" End Mill	Mill bonding surface 1 to create machined surface (1400 RPM)
		4	#36 Drill Bit	Drill 0.217mm holes in design locations on bonding surface 1 to 15 mm depth (600 RPM)
		5	6-32 Tap	Tap holes
		6	Vise	Clamp part in vise on mill table with bonding surface 2 parallel to mill table
		7	3/8" End Mill	Mill bonding surface 2 to create machined surface (1400 RPM)
		8	#36 Drill Bit	Drill 0.217mm holes in design locations on bonding surface 2 to 15 mm depth (600 RPM)
		9	6-32 Tap	Tap holes
		10	Sand Paper	Sand part surface and clean up the part
P02	Al 2024	1	Band Saw	Cut part out of the water jet cut base shape (300FPM)
	Rigid Main Body 2	2	Vise	Clamp part in vise on mill table with bonding surface 1 parallel to mill table
		3	3/8" End Mill	Mill bonding surface 1 to create machined surface (1400 RPM)
		4	#36 Drill Bit	Drill 0.217mm holes in design locations on bonding surface 1 to 15 mm depth (600 RPM)
		5	6-32 Tap	Tap holes
		6	Vise	Clamp part in vise on mill table with bonding surface 2 parallel to mill table
		7	3/8" End Mill	Mill bonding surface 2 to create machined surface (1400 RPM)
		8	#36 Drill Bit	Drill 0.217mm holes in design locations on bonding surface 2 to 15 mm depth (600 RPM)
		9	6-32 Tap	Tap holes
		10	Sand Paper	Sand part surface and clean up the part
P03	Al 2024	1	Band Saw	Cut part out of the water jet cut base shape (300FPM)
	Rigid Main Body 3	2	Vise	Clamp part in vise on mill table with bonding surface 1 parallel to mill table
		3	3/8" End Mill	Mill bonding surface 1 to create machined surface (1400 RPM)
		4	#36 Drill Bit	Drill 0.217mm thru holes in design locations on bonding surface 1 (600 RPM)
		5	6-32 Tap	Tap holes
		6	Vise	Clamp part in vise on mill table with surface 3 parallel to mill table
		7	1/4" End Mill	Mill Intrusion as shown in design
		8	Vise	Clamp part in vise on mill table with surface 2 parallel to mill table
		9	#36 Drill Bit	Drill 0.217mm thru holes in design locations on surface 2 (600 RPM)
		10	6-32 Tap	Tap holes
		11	Sand Paper	Sand part surface and clean up the part
P04	Al 2024	1	Band Saw	Cut part out of the water jet cut base shape (300FPM)
	Rigid Main Body 4	2	Vise	Clamp part in vise on mill table with bonding surface 1 parallel to mill table
		3	3/8" End Mill	Mill bonding surface 1 to create machined surface (1400 RPM)
		4	#36 Drill Bit	Drill 0.217mm holes in design locations on bonding surface 1 to 15 mm depth (600 RPM)
		5	6-32 Tap	Tap holes
		6	Vise	Clamp part in vise on mill table with bonding surface 2 parallel to mill table
		7	3/8" End Mill	Mill bonding surface 2 to create machined surface (1400 RPM)
		8	#36 Drill Bit	Drill 0.217mm holes in design locations on bonding surface 2 to 15 mm depth (600 RPM)
		9	6-32 Tap	Tap holes
		10	Sand Paper	Sand part surface and clean up the part
P05	E-glass SLFP 1	1	Band Saw	Cut to general length and width as marked on E-glass sheet
		2	Mill	Create squared edges and mill to 25.4mm X 41.13mm
		3	E Drill	Drill 1/4" thru holes at design locations X 4
P06	E-glass SLFP 2	1	Band Saw	Cut to general length and width as marked on E-glass sheet
		2	Mill	Create squared edges and mill to 25.4mm X 34.93mm
		3	E Drill	Drill 1/4" thru holes at design locations X 4
P07	E-glass SLFP 3	1	Band Saw	Cut to general length and width as marked on E-glass sheet
		2	Mill	Create squared edges and mill to 25.4mm X 40mm
		3	E Drill	Drill 1/4" thru holes at design locations X 4
P08	E-glass SLFP 4	1	Band Saw	Cut to general length and width as marked on E-glass sheet
		2	Mill	Create squared edges and mill to 25.4mm X 43.74mm
		3	E Drill	Drill 1/4" thru holes at design locations X 4

We then assembled the final prototype together using the following procedure.

Table 9: Assembly of Synchronized Recline Prototype with E-Glass

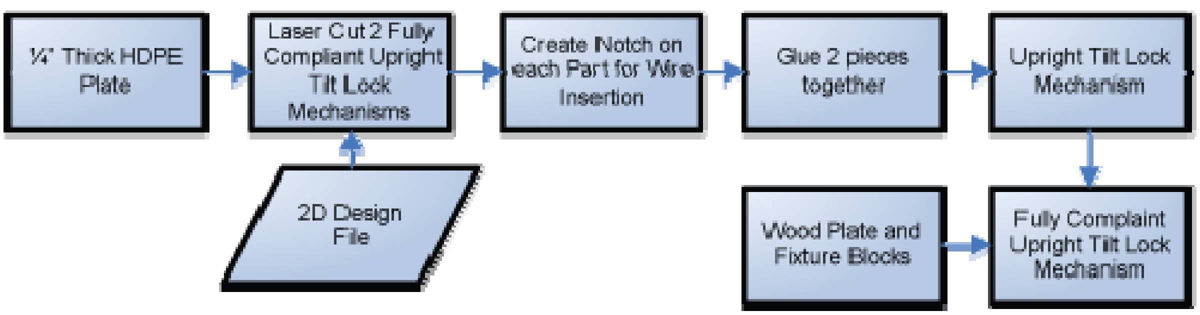
Sequence #	Tool	Procedure
1	Philip Screw Driver	Place 2 washers between 2 6-32 x 3/4" round head screws and P07 and screw P07 onto P02
2	Philip Screw Driver	Place 2 washers between 2 6-32 x 3/4" round head screws and P07 and screw P07 onto P01
3	Philip Screw Driver	Place 2 washers between 2 6-32 x 3/4" round head screws and P06 and screw P06 onto P02
4	Philip Screw Driver	Place 2 washers between 2 6-32 x 3/4" round head screws and P06 and screw P06 onto P03
5	Philip Screw Driver	Place 2 washers between 2 6-32 x 1" round head screws and P03 and screw P05 onto P03, add nuts
6	Philip Screw Driver	Place 2 washers between 2 6-32 x 3/4" round head screws and P08 and screw P08 onto P04
7	Plier	Place 2 washers between 2 6-32 x 3/8" hexagonal head screws and P08 and screw P08 to P01
8	Philip Screw Driver	Place 2 washers between 2 6-32 x 3/4" round head screws and P05 and screw P05 onto P04, close mechanism

