MEMORANDUM

9/17/2026

TO: Eric Ocegueda, Assistant Professor, Mechanical Engineering
FROM: Hong Dang, Chananeth Manava, Daniel Mendes, Apolonio Ordaz, ME 328 – 02
COPIES: 01
SUBJECT: Final Scooter Project

DESIGN OVERVIEW AND RELEVANT BACKGROUND

Foot and ankle injuries often require mobility assistance when in the recovery process. While crutches are a common solution, they can be uncomfortable and require upper body strength. The objective of this project was to design and prototype a low-cost knee scooter that would provide a safer and more comfortable alternative to the traditional crutches. Our final design was developed for a user who is 162 inches and weighs approximately 118 lbs., with additional consideration for extra loads such as personal items or groceries. Throughout the build and design process, anthropometric measurements, hand calculations, finite element analysis (FEA), and prototype testing were utilized to evaluate the performance of the scooter and guide the final design.

The final design consists of a three-wheel scooter constructed primarily from Schedule 40 PVC pipe. A truss-like frame structure was incorporated to improve the loading distribution and reduce bending while keeping the scooter lightweight and inexpensive. The scooter supports the injured leg on a padded knee platform while the user is intended to propel themselves forward with their healthy leg and steer using the handlebars connected to the front wheel axel assembly. Key design criteria included maintaining structural integrity under normal and abuse loading conditions, minimizing cost, providing adequate stability during turning operations, and ensuring user comfort. Design constraints included a limited budget, available resources, and mechanical limitations as structural material.

This scooter is intended for individuals recovering from a foot or angle injury who can balance on one leg and safely maneuver. It is not intended for users with injuries affecting both legs, users with balance impairments, or individuals who exceed the design load capacity. Potential users who are below the intended height (5’ 2”) may experience difficulties using the scooter and are advised to use other mobility options. Potential challenges during fabrication include ensuring the PVC components are properly aligned before the PVC cement cures, as it is not possible to adjust once it is cured. Accurate cutting and placement of the wheel mounting locations are also critical as small dimensional dissimilarities can result in an uneven knee platform or improper wheel alignment that negatively affects stability and steering performance.

Several loading scenarios were considered to ensure safe operation, including a normal use case, carrying a backpack, and an abuse case involving grocery bags being hung off the handlebars. A design safety factor of 2 was applied to all primary load cases, while FEA results showcase a factor of safety of approximately 6, compared to the yield strength of PVC. The analysis predicted a maximum stress of approximately 0.905 ksi, a maximum displacement of 0.1 inches for the main body, and a maximum displacement of 0.15 inches for the handlebars. This ensured that the scooter would remain structurally sound under the expected load conditions.

This report summarizes the complete design process, including the final design configuration, material selection, hand calculations, finite element analysis, prototyping construction, testing procedures, and recommendations for any future iterations.

DRAWINGS AND ASSEMBLY

Conceptual Designs

During the initial design phase, two conceptual scooter designs, depicted in Figures 1 and 2, were generated. As shown in Figure 1, design 1 incorporates a three-wheel arrangement with a storage basket and padded knee-rest area. In Figure 2, design 2 utilizes a similar three-wheel configuration, but with the two-wheel attached to the front of the scooter rather than the back. These concepts were analyzed to assess their feasibility and structural performance. However, since both designs feature a complex geometry that would require the manufacturing of custom parts, they were ultimately rejected before advancing to the final design.

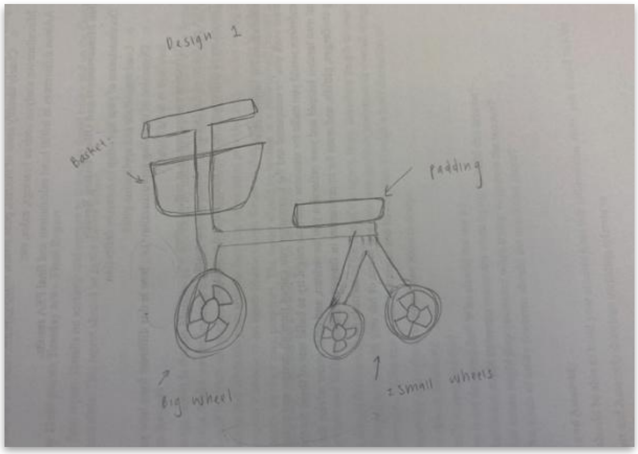

Figure 1. Iteration #1 of Scooter Design. Concept sketch of design #1, showing a three-wheel configuration with one large front wheel and two smaller rear wheels. The design includes a front handlebar, a storage basket, and a padded rear knee-rest area.

