Multi-Disciplinary Engineering Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P12007

EQUILIBRATE MECHANICAL SYSTEM UPGRADE

Sado Borcilo / Structural Design
Diana Rodriguez / Materials Analysis
David Lahn / Project Manager
Natalie Ferrari / Materials Analysis

ABSTRACT
This project investigates a mechanical redesign of the Equilibrate biomedical balance measurement system with a primary focus of weight reduction and improved aesthetics. Primary design constraints involve functionality, durability, and manufacturability. In this paper the benchmarking, concept selection, design iterations, prototyping, testing processes, and results are summarized in detail.

INTRODUCTION
The Equilibrate Balance system is a portable, clinical assessment, therapy, and data reference biomedical device. Primary market focuses are physical therapy, rehabilitation, concussion management, sports medicine, elderly care services, and fall management. The system, shown in Figure 1, is a profitable product and created and sold by BalancEngineering. The device works by performing postural based measurements. The user stands as motionless as possible, and changes in the their body position are measured in 2 ways: the lower body movements are measured via force plates the patient is standing on, and upper body movements are measured via a vision system tracking the movement of highlighted "markers" on a vest worn by the user (Figure 1). This data is then used to prescribe corrective action or corresponding therapies by the clinician.

Figure 1: Product in current configuration

Figure 2: Product in Carrying Case

The unit can be removed from its carrying case, set up in an office, clinic, or any other location, and be operational in within five minutes. The current weight of the total system is approximately 44lbs. It is transported between use sites in two carrying cases, the case shown in Figure 2 and a backpack for the included laptop. It can support a wide range of patient heights and weights with the only identified failure point being the point of attachment between the camera and structure.

The client Michael Compisi, president of BalancEngineering, is interested in continuous improvement of the design of their product and has already undertaken several product iterations. The key selling points of the product are flexibility and portability, and as such the present project focus is weight reduction and improved aesthetics, while maintaining current system cost, durability, and functionality with the system's proprietary software. Special considerations must be given to the limited manufacturing capability of the client, only light machining, drilling, and assembly are available in-house.

PROCESS
Defining Needs and Specifications
Customer needs were defined through live consults with the client, BalancEngineering. High level needs being:

- weight reduction for portability
- aesthetics for marketability
- ease of use & set-up for non-technical physician use
- stability for camera motion tracking
- adjustability for different customer body types
- functionality with current propriety software,
- maintaining or reducing budget and assembly man hours.

These needs were then translated to measurable engineering specifications by benchmarking the current product through a series of tests and client evaluations (Table 1).

Table 1: Engineering Specifications

Specification (metric)	Unit of Measure	Current System Benchmark	Ideal Design Value	Proposed Design	Prototype Test Results
Total Weight	**lbs.**	**44lbs**	**35lbs**	**33lbs**	
Foot plate weight	lbs.	4.35lbs / each	2.18lbs / each	2.83lbs / each	3.0lbs / each
Camera structure weight	lbs.	13.6 lbs	10 lbs	8.88 lbs	6.4 lbs
Foot Track System Weight	lbs.	9.12lbs	10lbs	10.09lbs	11.12 lbs
Total Aesthetics	**Qualitative (1-10)**	**5**			
Camera structure aesthetics	qualitative (1-10)	5	10	7	6
Cabling aesthetics	qualitative (1-10)	5	10	8	7
Total Set Up Time	**seconds**	**≤ 300 s**	**300s**	**300 s**	
Mechanical Camera structure set up time	seconds	78	75	75	75.6
Foot plate removal time	seconds	3 - 9s	2s	5s	
Total Stability					
Unintentional camera movement	inches	3	< 3	3.2	4.5
Unintentional foot pad movement	inches	0.05	<0.1	0.1	0.34
Total Adjustability					
Camera height adjustability	inches	18.5" - 57"	18.5 - 57"	18.5 - 57"	18.5 - 57"
Foot pads adjustability North - South	inches	0" - 44"	0" - 44"	0 - 44"	0 - 44"
Foot pads adjustability East - West	inches	0"	0"	0 - 12"	0 - 12"
Total Functionality					
Foot Plate Deformation under 165lbs	inches	0.0181	< 0.02482	0.03606	0.0288
Foot Plate Max Stress	PSI	5,500	5500	5900	>=5900
Camera X distance from Edge of foot pads	inches	44"	44"	44"	44"
Camera Y distance from center of foot pads	inches	27"	27"	27"	27"
Total Portability					
Total deployed footprint	feet	50" x 60"	50" x 60"	50" x 60"	
Total un-deployed size	inches	48"x21"x8"	≤48"x21"x8"	48"x21"x8"	