Full Scale Production Manufacturing Plan: In our prototype design, we used screws extensive to bond the E-glass SLFP inserts to the rigid main body components which is not feasible in terms of cost for the full scale production. As a result, we developed design variant for full-scale production that eliminated the needs of screws and nuts through the addition of slots for the E-glass inserts. For full-scale production, the 4 rigid aluminum components F01 to F04 would be die-cast using a single die. Additional holes should then be drilled on the components for integration with the chair. The 4 E-glass SLFP's would be stamped out of Prepreg E-glass sheets with a capable stamping press that can make clean cuts through fiber glass. To assemble the E-glass and rigid main components together, the rigid components must first be frozen to widen the tight slot. Afterward, the E-glass should be press fitted into the slots at their corresponding locations and as the metal components warm up, they would expand and tighten the slots. This would embed the E-glass inserts in the rigid main body components forming the final design. The required assembly time for our mechanism is relatively short.

Compliant Upright Tilt Lock Mechanism

We developed 2 physical prototypes for our complaint upright tilt lock mechanism. The first one we made was from HDPE plates. The manufacturing processes used to develop this prototype is shown below.

Figure 42: Compliant Upright Tilt-Lock Mechanism Prototype Manufacturing Plan Block Diagram



Due to the poor surface finish on our first prototype, we manufactured another prototype using CNC Mill with the help of Mr. Bob Coury. The material of this prototype was not the HDPE that our design was based on as it was made from Delrin.

TEST RESULTS

We validated our designs by manufacturing prototypes that had the same concepts and ideas. The prototypes were tested by applying enough force to allow for a full range of motion. After testing our prototypes we can validate that our final designs will work. We also used Ansys for finite element analysis to conduct simulations with varying forces on our designs. The only disadvantage of using Ansys is that we used a linear model instead of a non-linear model so if the input was doubled, the output would be doubled too.

Compliant Synchronized Recline Mechanism

Upon completing the manufacturing of both the one-piece aluminum prototype and the two-piece aluminum/E-glass prototype we fastened it onto the display boards and conducted tests on them. By applying a horizontal force on the back-rest we were able to cause an elastic deformation on the prototypes. The one-piece aluminum prototype had a vertical displacement of 0.5 cm given a range of five degrees on the back-rest. The other prototype with E-Glass SLFP segments had a vertical displacement of 1.2 cm given ±12 degrees of motion.

Using AnSys for finite element analysis, the one-piece aluminum prototype had a vertical displacement of 4.45 mm given a force of 67.5 N on the back-rest and 150 N on the seat pan. If a greater force was applied, the design would fail due to plastic deformation. The E-Glass prototype had a vertical displacement of 1.52 cm with a horizontal force of 180 N and a vertical force of 400 N on the seat pan. Since E-Glass has different material properties (Young's Modulus, Yield Strength) we can apply greater loads on the E-Glass model without worry about failure. The results from FEA and the prototypes can be seen in Table 10 below.

Table 10: Comparison of the Results from Real and Virtual Compliant Recline Prototype

Type	SLFP Material	Range of Motion (degrees)	Horizontal Force (N)	Vertical Force (N)	Displacement (cm)	Von Mises (MPa)	Yield Strength (GPa)
FEA	Aluminum	-	67.5	150	0.445	273	0.28
Prototype	Aluminum	5	-	-	0.5	-	0.28
FEA	E-Glass	-	67.5	150	0.57	265	1.6
FEA	E-Glass	-	180	400	1.52	770	1.6
Prototype	E-Glass	12	-	-	1.25	-	1.6

The discrepancies of the results are due to many factors such as uneven thicknesses for the SLFP segments on both prototypes, the force applied to the backrest is approximate, and losses due to friction. The SLFP segments were filed down in the one-piece aluminum prototype because the current dimensions could not be manufactured with water-jet cutting. This may have lead to uneven SLFP segments because filing is very rough and inaccurate. For the E-Glass SLFP segments the thicknesses were all the same because we only had one E-Glass Prepreg sheet. We had used different thicknesses in the finite element analysis with our final design. Another factor that contributed to the discrepancies was the measurement of forces. Since there is not an accurate way to measure forces in real life, we cannot precisely determine the force that we applied to the back-rest/lever. The different forces will cause some variations in the results. Finally, the E-Glass SLFPs were screwed onto the rigid links in the prototype so some losses due to friction can occur since the SLFPs were not precisely positioned.

Upright Tilt-Lock Mechanism

After the upright tilt-lock mechanism was completed, tests were done to determine how effective the design is. Compressing the middle of the prototype to a significant extent, the resulting displacement from the ends of the system was 0.7 cm in each direction. From finite element analysis, AnSys simulated a displacement of 0.657 cm in each direction given a 10 N force. The results can be seen in Table 11.

Table 11: Comparison of the Results from Real Virtual Compliant Lock System Prototype

Type	Material	Compressive Force (N)	Displacement (cm)	Von Mises (MPa)	Yield Strength (Mpa)
FEA	Delrin	10	0.657	51.26	60
Prototype	Delrin	-	0.7	-	60

The discrepancies in results could be due to the approximate forces applied to the prototype. Since a certain force can not be accurately applied on an object, any change in the force will result in a different displacement for the prototype. Another factor that could have caused the discrepancies is frictional losses. Since the prototype is lying on the display board, the friction forces generated by the prototype rubbing against the wooden board can cause the displacements to be smaller than it actually is.

DESIGN CRITIQUE

Synchronized Recline Compliant Mechanism

The strength of the final design is lowering the manufacturing cost by discarding nine parts from the current four-bar linkage mechanism. An additional strength is solving the problem of the complicated assembly process of the torsion bars. This was done by using the compliant mechanism to store the energy required to bring the chair into its upright position. The strengths of our design are summarized in the Table 12 below.