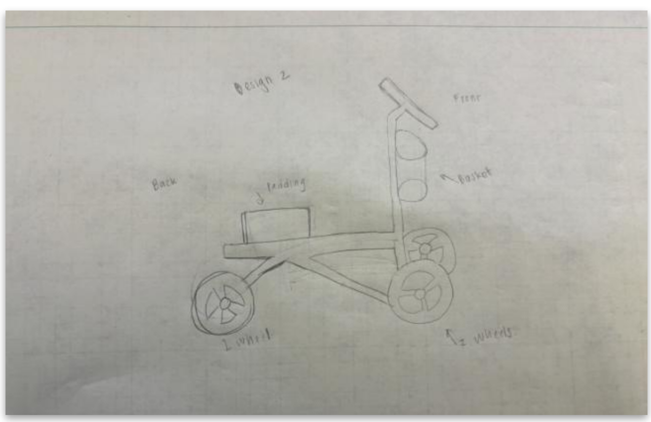

Figure 2. Iteration #2 of Scooter Design. Design features a three-wheel configuration, with two wheels in the front and one in the back. The main body comprised of a reinforced frame with support beams stemming from the knee-rest area at an angle. This design also features a basket attachment.

<u>Chosen Design</u>

The scooter design, depicted in Figure 3, features a rigid frame structure that serves as the primary support element that connects the handlebar column to the rear knee support section. The frame is reinforced with a rectangular truss-like structure, which improves load distribution and increases bending resistance when load is applied.

The knee support platform is positioned over the rear section and is supported by multiple cross members, allowing it to support concentrated loads from users while maintaining stability. The cross members function as structural support that distribute the rider's weight across the frame rather than concentrating loads at a single location. The platform is fastened to the cross members using bolts through pre-drilled holes, creating a rigid connection that minimizes deflection under load. By utilizing multiple cross members, the platform maintains stability and provides support during both normal and maximum loading conditions.

The handlebar is mounted on a vertical column connected directly to the front axle; this helps provide steering control and structural support. The wide front wheelbase increases lateral stability and reduces tipping risks, especially when loads are applied to handlebars.

Steering is achieved by rotating the handlebar, which is rigidly connected to the vertical steering column. To allow the column to rotate while remaining securely attached to the main frame, bored-out caps are installed at the top and bottom of the PVC steering tube. These caps are drilled through their centers to accommodate a bolt that acts as the steering pivot axis. The end caps are permanently bonded to the PVC tube using PVC glue, creating a strong connection while allowing the column to rotate freely about the bolt.

Additionally, the three wheel configuration (two in front and one rear dually wheel) helps with balance and maneuverability. All wheels will be equal in diameter and thickness. The extended wheelbase and low center of gravity further improve overall stability during normal and maximum load conditions. To mount the front wheels, the cylindrical protrusions on the hubs were slid into the PVC cross member attached to the steering column. A length of 5/8" x 3' threaded rod will run through the middle of the PVC pipe and nuts (either with thread-lock or jam nuts) will be used to keep the wheel in place. The PVC pipes would be cut using handheld PVC cutters, a tolerance of ± 0.125 inches was used. For the rear wheel, the PVC fork will have holes drilled through the sides in order to allow a length of threaded rod to be used as an axle, similar to the front wheels.

The design prioritizes strength, stability, and user support by reinforcing key loads bearing components and being able to distribute forces efficiently throughout the structure.

