Advanced Mechanical Design, University of Rochester
Final Design Report
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URMC MOTION LAB PERTURBATION DEVICE

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ABSTRACT

The team was tasked by the sponsor (University of Rochester Medicine Motion Analysis Laboratory) to engineer and develop a prototype of an integrated harness with load cells and amplifiers as well as modifying and improving other components such as floor coverings and safety mechanisms that the lab was already implementing. The project followed a predetermined deadline set in accordance with the sponsor, the course instructor, and the team.

Certain deliverables such as the harness, load cells, and amplifiers were purchased while other deliverables such as the floor coverings, corner markers, spools, amplifier boats, and guide bolts were built or modified to carry out the necessary functionality associated with it.

To ensure the deliverables met all the requirements specified, tests were carried out in the presence of the Motion Lab representatives. To test the specifications, a team member was hooked up to the entire system at the Motion Lab as if they were a patient, using the final prototypes. These tests included being hooked onto the frame, pulling on the harness with enough force to disturb gait, testing the load cells and amplifier interactions, raising the treadmill incline to 9 degrees, and ensuring the angle of the knee is larger than 90 degrees when tripped. The final prototypes passed all the necessary tests to match the predefined requirements and specifications. With the developments made this semester, the Motion Lab can begin to implement these prototypes and solutions while they begin to see patients with it.

PROBLEM DEFINITION

The University of Rochester Medicine Motion Analysis Laboratory studies the kinematics of human motion and develops experiments and therapies to help understand stability and to improve movement. This project focuses on the creation of a perturbation device. It includes hardware that is designed to safely trip a user so that their ability to recover can be safely measured and improved. It has been developed to replicate slip-like disturbances during gait, providing an objective platform to study neuromechanical responses and stability. The system integrates strain gauge feedback, enabling precise, multidirectional forces, and is implemented alongside treadmills, motion captures, and force plate systems.

Controlled perturbations allow measurement of response timing, compensatory strategies, and joint loading patterns. This approach offers surgeons, physical therapists, and rehabilitation specialists actionable insight to identify deficits in balance control, guide individualized post-injury rehabilitation, and implement targeted interventions aimed at restoring functional gait and reducing fall risk in orthopedic, neurosurgical, and balance-impaired patient populations. There are aspects of this device that have already been implemented in the lab, but other items needed lots of improvements before it can be used by patients full-time. The patients that will be using this device will likely have concussions, are recovering from surgeries, or will have other mobility issues because of issues like weight, illness, or injury. It is essential that this device is safe and comfortable in addition to its functionality. By improving current features such as alignment of the frame, harness design, cable management, and the VR environment, using the perturbation device will be efficient for both the healthcare provider and the patient. It will allow a healthcare provider to focus more on the patient and the data they are taking. On the other hand, it will allow a patient to feel comfortable and safe in this environment. It is necessary that patients seeking help from the Motion Lab can receive effective care. By making a device that is more streamlined, more robust, and safer, the lab will be able to see more patients, and in the end, help more people.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

To ensure the correct design and success of the project, certain requirements are defined in consultation with the customer (University of Rochester Motion Lab) and supervisor (Professor Muir). The requirements are as follows:

- Mounting plates on the frame must be aligned
- Harness must fit the 5th to 95th percentile of male and female body types in the US and be able to measure patients at the hip with motion trackers
- Packaging for load cell wires will be clean and will not interfere with tension of paracords
- Device must be able to disturb gait and catch a fall safely

- Prototype must be designed robustly for continuous everyday use
- Patients must be able to be pulled in the cardinal and ordinal directions

Glove and foot upgrades to incorporate motion trackers were also an initial requirement but was later removed by the sponsor because of time constraints.

To design and build prototypes to meet the mentioned requirements, certain specifications are determined and confirmed by the customer (University of Rochester Motion Lab) and supervisor (Professor Muir). The specifications are as follows:

- The designed components will be built by ensuring a factor of safety equal to 2 times the applied force
    - This includes built and bought items
    - This will be verified by calculating the specific forces that elements will see (see Appendix C, Figure 17 for example calculation)
- The harness, frame and any other deliverables must maintain functionality when the treadmill is inclined up to 9 degrees
    - This will be verified during implementation and testing
- The adjustment increments for the height adjustment of the pulleys will be no greater than 2 inches
    - This will be verified with a tape measurer/ruler during implementation and testing
- The harness will allow for adjustments such that the angle of the patient's knee does not go past 90 degrees
    - This will be verified using a protractor during testing
- The frame must be able to be set up by no more than two able bodied people
    - This will be verified during implementation and testing

At the end of the project, the following items were delivered to the University of Rochester Motion Lab:

- Functional prototype
    - This will include a frame, a harness, and load cell/amplifier placement on the frame and harness
- Technical report with test data
- Theory of operation manual
    - These will be a set of instructions for various items or functions to streamline use or maintenance in the future

CONCEPTS

Purchasing the waist harness and the frame alignment solution required concept selection via selection matrices.