Table 12: Strengths of Final Design

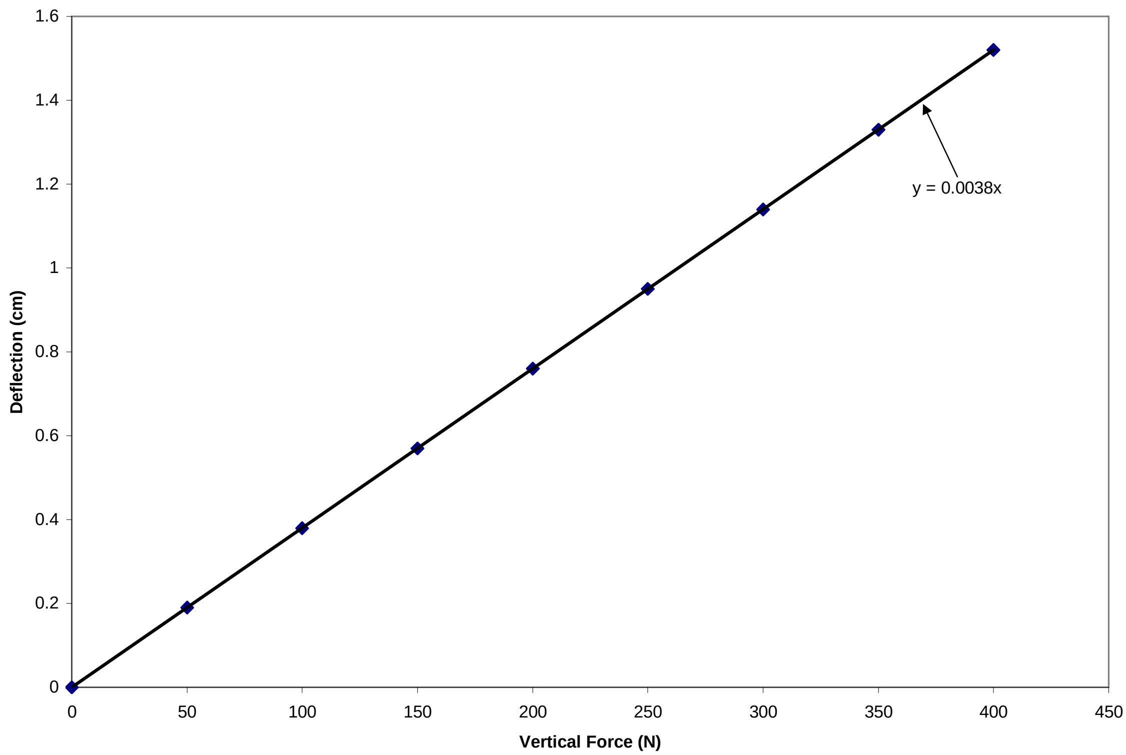
Strengths of Design
Eliminating 9 parts -> Reduces manufacturing cost
Storing energy -> Eliminates torsion bars -> Reduces assembly time -> Reduces manufacturing cost

However, our final design is not entirely one-piece, which is different from the original concept, because manufacturing our entire design out of E-glass would have been more expensive than the cost for the current chair. E-glass is the only feasible material for the Small Length Flexural Pivot (SLFP) given the geometric constraints. The constraints were found by the dimensions of current four-bar linkage on the chair (integrating the new design into the current chair is the customer requirement). Without limiting the geometric dimensions on the new design, other materials such as Titanium and Spring Steel could be used for SLFP segments, which cause the new design to be made entirely out of one piece. Another weakness of our design is that the final motions of the seat pan differ with different input forces, as shown in Figure 43 on page 38. The output displacement is proportional to the input force because we used a linear model in AnSys. This is realistic in some sense because we do not expect a child to be able to fully deflect the back-rest. This problem can be solved by shortening the SLFP lengths with changing the geometric constraint.

Table13: Weakness and Solutions of Final Design

Weakness	Solution
8 piece compliant mechanism	Changing dimensional constraint->Using spring steel or titanium instead of E-glass
Inconstant output motion	Changing dimensional constraint->Shortening SLFP lengths

Figure 43: Linear relationship between the displacement of the seat pan and the input force for the compliant synchronized recline mechanism



Upright Tilt Lock Compliant Mechanism

We were able to reduce the current locking mechanisms part count by three through using our final compliant mechanism. This will result in reducing the manufacturing cost of the chair. There is not any weakness for the new locking design except for the fatigue failure on SLFP. Unfortunately, we were not able to determine any fatigue life for the compliant mechanism because depending on its shape and forces the fatigue life would change even with the same material.

INFORMATION SOURCES

Benchmarking

We benchmarked the Knoll Life Chair Series 400 against four other high-end office chairs: Liberty Chair by HumanScale, Aeron Chair by Herman Miller, Think Chair by Steelcase, and an Office Star Chair by Knoll. The Life Series 400 chair costs between 21-2142 % more than the other chairs. The options available for the Life Series 400 chair are what cause the huge range of prices. The Life Series 400 chair had the most features among all the chairs. Such features included vertical adjustability, swiveling, adjustable arms, seat moves forward/backward, and reclining.

In terms of weight the Series 400 chair (35 lbs) is in the middle of the competition because while it is considerably lighter than the Office Star Chair (65 lbs) it is heavier than the Liberty Chair (27 lbs). The Series 400 chair is among the best in terms of using recycled material. The chair uses 64% recycled material but the Liberty chair uses an astonishing 90% recycled material. Overall, while the Life Chair Series 400 has impressive functionality and specifications, the high price tag of the chair is significantly higher than all other chairs and will surely deter some customers.