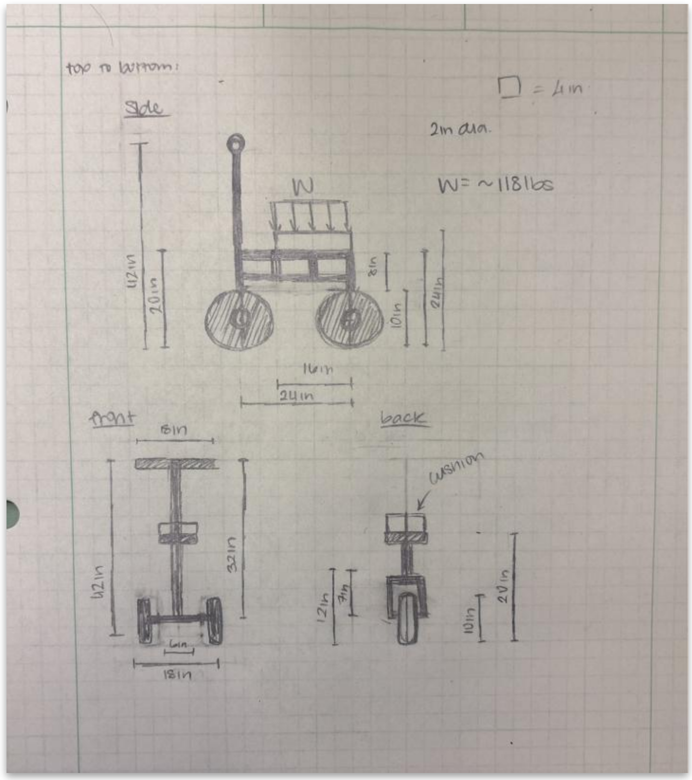

Figure 3. Final Iteration of Scooter Design. Hand-drawn sketch of scooter configuration, drawn roughly to scale. This design features a three-wheel configuration, with two wheels attached in the front and one attached to the back of the structure. The main body features a truss-like design. The knee-pad area is supported by cross-shaped PVC fittings. All measurements are ± 0.125 inches.

Parts List

Listed in Table 1 is the bill of materials that quantifies the total cost of the knee scooter. Schedule 40 PVC pipes with diameters 1 inch and 1.5 inches were used. Tools were borrowed from the Mustang '60 student workspace to assemble the final product.

Table 1. Bill of Materials

Bill Of Materials			
Material	Amount	Cost Per ($)	Total Cost
1.5 in PVC (per ft)	6 ft	0.768	4.61
1 in PVC (per ft)	8 ft	0.972	7.78
1.5 in PVC T Fitting	8	4.28	34.24
1.5 in PVC cross Fitting	2	8.96	17.92

1.5 in PVC 90 Elbow Fitting	3	2.53	7.59
1.5 in PVC End Caps	2	1.79	3.58
1.5 to 1 in T Fitting	1	4.45	4.45
1 In PVC T Fitting	1	1.76	1.76
5/8 Zinc All Thread	1	12.94	12.94
5/8 Nuts	8	0.47	3.76
10 Inch Wheel with Hub	4	8.99	35.96
Wood Board	1	5.18	5.18
Foam	1	9.98	9.98
Duct Tape	1	5.00	5.00
PVC Primer and Cement	1	18.58	18.58
Wood Screws	4	0.10	0.40
		Total	173.73

Assembly Process

The scooter was assembled using 1.5-inch PVC pipes, 1.5-inch PVC fittings, threaded rod, pneumatic wheels, a wooden knee platform, and foam padding. Construction began by cutting all the PCV pipe sections to their specified lengths according to the final design dimensions. The frame was initially assembled without adhesive to verify the alignments, dimensions, and wheel placement.

The main frame was constructed first by connecting the front wheel steering column, central truss-like support structure, and the rear knee support frame using PVC T-fittings, cross-fittings, and elbow joints.

During the preliminary assembly, all components were dry-fit to allow adjustment and ensure proper fit before permanent bonding.

Once dimensional checks were completed, PCV primer and glue were applied to all structural joints. Care was taken to maintain alignment while the adhesive was cured. The steering column was intentionally left unbonded within the larger tee fitting to allow free rotation for steering. We used lathe to bore out the end caps for steering, but simple hand tools can achieve the same results.

The wheel assemblies were constructed using a 5/8-inch threaded rod as axles. Holes were drilled through PCV and caps, allowing the threaded rod to pass through the wheel hubs. Nuts and washers were installed on both sides to secure the assembly and prevent lateral movement.

A wooden platform was then attached to the upper support members using wood screws. Foam padding was secured to the wooden platform and wrapped with duct tape to provide a comfortable knee-resting surface. After assembly, final alignment checks were conducted to verify wheel tracking, steering movement, and frame symmetry.

The completed scooter was subjected to static loading and maneuverability tests to verify structural integrity, stability, and user comfort prior to final demonstration.

CALCULATIONS AND MODELING

Design Safety Factors

1. *SF* = 1.25 to 1.5 for exceptionally reliable materials used under controllable conditions and subjected to loads and stresses that can be determined with certainty—used almost invariably where low weight is a particularly important consideration.
2. *SF* = 1.5 to 2 for well-known materials, under reasonably constant environmental conditions, subjected to loads and stresses that can be determined readily.
3. *SF* = 2 to 2.5 for average materials operated in ordinary environments and subjected to loads and stresses that can be determined.
4. *SF* = 2.5 to 3 for less tried materials or for brittle materials under average conditions of environment, load, and stress.
5. *SF* = 3 to 4 for untried materials used under average conditions of environment, load, and stress.
6. *SF* = 3 to 4 should also be used with better known materials that are to be used in uncertain environments or subjected to uncertain stresses.
7. Repeated loads: The factors established in items 1 to 6 are acceptable but must be applied to the *endurance limit* rather than to the yield strength of the material.
8. Impact forces: The factors given in items 3 to 6 are acceptable, but an *impact factor* should be included.
9. Brittle materials: Where the ultimate strength is used as the theoretical maximum, the factors presented in items 1 to 6 should be approximately doubled.
10. Where higher factors might appear desirable, a more thorough analysis of the problem should be undertaken before deciding on their use.