The frame that the Motion Lab was originally using did not align with the mounting posts that are permanently attached to the floor. Shown in Appendix A, Figure 10, each concept represents each team member's idea to resolve this issue. Zack Farnam, the Motion Lab's motion engineer, suggested a fifth solution to use bolts facing upwards with cone shaped tips as locators to guide the frame into place more easily than before (see Appendix A, Figure 9), which is listed as "Idea 1" in the selection matrix (see Appendix A, Table 3). Based on the evaluation criteria for the selection matrix, this idea won in the most important categories. This includes time to implement, speed, and safety (see Appendix A, Table 3 for all criteria, criteria descriptions, and criteria weight), so the team therefore decided to move forward with this solution. Bolts provided by the Motion Lab were modified to create the cone tip (see the manufacturing section for a more detailed process). This system was implemented and works well with the current frame set up. Figure 9 in Appendix A depicts what the system will look like without the frame attached, with the frame attached, and the floor covers. The latter is a solution to prevent someone from falling into those holes created by the frame posts.

In Appendix A, Figure 12, each concept represents each team member's idea for the waist harness solution. After meeting with Zack and talking through all ideas, the team decided to combine specific parts of several ideas to ensure maximum safety and comfort of the patient (see Appendix A, Figure 11), which is listed as "Idea 5" in the selection matrix (see Appendix A, Table 4). This idea ranked lower than or tied with some other ideas in the most important categories, including adjustable for all sizes, accessibility of amplifiers, time to implement, cost, and safety. However, it still had the highest total and weighted total in the matrix and was the safest by far (see Appendix A, Table 4 for all criteria, criteria descriptions, and criteria weight). Thus, the team decided to move forward with this idea. Combining this harness with a strap on pouch allows for the load cells, amplifiers, and NI device to be attached directly to the patient. This decreases the number of cords and wires that need to be wired to the patient from outside the frame assembly. Harness criteria included waist size ranges from the 5-95th percentile (28 inches to 54 inches) [1], could still attach the paracord wire to the waist of the harness, could attach the load cell amplifiers to the harness, and could attach the safety cord to the harness. Ultimately, not all of these requirements could be met with a single harness. Because of this, the team utilized the Motion Lab's existing shoulder harness to attach the safety cords. It did not work to attach the pouch, load cells, and amplifiers, but it worked well to attach the safety cords because of the loops on the shoulders. Additionally, a pouch was purchased to clip onto the waist harness to house the amplifiers. All these details can be seen in Appendix A, Figure 11.

MECHANICAL ANALYSIS

Tolerance Analysis:

This analysis determines how far each motion capture marker ball center can deviate from its nominal position when the 3D printed plates are mounted via its two bottom pegs into fixed holes in the frame base. It is important that these plates are mounted in precise locations because they are used to calibrate the motion tracking system. The peg diameter below the 3D printed plate is 0.135 ± 0.00787 in. (± 0.2 mm from Prusa MK4S spec sheet), and the hole diameter in the frame base is 0.138 in. (treated as exact), giving a nominal diametral clearance of

$$\text{Nominal Diameter Clearance} = d_{hole} - d_{peg} \tag{1}$$
$$0.138 - 0.135 = 0.003 \text{ in.}$$

The worst-case maximum clearance is

$$\text{Max Clearance} = d_{hole} - (d_{peg} - \text{peg tolerance}) \tag{2}$$
$$0.138 - (0.135 - 0.00787) = 0.01087 \text{ in.}$$

The worst-case minimum clearance is

$$\text{Min Clearance} = d_{hole} - (d_{peg} + \text{peg tolerance}) \tag{3}$$
$$0.138 - (0.135 + 0.00787) = -0.00487 \text{ in.}$$

This means that there is a slight theoretical interference at the worst-case minimum clearance limit. The radial float in each peg is half the diameter clearance and calculated in Equation 4.