DEFINING SUBASSEMBLIES

A functional decomposition of the device was created and utilized to break the assembly into three independent sub-assemblies or components. They are as follows: foot-plates, camera structure, and foot-track. Each component was managed by a separate team member. Please see figure 12 for a decomposition of the functions required for each component.

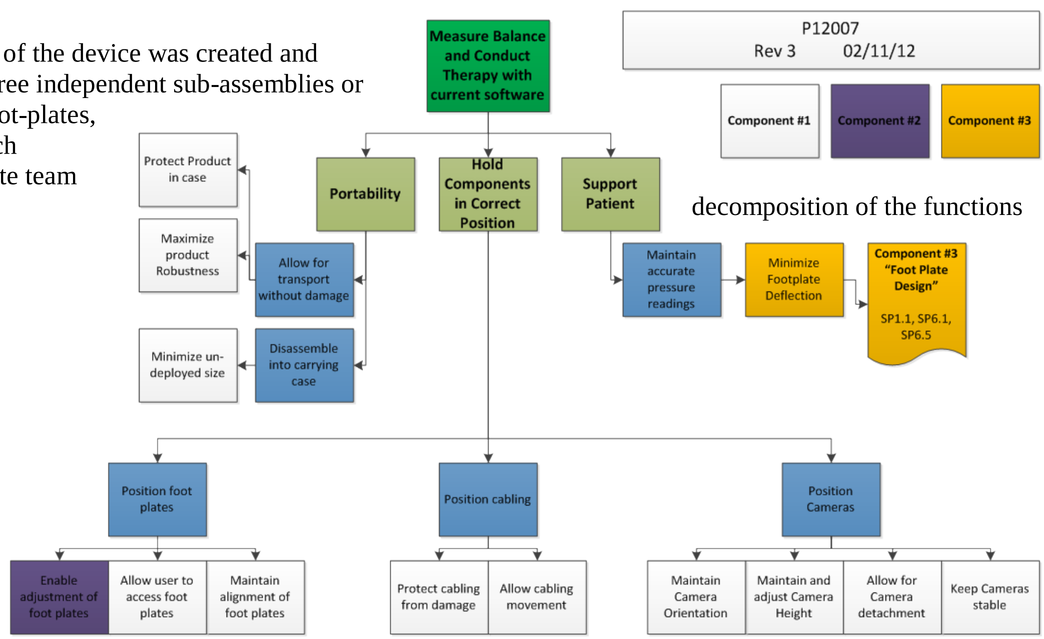

Figure 3: Functional Decomposition for Equilibrate System Upgrade

FOOT PLATES

Required Functions

The required function of the footplate is to provide accurate readings to the force sensors. The sensors are located in each of the four corners underneath the foot plate. In order to supply precise data, the plate must be able to withstand a weight of 250lbs with no sensible deflection to the subject using the device.

Concepts

Concept selection for the foot plate stemmed from the current plate the equilibrate system utilizes. The overall goal for the proposed design was to reduce the weight of the plate without compromising specifications set forth by the customer. The requirements for the plate were weight reduction and maintenance of the current deflection and stress performance under a 250lb load. Also the footprint (15" x 8") of the plate needed to remain the same in order to make contact with the data collecting force sensors in each of the four corners.

The material of the plate was decided upon first. The current material used for the foot plate is 6061-T6 Aluminum. Other materials such as steel, for increased strength, and plastics, for decreased weight, were researched as potential alternatives. Table 2 is a comparison of the weight of Steel and ABS to aluminum at various thicknesses.