Figure 4. Approximate Design Safety Factors from "Fundamentals of Machine Component Design"

When choosing an initial design safety factor, Figure 4 was referenced to choose an appropriate safety factor. For this project, the structural material used was Schedule 40 PCV, which is a brittle material with a documented ultimate stress. The scooter is not going to be subjected to large impacts, and a conservative approximation of the maximum stress and loads are calculated by hand and through FEA. For these reasons, a design safety factor of 2-3 was deemed reasonable and was considered during the design process. As stated in #9 of the figures above, brittle materials should have the safety factor approximately doubled, which will be addressed again later in the report.

Load Cases

To evaluate the scooter's effectiveness in everyday usage, three different load cases were assessed. The first load case represented normal operation, where the user's weight is applied to the knee support platform. This case was used to evaluate the structural stiffness of the frame and ensure that excessive deflection would not occur with repeated use. The second loading case includes the user's weight and their backpack load. This loading was used to assess the maximum expected load and to verify that the scooter could safely support daily transportation with an increased load without compromising structural integrity. The final load case represented the abuse case in which the user carries groceries or a handbag, up to 10 lbs., from each side of the handlebars. This scenario was included to evaluate the strength and stiffness of the handlebar and steering column assembly that loading conditions that may occur but are not under the intended operation. Hand calculations were performed for the critical components associated with these load cases and were later compared to FEA results.

Hand Calculations

Hand Calculations were performed to estimate the stress and deflection of the scooter under the critical loading conditions as discussed above. These calculations provided an initial assessment of the structural performance and helped identify if the current design was adequate. The scooter was analyzed using simplified beam theory while also assuming rigid connections between members and uniform material properties throughout the PVC frame.

Load Cases 1 and 2: Knee Support Loading

Load Case 1 represents the normal loading operation where the users' body weight was applied to the knee support platform. Load Case 2 included the same loading configuration with the addition of a backpack load resulting in a higher overall force acting on the frame. Both of these load cases utilize the same loading and only differ in the load magnitude. Because of this, hand calculations were performed only for Load Case 2. Analyzing the larger load provides a conservative estimate of performance and ensures the scooter will also satisfy the requirements of Load Case 1.

For this load case the knee support region was modeled as a fixed fixed beam with a partially distributed load. Applying a factor of safety of 2, the resulting deign load was approximately 246 lbs. Using the material properties of Schedule 40 PVC, 1.5-inch PVC, the maximum downward deflection was approximately 0.080 in. The maximum deflection occurred near the center of the loaded region, indicating the knee platform was a key critical area for stiffness under the operating conditions.