$$\frac{0.01087}{2} = \pm 0.00544 \text{ in} \tag{4}$$

This would be worst-case. The 3D printed plate itself has two pegs spaced 2 in apart center to center. As discussed above, the pegs are smaller than the holes in the frame base, therefore the plate can undergo both translation and rotation. The maximum translation is the radial float (± 0.00544 in worst case). The maximum rotation is found by taking the arctangent of twice the radial float divided by the peg separation [2].

$$\tan^{-1}\left(\frac{2 \times \text{radial float tolerance}}{2}\right) \tag{5}$$

$$\tan^{-1}\left(\frac{2 \times 0.00544}{2}\right) = \pm 0.3115°$$

(or 0.005437 radians) worst case. Each marker ball center is at (0.327, 0.327) inches from their corners on the plate, making them 2.186 in. from the plate's rotation center at (2.5, 0.565). The rotational displacement of the ball center is

$$distance\ from\ center \times \sin(\max rotation) \tag{6}$$
$$2.186 \times \sin(0.005437) = 0.01188 \text{ in}$$

for worst case. Now, combining translation and rotation gives a total peg-and-hole positional error of

$$\sqrt{(radial\ float^2 + rotational\ displacement^2)} \tag{7}$$
$$\sqrt{(0.00544^2 + 0.01188^2)} = 0.01307 \text{ in}$$

for worst-case. The final step is the ball base with a diameter of 0.654 in, sits in a cutout of diameter 0.69 in. This yields a fixed wiggle of

$$\frac{cutout\ diameter}{2} - \frac{ball\ base\ diameter}{2} \tag{8}$$
$$0.345 - 0.327 = 0.0180 \text{ in}$$

Adding the peg-and-hole error with the cutout wiggle gives a total worst case positional uncertainty of ± 0.03107 in (± 0.789 mm). This means the marker ball center can be at worst case ± 0.789 mm away from its expected position. This value is within the given total positional tolerance range of ± 1 mm.

Fatigue Analysis:

This analysis focuses on whether the load cell and eye bolt attachment are susceptible to fatigue failure under cyclic loading from being pulled by the motors. A safe assumption for the maximum pull force from the motor is 10 kg (98.1 N). There is always tension in the paracord, so the minimum pull force that is present when the motor is not pulled is 1 kg (9.81 N). The approximated number of pull cycles over the load cell and eye bolt lifetime is 100,000. Both the load cells and eye bolt attachment are 304 stainless steel. For this material, the yield strength is 35 ksi and the ultimate tensile strength is 85 ksi. The cross-section being analyzed is the area of the threaded connection at the root between the eye bolts and load cell. Both the load cell pegs and eye bolts are size M5. The stress area for the threads is calculated by the following equation

$$A_t = \left(\frac{\pi}{4}\right)\left(5 - (0.9382)(0.8)\right)^2 = 14.18\, mm^2 \tag{9}$$
$$= 0.02198\, in^2$$

Converting forces to lbs. yields F_{max} to be 22.05 lb and F_{min} to be 2.205 lb. Using these values,

$$\sigma_{max} = \frac{22.05}{0.02198} = 1003\, psi \tag{10}$$

$$\sigma_{min} = \frac{2.205}{0.02198} = 100\, psi \tag{11}$$

The midrange stress is the average stress level experienced on the system, and the alternating stress is the fluctuation from that average. These values are

$$\sigma_{mid} = \frac{(1003+100)}{2} = 552\,psi \tag{12}$$

$$\sigma_{avg} = \frac{(1003-100)}{2} = 452\,psi \tag{13}$$

The initial endurance limit estimate S_e' is based on the ultimate tensile strength of the material. Since the material used here has an ultimate tensile strength of 85 ksi, the following relationship applies

$$S_e' = 0.5(85000) = 42500\,psi \tag{14}$$

The actual endurance limit S_e, as defined in lecture, is

$$S_e = k_a k_b k_c k_d k_e k_f \mathrm{S_e} \tag{15}$$

Where k_a is the surface condition factor, with factor a as 2.7 and b as –0.265 for a machined surface finish. This yields

$$k_a = 2.7(85)^{-0.265} = 0.83 \tag{16}$$

k_b is the size factor, and since axial loading has no size effect, $k_b = 1$. k_c is loading type, and again since axial, $k_c = 0.85$. k_d is temperature factor, and since the system operates at room temperature, $k_d = 1$. k_e is reliability factor. Since this device is for medical and rehabilitation purposes, a reliability level of 99% is chosen. From this, $k_e = 0.814$. k_f, the miscellaneous effects factor is set to 1 because things like corrosion, residual stress, and coatings are not considered. Computing S_e from the values above gives a value of 24380 psi. The system will survive infinitely if the stress stays below this value. The M5 thread root creates stress concentration that amplifies local stress. For a threaded fastener under axial tension, the stress concentration factor $k_t = 3$ (conservative estimate from Shigley's). K_a through k_f values come from Professor Muir's lectures. For stainless steel at this geometry, notch sensitivity q = 0.9.