CONCLUSIONS

Upon completion of the project, we can conclude that we have achieved the goals set forth. The main motivation of the project was to reduce the cost of the current chair by limiting the number of parts used while still maintaining the various functions of the chair. We reduced the synchronized recline and the upright tilt-lock mechanisms' part counts from 30 to 21 parts and 6 to 3 parts, respectively. This will help reduce the cost of manufacturing the chair as well as the indirect costs such as overhead because it will reduce assembly time. The other focus of the project was to maintain the current functions of the chair. We feel that this objective was achieved due to the prototype test results that we obtained. The current chair has a positive vertical displacement of 1.55 cm on the seat pan and the upright tilt-lock mechanism displaces 1.3 cm on each side. The prototypes that were tested had similar results. The compliant synchronized recline prototype (with E-Glass SLFP segments) had a vertical displacement of 1.2 cm and the compliant upright tilt-lock prototype had horizontal displacements of 0.7 cm on each side. Since we were unable to achieve the dimensions of the final designs in the prototypes we feel that using finite element analysis we can simulate the real results. From FEA we were able to obtain 1.51 cm of vertical displacement for the compliant synchronized recline mechanism and 0.7 cm for the compliant upright tilt-lock mechanism. Based on these results we feel that we have achieved the goals of the project because we reduced the number of parts which will in turn reduce the cost of the current chair. We also maintained the current functions of the chair because the results we received from our prototype were similar to the current chair's attributes. We recommend that distributed compliant mechanisms be explored in the future work and also be able to integrate the designs onto the current chair.

RECOMMENDATIONS

We have two recommendations concerning the synchronized recline mechanism for Knoll and future design teams. We feel that the development of a distributed compliant one-piece mechanism should be explored. We also recommend the future teams to try and integrate the design onto the chair. We did not have enough time, resources, or knowledge of manufacturing to be able to integrate our design onto the existing chair.

The first recommendation is to explore the benefits of using a one-piece distributed complaint mechanism. The distributed compliant mechanism will be able to store energy without the use of

SLFP segments. It will also have the luxury of being entirely one-piece. After manufacturing our aluminum one-piece design we discovered the advantages of having a one-piece mechanism. It is much simpler to manufacture a part out of one piece than having to deal with multiple materials and how to integrate them with one another. This will save time and money to whoever continues the project.

The only disadvantage in developing the one-piece design is the time spent on designing it. Currently, there is not any software available that is able to design distributed compliant mechanism. We had tried using a graduate student's program but failed to achieve any desirable results. We lacked the knowledge to be able to design a distributed complaint mechanism since there are numerous variables to account for. The design will be very complicated and the future teams needs to be weary of parasitic or unwanted motion. The main objective of the project was to insure that the current functions of the chair were maintained, future teams must pay close attention in matching the motion of the current chair.

The other recommendation is to integrate the design onto the existing chair. We did not have enough resources (time and money) to be able to complete this task. First, we did not have enough time because we also focused on redesigning the upright tilt-lock mechanism. Time must be spent on properly measuring and designing the mechanism to be able to fit properly in the current constraints. The other resource that we did not posses was enough funding to be able to manufacture a 3d design. The costs of manufacturing our three prototypes already put us near the max of our budget. It will be very costly to contract out a skilled machinist/manufacturer to produce a product that has contours and variations in 3 dimensions. We feel that integration onto the chair is possible and should be done in the future.

ACKNOWLEDGEMENTS

We would like to thank the people who helped us make our senior design project a success. First, we want to thank Professor Sridhar Kota for sponsoring the project and guiding us along whenever we got stuck. Next, we want to thank the graduate students, Michael Cherry, Youngseok Oh, and Tanakorn Tantanawat, for helping us with the design process and the validation of our project. Finally, we want to thank Robert Coury and Steve Emanuel for helping us manufacture our prototypes.

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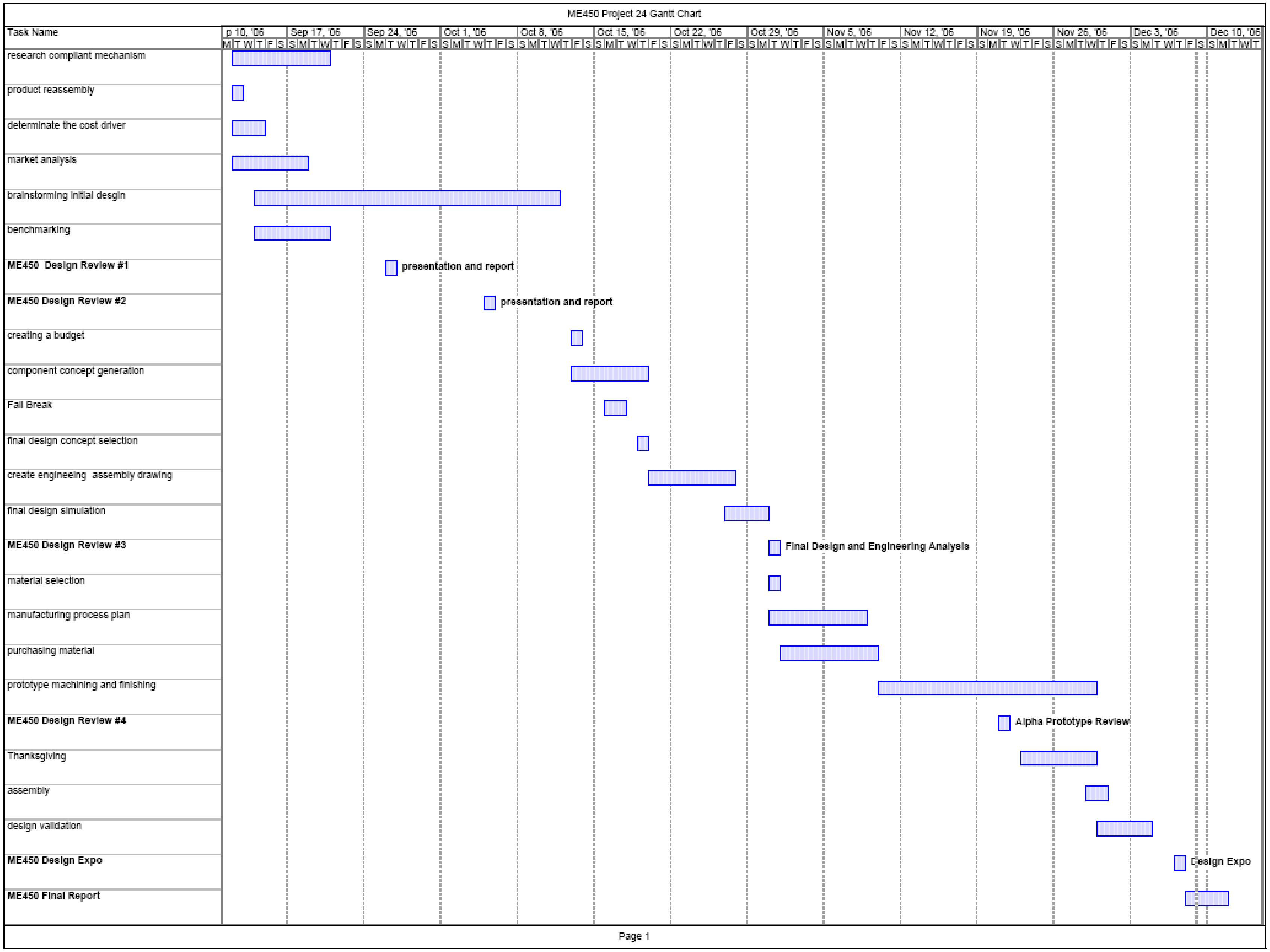
1. Goe, M. Moreno, A. *Knoll Life Chair Series 400 Re-design Report.* University of Michigan, Ann Arbor. 2006.
2. Howell,L. *Compliant Mechanisms* John Wiley & Sons, Inc 2002
3. Li, S. *Design Procedure of Compliant Gripper* University of Michigan, Ann Arbor. 2005