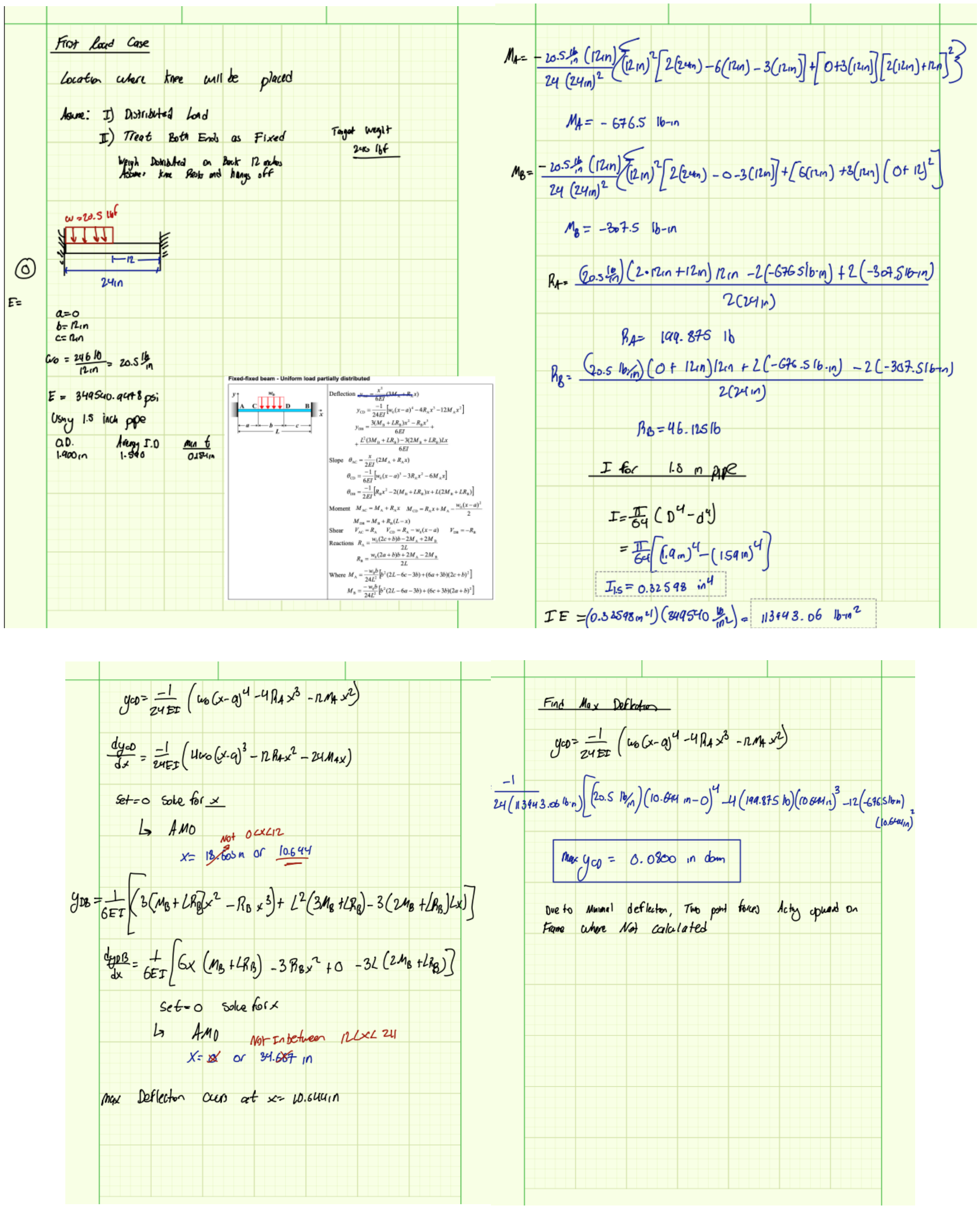

Figure 5: Load Case 2. Distributed Load on the main Knee Area

Load Case 3: Handlebar Abuse Case

The final load case evaluated an abuse case in which a 10lb grocery bag could be suspended from each side of the handlebars, The handlebar was modeled as a cantilever beam with concentrated loads at the free ends. Using a handlebar length of 9 inches on either side of the steering column, the maximum bending force was calculated as 90 lb.-in. The resulting maximum bending stress was approximately 262 psi, while the predicted tip deflection was 0.013 in. These values were significantly below the yield strength of PVC, indicating that the handlebar assembly can safely withstand the anticipated abuse loading without permanent deformation.

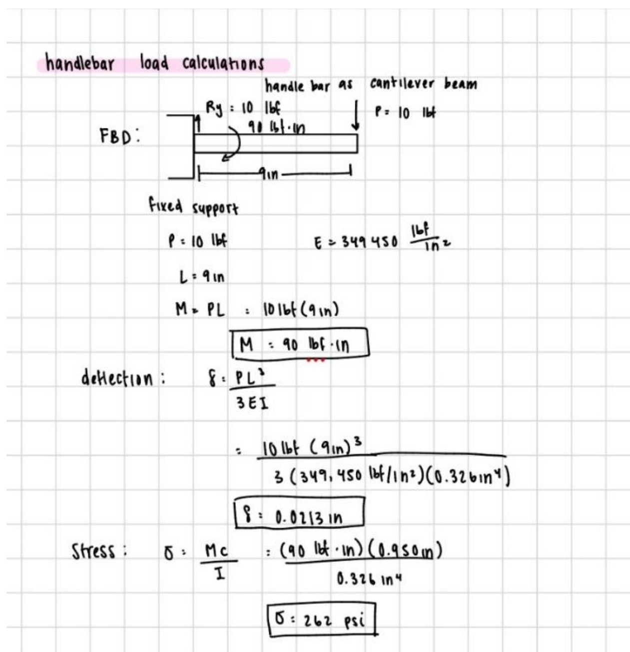

Figure 6: Load Case 3. 10 lbs. off the Handlebars

FEA Modeling

During the first iterations of the FEA, the entire scooter was modeled using 1.5” PVC in order to match the hand calculations. The goal of the FEA was to locate and analyze critical points in the structure of the scooter, so the wheels and axles were excluded, as those were designed for much heavier loads (300 lb. per wheel). A solid element study was chosen with a maximum element size of 0.1 inches.