Table 2: Weight, Thickness, and Deflection Comparison for Foot Plate Materials

Material	Elastic Modulus ksi)	Density (lb/in^3)	Thickness (in)	Weight (t)	Comparable Deflection (in) (Used Cantilever Beam)
Aluminum (current)	10,000	0.0975	0.375	4.35	1.90
Steel	11,603	0.278	0.125	4.13	44.13
ABS	334	0.0488	1.125	5.03	2.11

In order to utilize steel, the thickness of the plate would have to be reduced because steel is denser than aluminum. Even at on third the thickness of the current aluminum plate, the steel plate only weighed 0.22 lbs less than the aluminum plate. Also, the comparable deflection at this thickness does not hold up to that of the aluminum. This proves that steel is too heavy to use for this application and the thickness cannot be reduced to a lower value without compromising the amount of deflection. As for ABS, the thickness would have to be increased because ABS is less dense than aluminum. In order to be able to compare to the deflection specification set by the aluminum, the ABS would have to be three times the thickness which makes it weight more than the current plate. Ultimately, the current material, 6061-T6 aluminum was found to be most fitting and affordable.

Design, Drawings, Design Analysis

The current foot plate underwent a simulation study to determine a benchmark for the deflection and stress. The plate was placed under boundary conditions of roller supports in three corners and a pin support in the fourth corner. This configuration was chosen to mimic how the plate sits on the forces sensors and reacts under a load. As for the load applied, the plate was subject to the worst case scenario of a single point load placed in the center of the plate. A load of 250lbs was used because this is the upper bound of body weight for people that will be using the current system. If the foot plate can withstand a static load when the person steps onto one plate then it is expect to be able to hold a person when the weight is evenly distributed over both plates. The load experienced by the plate would be cut in half, registering around 125lbs per plate. Figure 3 displays the simulation boundary conditions placed upon the plate to replicate what is experienced in the field.

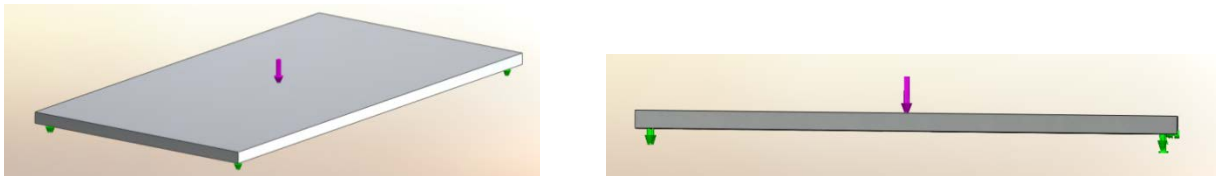

Figure 4: Solidworks Setup for Theoretical Testing

A series of proposed designs involving different patterns of removed material were run through the simulation model. The design started with a drastic removal of material and stepped towards a pattern that complied with the specifications. Figure 4 is solid models of the proposed designs for an improved foot plate design. If the weight and deflection experienced were not comparable to that of the current plate, the design was throw out. The final design resulted in an improvement of 1.5 lbs and a reasonable deflection of 0.029 in.