APPENDIX A. Figure A1 Gantt Chart Diagram

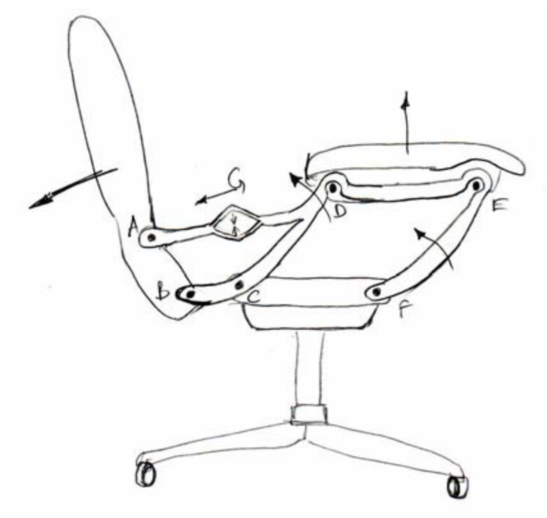


Appendix B. Preliminary design concepts

Synchronized Recline Mechanism

<u>Concept 1</u>

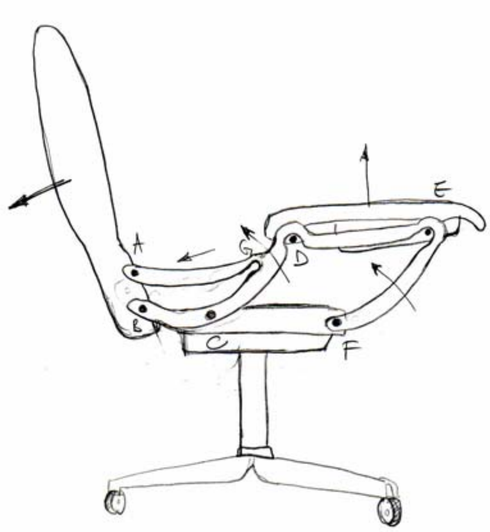
Figure B1: Design Concept 1



Concept 1 presents a design that is a fully compliant system with distributed compliance that replaces the original linkage mechanism of the synchronized recline system. As the user leans on the back of the chair, an input bar with a expandable compliant joint G shown in Figure 3 in the left pulls on the compliant linkage mechanism and causes rotation of its links which raises the seat pan upward parallel to the seat base. The compliant linkage mechanism is attached to the seat pan and pinned to the seat base (ground) at points C and F in Figure B1

<u>Concept 2</u>

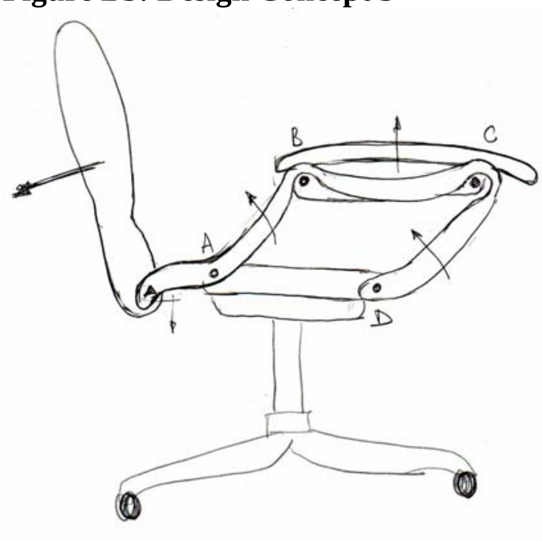
Figure B2: Design Concept 2



Concept 2 presents a design that is a fully compliant system with distributed compliance that replaces the original linkage mechanism of the synchronized recline system. The user's leaning back motion activates the input linkage which is pinned to the back and compliant jointed at point G in Figure B2 in the left to the main compliant mechanism structure. This forces the links of the main compliant mechanism structure to rotate which raises the seat up parallel to the seat's base (ground). The compliant linkage mechanism is attached to the seat pan and pinned to the seat base (ground) at points C and F in Figure B2.

Concept 3

Figure B3: Design Concept 3



Concept 3 diverges from the previous 2 concepts (concept 1 and 2 on page 7) in that it is a fully-compliant linkage system that only has 4 links. The input link is activated by the reclining motion of the chair's back. Acting as a lever, the downward force on the input link forces the whole mechanism to rotate with the fulcrum at point A in Figure B3. This in turn achieves the parallel upward movement desired for the seat pan. The links of this compliant linkage mechanism are attached to the seat pan and pinned to the seat base (ground) at points A and D in Figure B3.