To compensate for where the wheels would be mounted, these locations were given rigid fixtures (fixed geometry). The four rigid fixtures can be seen in green at the bottom where the wheels are mounted in Figure 7.

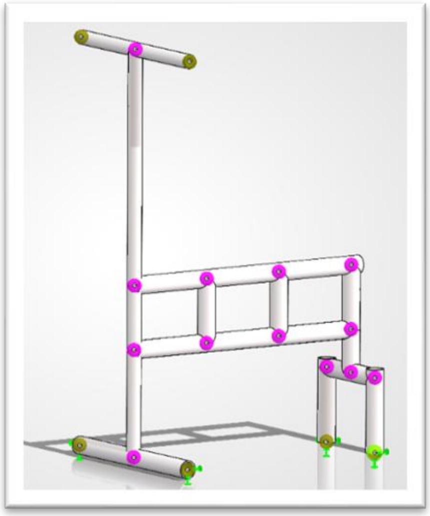

Figure 7: Rigid Fixtures in FEA

In order to model the largest stresses and deflections, the FEA performed with the largest loads (150lb on the seat and 10lb on each handlebar). The 150lb load was uniformly distributed over the top of the frame, where the seat would be. The handlebar loads were modeled as point loads on the ends of the handlebars.

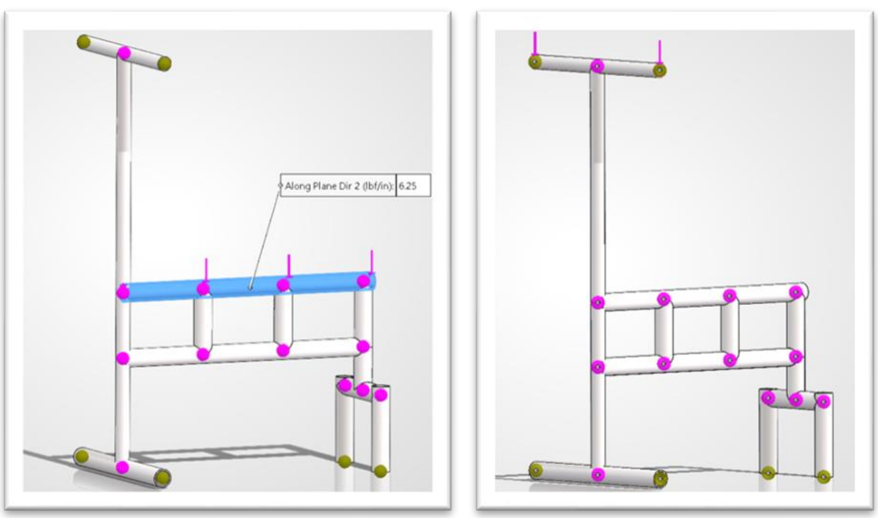

Figure 8: Loads Modeled in FEA

Once these parameters were put into the FEA, both stress and deflection studies were performed.