$$k_f = 1 + 0.9(3 - 1) = 2.8 \tag{17}$$

The stress concentration is applied to both alternating and midrange stresses.

$$\sigma_{alt} = 2.8 \times 452 = 1266\,psi \tag{18}$$

$$\sigma_{mid} = 2.8 \times 552 = 1546\,psi \tag{19}$$

The final step is to input these values into the Modified Goodman criterion and Soderberg criterion.

$$\frac{1266}{24380} + \frac{1546}{85000} = 0.07 \tag{20}$$

0.07 < 1, meaning the Modified Goodman criterion predicts the system will have infinite life.

$$\frac{1266}{24380} + \frac{1546}{35000} = 0.09 \tag{21}$$

0.09 < 1, meaning the Soderberg criterion also predicts the system will have infinite life.

Fastener Torque Calculation:

Verifying that bolted connections are torqued properly is critical to ensure safety in an assembly. By finding the proper bolt torque for these connections, it is certain that the bolts will remain in place. The bolt being analyzed is a 1/4-20, 2-inch bolt made of 18-8 stainless steel, zinc-coated, and non-permanent. Using Equation 22 provided in Shigley's, the torque can be found.

$$T = KF_i d \tag{22}$$

Where T is the torque needed, K is the bolt connection coefficient, F_i i s the preload, and d is the nominal bolt diameter. 0.2 was used for the bolt connection coefficient (K) because they are zinc-coated bolts. The nominal bolt diameter (d) is 0.25 inches. F_i is found using Equation 23

$$F_i = 0.75F_p \tag{23}$$

where F_p is the proof load. This equation was provided in the class notes and is used for non-permanent connections. F_p is found using Equation 24 which was provided in the class notes.

$$F_p = A_t S_p \tag{24}$$

Where A_t is the stress area and S_p is the proof strength. The stress area (A_t) is 0.0318 square inches and the proof strength (S_p) is 30 ksi. The proof strength was not explicitly given in the item specifications but was estimated using table 8-9 in Shigley's and in the course notes.

Using these equations and values, the proper bolt torque was calculated to be 2.98 lb-ft. This value can easily be achieved because this much torque can be applied using a wrench.

Material Selection:

An important part of the integrated harness is the connection between load cells and motors. The motors are placed in the floor which are connected to the load cell using a paracord. The connection between the paracord and the motor is facilitated by a spool, therefore making the spool an integral part of the system.

The material chosen for the spools was PLA, which is readily available for non-commercial 3D printers. In addition to that, PLA is inexpensive and is easier to replace in the case of fatigue compared to aluminum or steel.

Because the paracord comes from the motors in the ground, there needs to be a hole in the ground to allow it to come up. This creates a potential hazard. To avoid injury caused by stepping on the opening; floor covers were created. These coverings for the floor were made of plywood. Plywood is chosen as it is easy to machine and customize. Other materials such as aluminum and steel were not considered due to the related cost and manufacturing time.

Additionally, the Motion Lab uses motion tracking sensors to determine the different movements of patients and their relative position during the test. This requires calibration and a zero point which can be used as coordinates for measuring the relative position. These calibration markers are positioned in the four different corners of the treadmill. The calibration markers were designed in NX and 3D printed using PLA for its mainstream availability and low cost.

Computer Based Structural FEA Analysis:

Appendix B, Figure 14 represents the finite element model of the simplified frame CAD model seen in Figure 13. The green mesh represents the aluminum tubes, which are CBEAM elements made of aluminum 6061 in NX with tube cross-sections (inner diameter: 1.6 in; outer diameter: 1.9 in). The red mesh represents the paracord cross-braces, which are CBEAM elements made of nylon in NX with rod cross-sections (diameter: 0.13 in). Beams were used for this analysis due to minimal curvature in each part, each cross-section was constant along length, and small cross-sections compared to length. Additionally, an element size of 6 in was used for all geometry, since each metal tube and paracord wire is at least three feet. The red, downward arrows represent a 2500 lbf force in the –Z direction, split based on where the safety cords would attach to the harness. 2500 lbf is the maximum force the frame would undergo, based on the requirement of the 95th percentile male and female body type in the US (see Figure 17 in Appendix C for statics analysis based on this requirement). The bottoms of each of the four legs are fixed (SPC 123456), simulating the bolting of the frame to the plywood on Design Day.