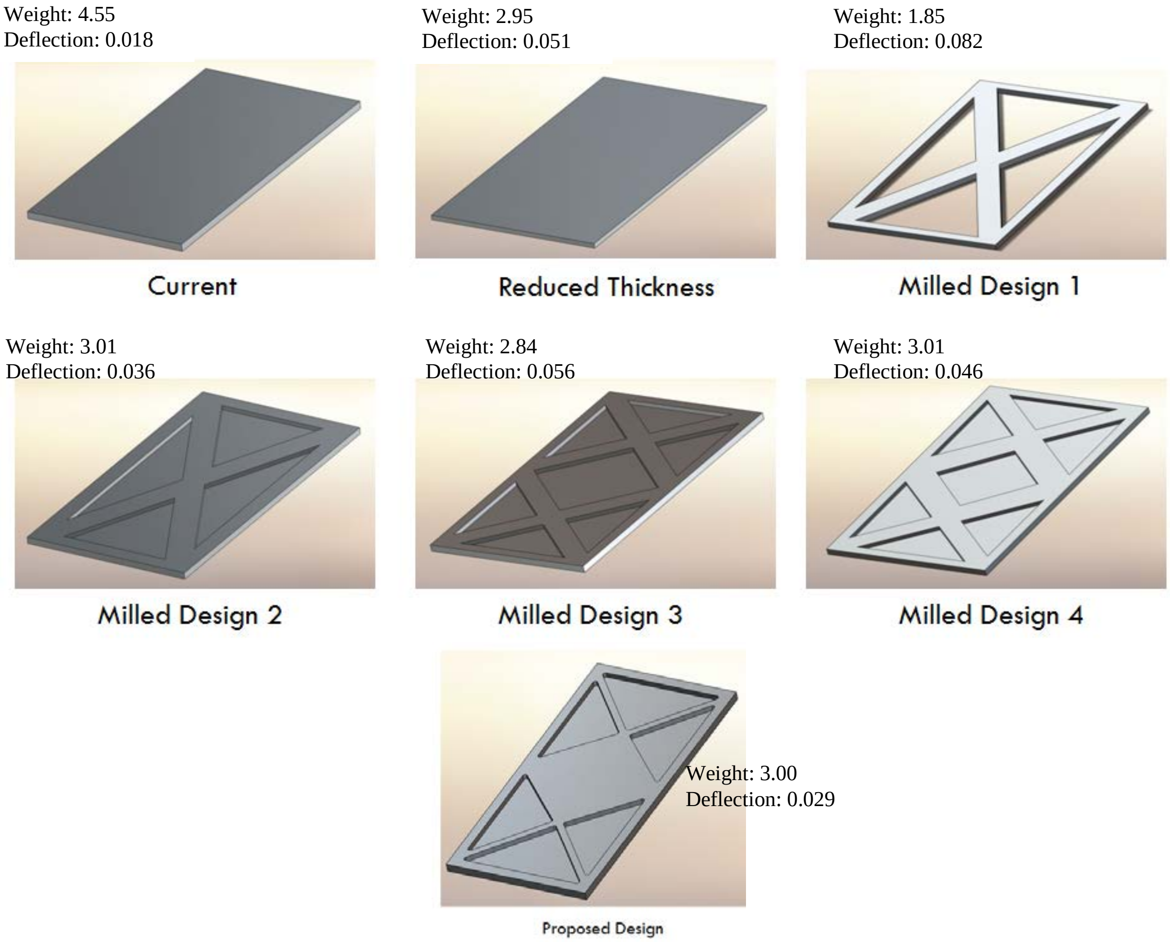

Figure 5: Possible Designs for Foot Plates

Prototyping and Testing

A prototype plate was machined and tested. The proposed pattern was milled out by the Brinkman Lab. The plate was placed upon four, 0.125 in aluminum squares to support the corners. From the bottom, a dial indicator was placed up through the table, centered in the middle of the plate and zeroed. A person weighing approximately 165 lbs stepped onto the plate, the measurement was read off the indicator, and the person stepped off. This was repeated nine more times and the data were averaged to find an average deflection associated with the plate. Figure 6 displays pictures taken during the experimental testing of the foot plate.

Figure 6: Prototype of Foot Plate

Figure 7: Testing Setup for Foot Plates

Evaluation

The proposed plate design meets the design specifications set for by the customer. It performed substantially better than the thin plate, which was a previous design iteration and deemed uncomfortable to stand on. The weight was decreased by about 1.5 lbs (3 lbs for both) while maintaining a reasonable deflection that only deviated about 0.01 inches. This distance is considered to be acceptable.

Table 3: Weight vs. Deflection Data for Foot Plates

Experimental Foot Plate Data			
Design	**Plate Thickness (in)**	**Weight (lb)**	**Max Deflection (in)**
Current	0.375	4.55	0.018
Proposed	0.375	3.00	0.029
Thin Plate	0.250	2.90	0.051

CAMERA STRUCTURE

Required Functions

The goals of redesigning the camera structure were to reduce the overall weight, increase aesthetic appeal, hide wiring, and reduce cost. What also needed to be considered was that with any change, the structural integrity had to match the originals. If they did not, there needed to be an overwhelming benefit from it.