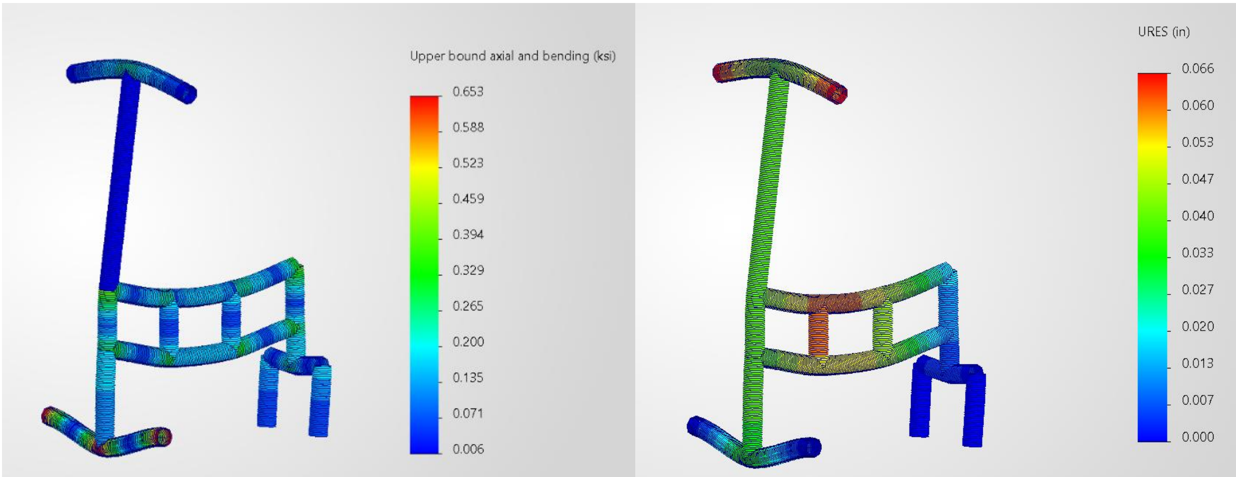

Figure 9: Maximum Stress and Displacement of First FEA Study

Since the predicted stresses and deflections in the main truss and handlebars closely matched the hand calculations, this gave assurance that the parameters of the FEA are correctly modeled. The calculations are not the same as the FEA results due to the nature of the hand calculations. The hand calculations simplify the body of the truss and the handlebars into segments that can easily be calculated by hand, while the FEA study performs all calculations according to the model. The numbers are close and are of the same magnitude, giving enough confidence that the FEA is correctly modeled. Now that the FEA is confirmed to be accurate, the safety factor of the design can be calculated. Since the maximum stress is ~0.65 kpsi and the PVC has an ultimate tensile strength between 6 kpsi and 8 kpsi, this gives a safety factor around 10. This means that the current configuration is much stronger than initially intended, giving us some flexibility to alter the design for better optimization. While changing the design to bring us closer to the desired safety factor, we also discovered that our original method of steering needed to be redesigned. For these reasons, the steering column and handlebars were reduced from 1.5” PVC to 1” PVC. The model was updated, and the FEA studies were performed again.

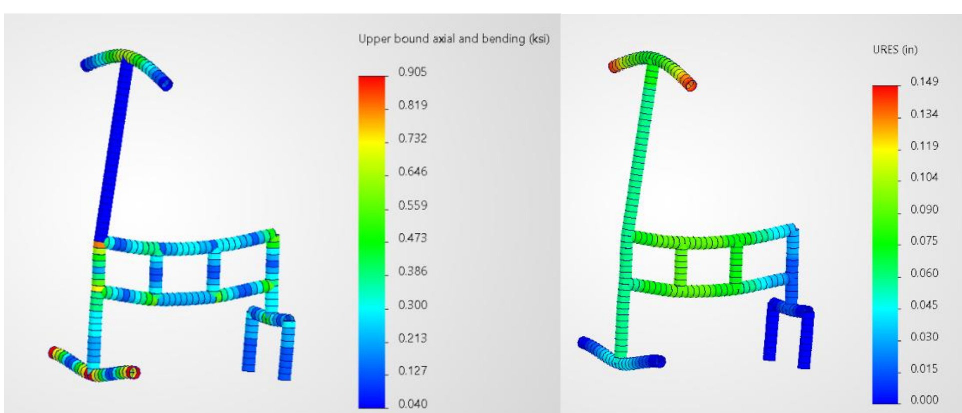

Figure 10: Maximum Stress and Displacement of Final FEA Study

For the final FEA iteration, it had a maximum stress of ~0.9 kpsi. This results in a safety factor between 6 and 7. As mentioned earlier in the report, our design safety factor was 2–3, but structures that are likely to fail from brittle failure should roughly double the design factor. This means that our safety factor from FEA is much closer to the desired design factor, and the group should not try to get this safety factor any lower. The FEA reveals that the critical points with the highest stress are where the steering column meets the crossbar where the wheels are going to be mounted. This is as expected, and the real-life scooter will utilize a PVC T fitting at this point, giving it even more strength than modeled in the simulation. The maximum deflection is at the ends of the handlebars where the simulated loads are placed. This deflection is ~.15 inches and will be compared to the deflection of the real-life scooter during testing.

DEFLECTION MEASUREMENTS AND OTHER TESTING RESULTS

Testing Plan and Results

Testing procedures were conducted to evaluate the structural performance, durability, stability, and usability of the scooter design. Testing included static load assessments, structural integrity evaluations, maneuverability assessments, and user fit evaluations.

A maximum load capacity test was performed by loading the scooter with about twice the intended weight. This was done to determine the maximum weight the scooter could support without excessive bending or structural failure. During testing, load was initially applied at the knee pad area to simulate user weight and was gradually increased (by adding the weight of another person) until the structure saw deformation. The first iteration of the scooter, before gluing, showed promise as it was able to withstand twice the expected weight with little to no deflection. The fittings and short PVC sections allowed the frame to be reinforced without other properties.