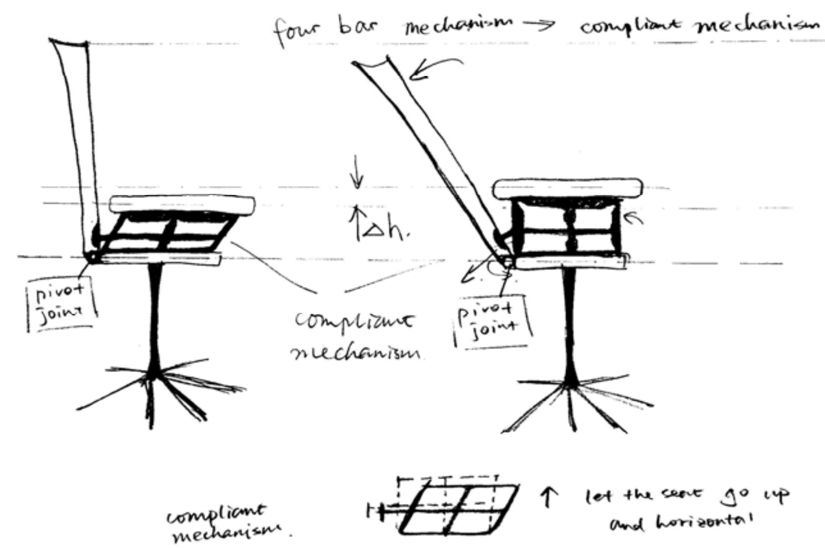
Concept 4

This concept has the chair being naturally reclined because it will be the compliant mechanism's initial position. The compliant system will include the back rest with a seat pan able to slide on top of the seating area, as shown in Figure B4. When the user sits up properly in the chair, the compliant mechanism will compress into its second position and act as a normal upright chair. A new locking mechanism will have to be designed to keep the chair in the upright position, but as soon as the lock is released the chair will return to its original reclined position. The compliant mechanism is designed to replicate the traditional four bar linkage that was originally on the office chair. The manufacturing of the concept will be a problem due to the unusual shape of the chair. Also, the integration of the concept onto the existing chair will also cause a problem because the concept will replace most of the current chair.

Figure B4: Design Concept 4

Concept 5

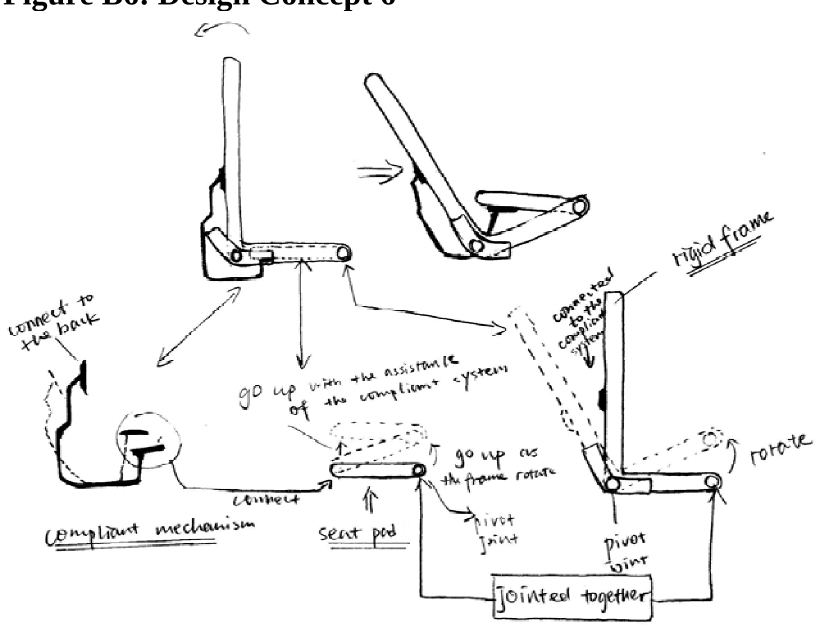
Figure B5: Design Concept 5



In this concept, the back is connected to the base of the seat by a pivot joint in order to go back and forth. Once the back has been pushed backwards, the compliant mechanism connected to the back will change from a diamond to a rectangle shape, so that the pad fixed on the mechanism will go up and be horizontal to the ground, as shown in Figure B5.

Concept 6

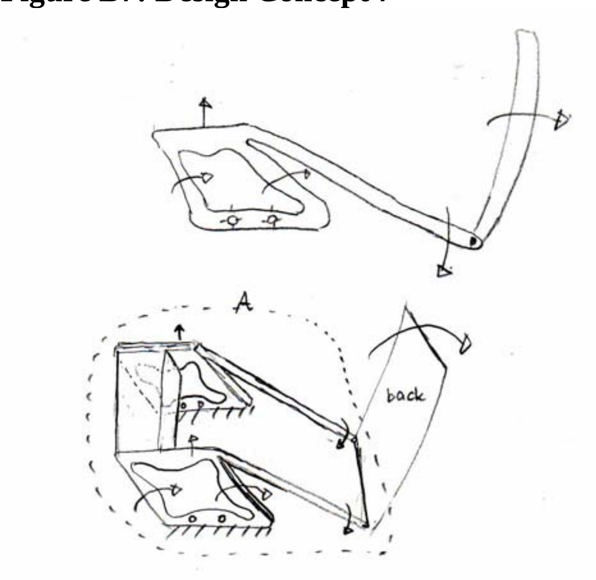
Figure B6: Design Concept 6



This concept is composed of three major parts: A rigid frame which has a pivot point at the corner so that it can be pushed back and forth, a seat pad that connected to the frame with a pivot joint at one side as show in Figure B6, and the compliant mechanism bar which connects the rigid frame with the seat pad. Once the frame is pushed back, the pad will also go up and be tilted. In order for the seat pad to be parallel to the ground, the compliant mechanism assists the other side of the pad to go up.

Concept 7

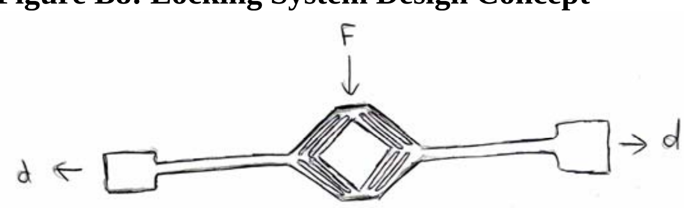
Figure B7: Design Concept 7



This concept reduces four parts using a compliant mechanism for the four-bar linkage while maintaining all functions of the current chair. The part A shown in Figure B7 on the left is attached to the seat base using four screws. When the ground attached back is reclined, the back pushes down two bars of the part A. Then, the rest of linkages follow their own paths and eventually lift up the front part of the seat.