Concepts

The first step taken in designing the camera structure was deciding what material to use. The material that was chosen would have to have to be able to fulfill all the desired requirements given to us by BalancEngineering, in addition to being readily accessible and available for mass production. After deliberating the possibility of various materials, the obvious choice was to stick with 80/20 and see what other extrusions they had that would be suited for the redesign. The reasoning behind the choice was that BalancEngineering already had a dependable supplier, and this would make it easy for them to obtain additional components that may be needed. There was also an attempt to stray from the more expensive fixtures, such as the sliding pieces from the original design, so to reduce the cost.

Once the decision had been made to use 80/20, the search, for the right pieces to meet the needs, began. After looking through the 80/20 catalog, three designs had been created to fulfill most, if not all the needs. The three designs are shown in Figure 8. With all three figures, the decision was made to go with a Y base design. The reasoning for this was to reduce material, and in return reduce overall weight. The way the Y base was created, was that the cameras were left in their original position. From there the length of the footplate track was determined. The track has a max length that it travels on. With those two dimensions, some trigonometry was done, and the Y shape was determined.

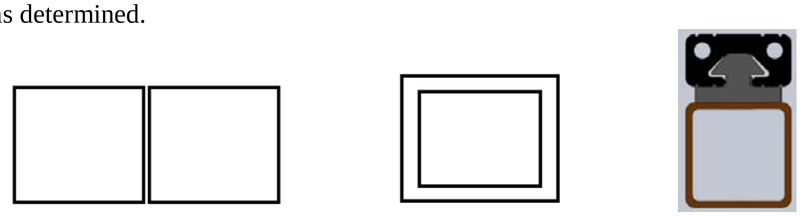

Figure 8: Possible Designs for Camera Structure (Left: Design 1, Middle: Design 2, Right: Design 3)

Design 1 is a 1" square tube within a 1.5" square tube. The base is made of 1.5" tubing. Design 2 is a rework of the original design using 1" square hollow tubes instead of the solid 80/20 extrusion that was originally used. Design 3 was the selected choice (Figure 8). This design has a 1" square hollow tube as the main support, and a 1" by 0.5" sliding rail on its side to allow for height adjustability. Plastic guide rails were fastened to the side of the 1" tubing to aid in alignment of the sliding rail as its position changed vertically. The base connections are made up 1" square tubing as well. All three designs have an addition feature, which is a set of adjustable feet, shown in Figure 9. The feet are purchased parts from 80/20 and have a bolt within the tubing that allows for adjustment in the vertical direction.

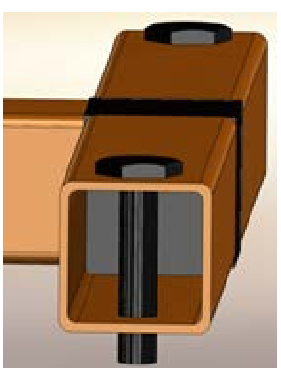

Figure 9: Feet Design for Camera Structure

The reason that design 3 was chosen is shown in Table 4. With each design, an analysis on three main features was taken. The tree determining factors included; weight, deflection, and cost. The weight parameter was a simple summation of the components weights that would be used in each design. These numbers were found in the 80/20 catalog. The deflection portion of the analysis was used to verify that the structure would be as ridged and sturdy as the original. The way this was calculated was that a theoretical 5lb force was applied to the top of each vertical support at maximum extension, and the deflection was obtained for each design. The vertical support was modeled as a single beam with a fixed base. This did not take into consideration bending or deflection of other parts of the assembly.. Results are shown in Table 4

$$I_{hollow} = \frac{WH^3 - W_I H_I^3}{12} \quad \text{.....(1)}$$

Table 4: Design Feasibility for Camera Structure

Design	Weight (lbs)	Deflection (in)	Cost ($)
Original	15.97	0.64922	587.64
Design 1	17.60	0.09581	273.37
Design 2	9.74	0.86021	294.94
Design 3	8.91	0.69977	231.30

The values for each design were then compared to the original. The final comparison parameter was the cost of the system, which was based on individual component costs found in the 80/20 pricing catalog. As it can be seen, Design 3 was the design that did the best in this comparison and is why it was chosen as the final design. Design 3 also had the beneficial feature of allowing wires to be canceled within the hollow tubes. This benefit also makes Design 3 much more desirable than the other two.