Another static load test was utilized to simulate the abuse case, where a total of 20lb of load was applied to the handlebars. The passing criterion required the structure to meet or exceed a load equal to 20lbs multiplied by a safety factor of two. Using backpacks (which weighed roughly 13lbs) to mimic the load, both handlebars were equipped with weight. The handlebars saw a deflection of ~0.0625 inches (1/16”).

Structural integrity testing was performed to assess the durability and wear resistance of critical components, including the frame, wheels, brakes, and steering system. This evaluation consisted of visual inspections and operation of the scooter under normal driving conditions to identify any signs of cracking, deformation, or structural weakness. This was done with a visual inspection of the structure while the user simulated use. No major deflection was detected.

Turning and lateral stability were evaluated through practical driving tests under normal operating conditions. The purpose of this test was to assess the responsiveness of the steering system and the scooter’s ability to maintain stability while maneuvering. The passing criterion required successful completion of both a 90° turn and a turn exceeding 180° without loss of control or instability. The first iteration of the scooter, before being glued, showed twisting within the main body of the scooter during an attempt to conduct a sharp turn. The PVC pipes would twist while set in the fitting. To negate this, all pipes were then glued to each fitting, except for the main steering column.

An ease of use and fit assessment was conducted to evaluate overall user comfort and usability. Test participants operated the scooter under normal driving conditions and provided feedback regarding ergonomics, comfort, and ease of operation. User responses served as the primary measure for determining whether the design met usability requirements. Upon visual inspection, the scooter was deemed too tall for the original user (Chananeth). This was a result of neglecting the height the fittings would add to the structure. However, for user #2 (Apolonio), the scooters fit comfortably.

FEA of Displacement of Critical Point

A comparison of the FEA-predicted displacement and the measured displacement at the critical point showed that the stimulation produced a conservative estimate of the scooter's structural response. The critical location identified by the FEA was at the end of the handlebars, where the maximum displacement was predicted to be approximately 0.15 inches under the applied load. During physical testing, the handlebar displacement was measured to be approximately 0.0625 inches, which is less than half of the predicted value. Although the displacements differed, both the simulation and experimental results identified the handlebars as the region most susceptible to deflection, which indicates that the FEA accurately captured the overall deformation pattern.

The frame of the scooter did not display any measurable deflection when loaded with the intended weight. The measured displacement of the frame of the scooter suggests that the actual scooter structure possessed greater stiffness than the numerical model, likely due to reinforcing the PVC fittings. Therefore, while the FEA overpredicted the displacement, it successfully identified the critical deformation location and provided a conservative assessment of the scooter's structural performance.

Measured versus Predicted Differences

The experimental testing results generally agreed with the predictions from the FEA simulations, which validated the overall structural design of the scooter. The final FEA model predicted a maximum stress of approximately 0.9 kpsi and a handlebar deflection of about 0.15 inches under the design load. During physical testing, the scooter successfully supported the required load without any signs of structural failure, excessive deformation, or material cracking, confirming that the actual stress remained well below the material's allowable limits. The measured handlebar deflection during the static load test was approximately 0.0625 inches, which was lower than the simulated value, indicating that the physical structure was stiffer than predicted. This discrepancy is likely due to conservative modeling assumptions and the additional stiffness provided by PVC fittings and glued joints that were not fully represented in the simulation. Overall, the similar results between the predicted and observed performance demonstrate that the FEA model provided a reliable estimate of the scooter's structural behavior and safety margin.

RECOMMENDATIONS FOR IMPROVEMENT

Although the final prototype successfully met the project's objectives and demonstrated adequate strength and stability, several improvements could be implemented in future iterations.

The most significant improvement would be incorporating an adjustable handlebar and knee platform height. During testing, the scooter was found to be slightly too tall for the intended user due to the additional height introduced by PVC fittings. An adjustable design would allow the scooter to accommodate users with different body dimensions and improve overall ergonomics.

One major improvement could be reinforcing connection between the steering column and axel. This connection was the weakest connection from the regular testing and was the main reason for the wobble on the scooter. A 3D printer connection or a longer female part connecting the 1 in steering column can go a long was in improving the stability of the overall scooter.

Another improvement would be replacing the PVC material with lightweight aluminum tubing. While PVC provided a low-cost and easily manufactured solution, aluminum would significantly increase stiffness, durability, and impact resistance while reducing long-term deformation and joint wear.

Future design could also incorporate braking systems. The current prototype relies on the user stopping with their healthy leg, which may not be practical on slopes or uneven terrain. A simple hand-operated brake would improve safety and control.