Upright Tilt Lock Mechanism

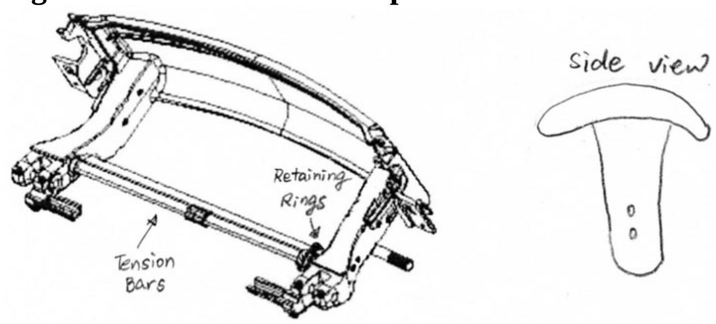
Figure B8: Locking System Design Concept



The current upright tilt locking mechanism consists of six plastic parts that can easily fall apart. The new concept, shown in Figure B8, will replace the current mechanism with a compliant one-piece mechanism. The new compliant system will work through compressing the middle of the mechanism. This will in turn push the sides of the mechanisms outward and into slots, thus locking the chair in one position. The only problem with the new compliant mechanism is the cable assembly recline lock will need to be repositioned. Currently the cable assembly recline lock is positioned parallel to the displacement of the mechanism, but in order to compress the middle of the mechanism the cable assembly recline lock will have to be positioned perpendicularly. The compliant mechanism will have a benefit in the assembly of the chair because it will be just one complete piece instead of six separate pieces.

Design for Assembly

Figure B9: Back Cast Concept



Knoll, our sponsor, has asked us to simplify the assembly process for the torsion spring bars. Therefore, the concept shown in Figure B9 reduces not only the number of parts but also the assembly time. There are two holes on one side of the part, so that the two spring bars can be slid into place. Then the spring bars will be locked in by retaining rings.

Appendix C. Dimension analysis for SLFP segments of Compliant Synchronized Recline Mechanism

Model used in the parameter analysis

Figure C1: Model for the original four-bar linkage recline mechanism

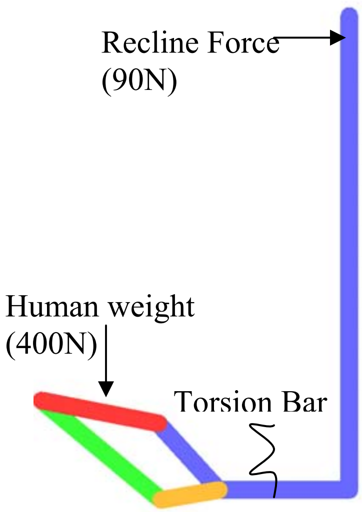
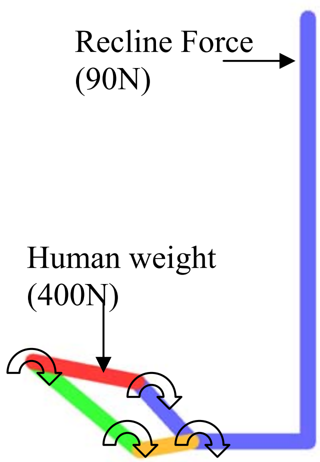


Figure C2: Pseudo-rigid-body model for the Compliant recline mechanism



Mechanism Parameters

Table C1: Angles of each pivot joint

Pivot Joint	Initial Angle (˚)	Final Position (˚)	Angle Range (˚)	Angle range (radians)
pivot 1	57.60	73.60	16.00	0.28
pivot 2	143.27	131.24	-12.03	0.21
pivot 3	28.75	34.46	5.71	0.10
pivot 4	130.38	118.71	-11.67	0.20

Using the force and energy equations mentioned in the report, energy and stress data was calculated in the Excel spreadsheet as shown below.

Table C2. Energy and stress data calculated in Excel spreadsheet

SLFP	Energy stored	bending stress	tension stress	Total Stress	Safety Factor
Segment 1(pivot 1)	1.85E+00	7.82E+08	3.42E+06	7.85E+08	2.09E+00
Segment 2(pivot 2)	1.39E+00	7.84E+08	3.42E+06	7.87E+08	2.08E+00
Segment 3(pivot 3)	7.95E-01	4.19E+08	2.05E+06	4.21E+08	3.90E+00
Segment 4(pivot 4)	2.77E+00	7.13E+08	2.05E+06	7.15E+08	2.29E+00