Once Design 3 was determined to have the acceptable deflection, additional analysis was done to determine the most likely point of failure under loading. The focus was on where bending or shear would occur when loading was applied. The results show that the structure would collapse on itself first due to a load, before failure would occur anywhere else. This would be the case with either the original design, or the new one, only the forces may be different. The analysis and results are shown below.

$$\boldsymbol{\sigma_{bending}} = \frac{\boldsymbol{F \times L}}{\left(\boldsymbol{I}/_{\boldsymbol{0.5H}}\right)} \ldots..(2) \qquad \boldsymbol{\tau_{bolt}} = \boldsymbol{F} \times \boldsymbol{A} \ldots..(3) \qquad \boldsymbol{\tau_{surface}} = \frac{\boldsymbol{M_C}}{\boldsymbol{I}} \ldots..(4)$$

With design 3, there is some additional machining that needs to be done, either by 80/20 before the products reach BalancEngineering, or by BalancEngineering themselves. Additional machining needs to be done to the vertical support beam, as well as an additional hole in the base support to allow wires to be maneuvered through the base tube. This is the only additional machining to the camera structure that Balance engineering would have to do in comparison to the original structure. All the machining can be seen in the drawing package attached.

Table 5: Failure Analysis for Camera Structure Design

				Yield Strength	35000	lbs/in^2			
	Force required for Bending			Tensile Strength	38000	lbs/in^2			
Original	55.25	lb							
Slider (x) @ 28 inches	37	lb		Bending	F=Yield*I/(L*.5H)		Shear Force=load/area		
Slider (Y) @ 28 inches	80.75	lb							
Hollow Tube @ 28 inches	83.25			I (80/20)	0.0442	in^4	I (pivot joi	0.0833	in^4
				I (Hollow Tube)	0.0333	in^4			
Assumer Slier does not bend				Ix (sliding piece)	0.0074	in^4			
Hollow Tube @ 56 inches	41.625			Iy (sliding Piece)	0.0323	in^4			
Max force for before yielding is 41 lbs				Original Length	56	in	Assume 1x1 rectangle		
				Slider	28	in	h	1	in
Force applied to Pivot connection due to 41 lbs	2331	lbs		hollow tube	28	in	l	1	in
(summation of moments)							w	0.158	in
				h (tube & 8020)	1	in			
Yield stress due to 2331 lbs on pivot	55966.4			hx (slider)	0.5	in			
				hy (slider)	1	in			
55966 > 35000 there fore bending occurs at pivot									
				Bolts are ASME Grade 5					
				yield	75000	lbs/in^2			
Bolt Shear	Shear Load			Coefficient Of Friction					
Summation of moments at pivot	2289	lbs		Aluminum	0.3				
(with 41 lbs)									
Shear Force	32382.7								
75000 > 32382 therefore failure does not occur at bolts									
Normal Force required to counter 41 lbs	7770	lbs							
(sum of moments)	Not realistic, so vertical arm will fold when 41 lbs is applied in the direction of folding.								

Testing

Once the prototype was fully built, tests were performed to see how the physical modeled compared to the theoretical one. The way the testing was performed was the prototype was erected to full extension, than with a force gauge, a load of 5lb was applied to the highest point of the vertical bar. The load was applied in each direction (front, back, and east and west) and values were recorded for how far the structure deflected. To get the values, a mark was placed on a whiteboard to signify its original position, and then another mark was drawn at the deflected position. A ruler was then used to measure the deflection. There were two observances that were noticed that needed mentioning. One was that when the 5lb load was applied to the back of the structure, this would be in the direction of how the system collapses; it took less than 5lbs for the system to collapse. So, instead of measuring the deflection, the load at which the system collapsed was taken. Two, the structure deflected much more than the theoretical model. This can be explained easily. The reasoning is that the theoretical model considered the structure a beam with a fixed bottom. The actual structure was not only deflecting at the top, bending was occurring throughout the entire structure increasing the deflection at the top. The test was done on both the original and the new prototype, and the results are shown below.