Appendix D. Force analysis for each pivot joint using ADAMS Model

Fig D1. Initial forces in X and Y directions on SLFP1

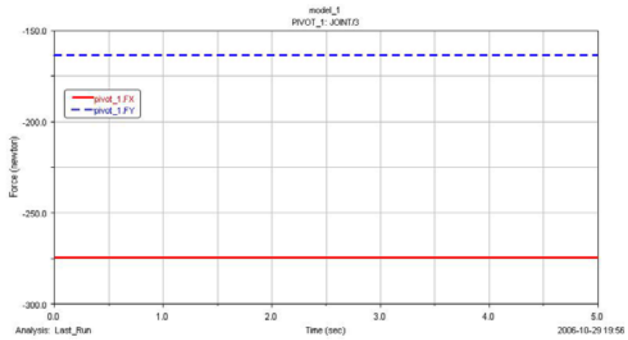


Fig D2. Final forces in X and Y directions on SLFP1

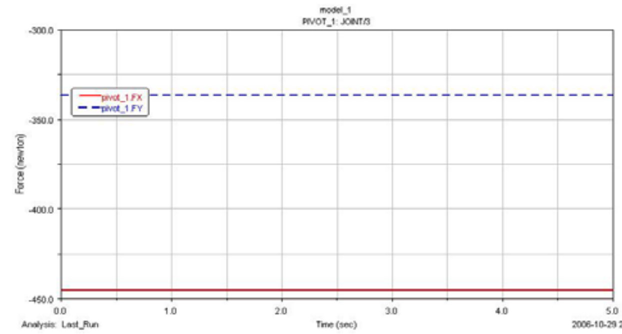


Fig D3. Initial forces in X and Y directions on SLFP2

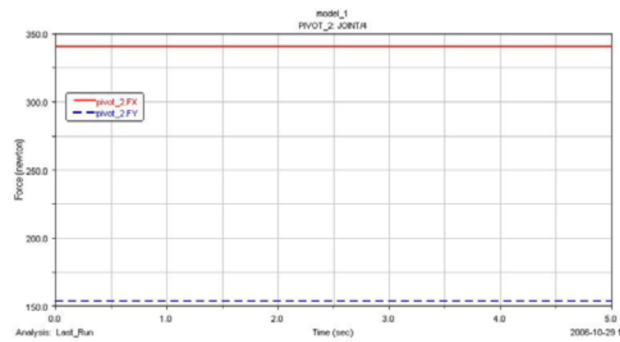


Fig D4. Final forces in X and Y directions on SLFP2

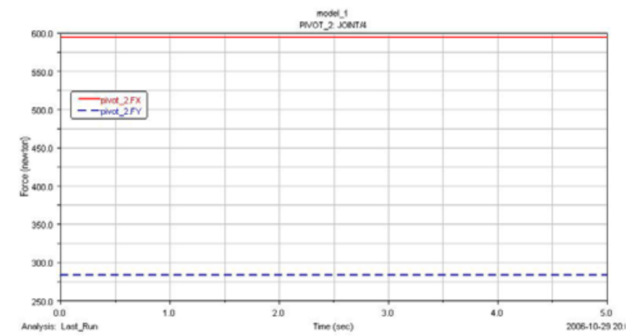


Fig D5. Initial forces in X and Y directions on SLFP3

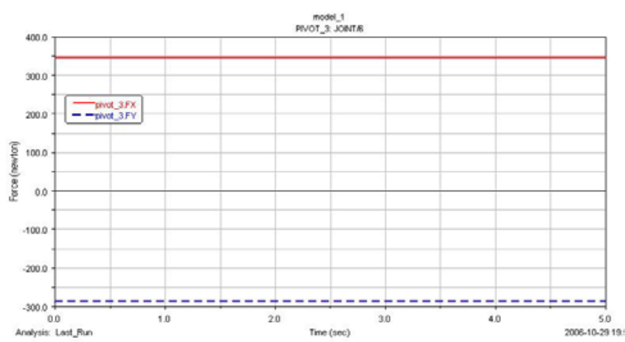
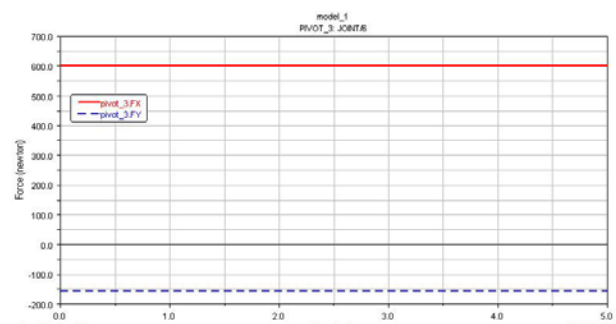


Fig D6. Final forces in X and Y directions on SLFP3



FigD7 . Initial forces in X and Y directions on SLFP4

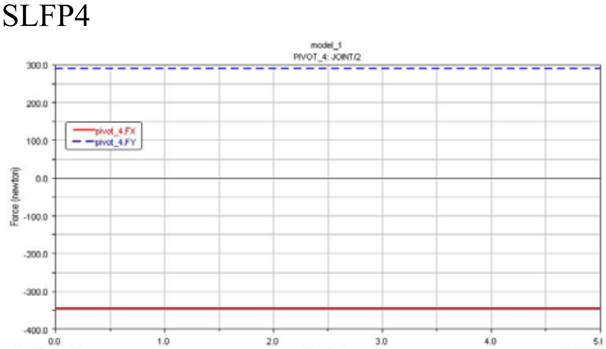
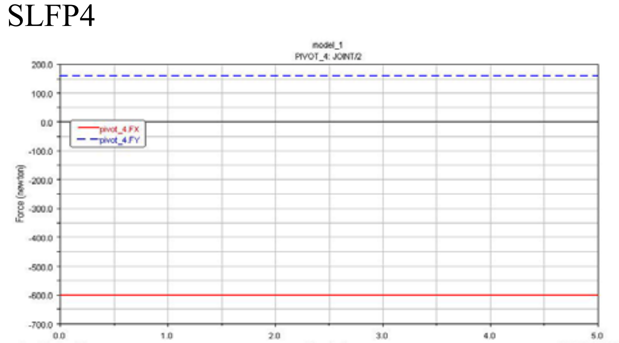


Fig D8. Final forces in X and Y directions on SLFP4



Appendix E. Bill of Material

Table E1

Part ID	Quantity	Part Description	Part Source	Part Cost (Each)
P09	12	6-32 x 3/4" round head UNC screws	University of Michigan	$0.00
P10	2	6-32 x 1" round head UNC screws	University of Michigan	$0.00
P11	2	6-32 x 3/8" hexagonal head UNC Screws	Plymouth Hardware	$0.17
P12	2	6-32 Machined Nut	University of Michigan	$0.00
P14	16	1/4" Inner Diameter Washers	University of Michigan	$0.00
P01	1	Al 2024 Rigid Main Body Component 1	Quasar Industries	$91.25
P02	1	Al 2024 Rigid Main Body Component 2	Quasar Industries	$91.25
P03	1	Al 2024 Rigid Main Body Component 3	Quasar Industries	$91.25
P04	1	Al 2024 Rigid Main Body Component 4	Quasar Industries	$91.25
P05	1	E-Glass SLFP Insert 1 - 2mm(thickness) x 25.4mm(width) x 41.13mm(length)	University of Michigan	$0.00
P06	1	E-Glass SLFP Insert 2 - 2mm(thickness) x 25.4mm(width) x 34.93mm(length)	University of Michigan	$0.00
P07	1	E-Glass SLFP Insert 3 - 3mm(thickness) x 25.4mm(width) x 40.00mm(length)	University of Michigan	$0.00
P08	1	E-Glass SLFP Insert 4 - 3mm(thickness) x 25.4mm(width) x 43.74mm(length)	University of Michigan	$0.00

Table E2

Part ID	Quantity	Part Description	Part Source	Part Cost (Each)
L01	1	DELRIN SHEET ½’’ THICK 12’’× 12"	University of Michigan	$0.00
L02	1	POLYETHYLENE (HDPE) SHEET 3/8’’ THICK 12" × 12"	MCMASTER-CARR	$0.00