Original		
	Load Applied (5lb)	Deflection (inches)
	Front	1 1/4
	Left	3
	Right	4 15/16
	Collapse Load	4.34 lbs

Table 6: Deflection Data for Original Design

New		
	Load Applied (5lb)	Deflection (inches)
	Front	0.75
	Left	4.5
	Right	4.25
	Collapse Load	2.69 lbs

Table 7: Deflection Data New Design

Evaluation

When comparing the original with design with the final product, there were some alterations made before the design could be deemed acceptable. When comparing the calculated results for the deflection vs. the actual deflection results, Figure 5 vs. Figures 7 and 8, it can be seen that the actual results are much more than the calculated ones. This is the case for both the original and the new design. The reason for this is that the calculated system was modeled as a single bar with a fixed base. It did not take into account how the other components would react to the loading. With the actual testing, bending occurred at more than just the vertical bar and is why the deflection was greater. Though, it can be seen that the deflection of the new design was not too far off from the original. Some areas are even better than the original.

Certain recommendations that should be mentioned to better improve the system are as follows. One, an option to increase stability of the structure would be to add some additional weight at the base of the vertical bar to counteract the torque at when the vertical bar is fully extended. If weight is not an option, extending the length of the feet supports should also have the same effect. These would be the main modification that could be made to the final design.

FOOT TRACK

Required Functions

Position the foot pads while allowing adjustability for stances of different widths. Maintain portability and software functionality.

Concepts

It was decided early on that the west/east (W/E) tracks would enter the side of the foot plate base. A few concepts involving one of the tracks running along the side of the base were considered, but were found to be unfeasible. The needed details of the design were the number of tracks, position of track(s), and how to lock the track(s) in place.

Originally, the design consisted of one track in the center of the base. This was expanded to two tracks to help prevent horizontal bending from north/south (N/S) movement while W/E tracks are fully extended.

The first design, involving two tracks, had them placed close together in the center of the base. They were later moved more towards the outer edge of the box. This placement was decided upon to insure that the tracks would not interfere with any deflection of the foot plates and also to prevent against horizontal bending of the W/E tracks.

The last detail decided upon was how to lock the track in place for testing. Because the W/E tracks are nearly completely internal to the foot plate base, they could not use a locking mechanism similar to the N/S track. One idea that was considered was lining the hole in the base with rubber or some other material to add friction. This idea was not used because the costumer did not want a resistance 'lock'. An acceptable concept for this aspect of the design was not finalized until after the detailed design review. The lock that was found to be acceptable consists of two types of McMaster headless screws and a triple T-Nut from 8020 and placed on the front W/E track (Figure 10).

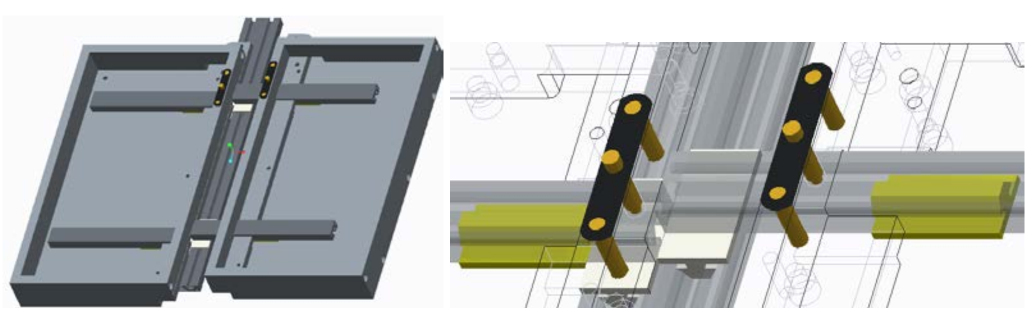

Figure 10: Design Iteration One

For this track design, the foot plate bases are not directly connected to the N/S track, therefore the N/S lock had to be changed. The lock is now placed in the rear W/E track. A hole was drilled and threaded through the track and the slider and a McMaster headless screw is used to hold the W/E track against the N/S track.

Prototyping

For making the prototype, the foot plate box needed to be machined to house the W/E track. A band-saw was used to cut the box slider into the three pieces. The pockets in the base slider and the inner wall were cut using the mill. And, finally the holes were made using the drill press and were then threaded with the needed size.

Figure 11: CAD Model of Final

Design Iteration Two

Using an Allen wrench to lock the tracks in place was decided to be too difficult by the customer. For the second iteration, the W/E track utilized an indexing system for the locking mechanism. For the N/S track, the locking mechanism was changed to a setup very similar to the original design. It used the double-hole t-nut from the original lock. The t-nut is attached to a plastic shim which is attached to one of the W/E tracks. A thumbscrew is used to tighten and loosen the lock.

The base of the foot plate box is extended a bit past the front wall, so that one W/E track and slider is outside the box so that the thumbscrew is easier to access. A CAD model of this design is shown in Figure 11.

Design For Foot Plate Track Testing

The main aspect to be tested is the deflection cause by a force on the box. A force gage was used to measure the force applied in the N/S or W/E direction, the deflection was measured with calipers. The testing set up for the final design is shown in Figure 12 and the results of the testing are shown in Table 8.

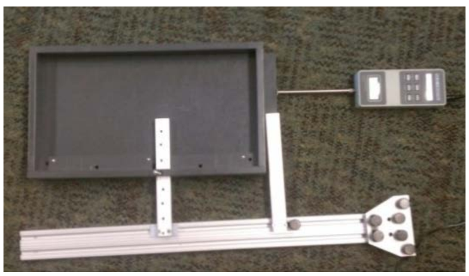

Figure 12: Testing Setup for Final Foot Plate Track Design

Table 8: Deflection of Track System Under a 20lb Force (in)

	North/South	West/East
Current Design	0.05	0.1
Proposed Design	0.34	0.1

The W/E deflection for this design did not change from the previous design. The N/S deflection increased by nearly a factor of 7. However, the reason for this increase was readily visible. Only the rear W/E track has the pin locking, which can be seen in Figure 12. When the force was applied in the N/S direction, perpendicular to the W/E track, the front track would shift against its slider since it was not being held in place in by anything more than friction. This problem can easily be fixed by the having the pin locking setup for both W/E tracks. With this addition, the deflection should fall to a more reasonable value.

SYSTEM INTEGRATION

System Testing and Evaluation

Final system integration with the equilibrate software did not occur due to software and time constraints. System testing was conducted on the prototype and the results are summarized in Table 10.

Table 10: Deflection of Track System Under a 20lb Force (in)

	Original	Prototype	Improvement
Weight (Lb.)	31.42	23.52	7.9 Lb. Reduction
Aesthetics (Rating)	5	6.5	1.5 Customer Rating
Assembly (s)	78	76	Maintained
Cost	587.64	242.6	$345.04 Reduction

Conclusions and recommendations

Overall the project was successful with favorable system outcomes and customer acceptance. The track system component still requires an additional design iteration to increase usability and stability. It is recommended that the customer also investigates the following: lighter material for the ABS foot plate housing, custom length extruded plastic guides for the telescoping components, and wireless cameras and controls

During the course of the project the team learned several lessons for a product redesign. Bench mark the current system for specific measurable results as soon as possible. Begin prototyping as early as possible to allow for multiple design iterations. Finally, we learned to have pride in our work.

ACKNOWLEDGMENT

BalancEngineering
MichaelCompisi

Rochester Institute of Technology
John Kaemmerlen Tim Landschoot
Matt Marshall Mark Smith
Elizabeth DeBartolo