Appendix B, Figure 15 represents the linear statics solution (Solution 101) results of the finite element model seen in Figure 14, Appendix B. The left result displays the magnitude of the nodal displacement in the frame, where the maximum displacement due to the applied 2500 lbf load is 1.729 in. The right result displays the element-nodal stress in in the frame, where the maximum stress due to the applied 2500 lbf load is 3.771e4 psi. This post view uses the Von-Mises stress and maximum of all available locations on beam results. Since the material used for the frame (aluminum) is ductile, Von-Mises is the appropriate stress to evaluate in this context (via Professor Muir's solids review lecture from ME204).

Appendix B, Figure 16 represents the linear buckling solution (Solution 105) displacement results of the finite element model seen in Figure 13. The maximum displacement is 1.003 in in one of the paracord cross-braces, showing that this feature would "buckle" first (since the paracord is a nylon rope, it would simply become slack). However, since the displacement in the statics analysis is relatively low, no reinforcements to prevent this "buckling" are needed.

Fundamental Analysis – Statics:

Calculations for maximum force the safety cord and harness would be subjected to if a 95th percentile male were to fall 1.5 feet was conducted for the factor of safety evaluation. Figure 17 in Appendix C is the primary mechanical analysis for the safety cords that will keep the patient from hitting the ground. The purpose of this analysis is to estimate the maximum tension experienced by the two supporting ropes in the event a 250 lb. (95th percentile) male falls 1.5 ft (roughly where their knees bend 90 degrees) while suspended in the harness system. The patient is stopped with a two-inch stopping distance due to harness stretch/rope absorption in the system. The peak rope tension is used to verify whether the rope selections will be able to successfully handle the load. Two ropes support the patient distributing the load between them, yielding the equation

$$T_{total} = T_1 + T_2 \tag{25}$$

The patient's weight, w, is 250 lbf, free-fall distance, h, is 1.5 ft, and stopping distance, s, is 0.1667 ft. The equation to calculate the force is given by

$$F = w + \frac{wh}{s} \tag{26}$$

Inputting the values above yields 2,500 lbf., meaning each rope holds 1,250 lbf. This value influences design decisions in that the ropes must hold 1,250 lbf with a factor of safety of 2 (2,500 lbf) in accordance with the specifications.

MANUFACTURING

The final system had components that were custom-fabricated, bought, and repurposed from other groups/projects. The manufacturing choices were made mostly based on complexity and time to implement. Some components required very specific custom geometry which were 3D printed, while other parts were cut and assembled using the Rettner and Taylor shops. The following sections show the process for creating each component.

3D Printing

To create the corner markers, spools, and amplifier "boats", creating each design in CAD and 3D printing them was the most efficient option.

The corner calibration marker plates (see Figure 1 below) were designed in Siemens NX. The holes in the frame base and necessary thickness were measured with calipers at the Motion Lab. The markers were 5 in. x 1.13 in. x 0.145 in. The calibration marker base was measured with calipers and the holder on the marker plate was slightly larger to clear the marker bases. The front left marker plate has a hole in the center due to two screws in the frame base that could not be removed. The other three were solid plates.

Once the modeling was done, the group sliced them in PrusaSlicer, added necessary support, and printed them with 30% infill in the Hopeman 3D printing room.

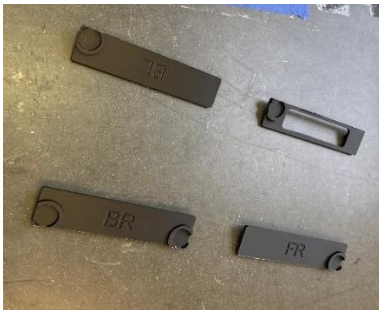


Figure 1 – Corner calibration markers

The motor spools were modeled in Siemens NX with a 14.1 mm internal diameter to fit around a 14 mm motor peg. To secure them, a keyway was cut out of the model, and a key was placed in the spool. Four through holes were put into the wall of one side of the spool to tie the end of the paracord. The parts were sliced using PrusaSlicer and 100% infill was used to make them as strong as possible because the spools snapped using 50% infill on a previous test. Necessary supports were created for each print, and parts were printed in the Hopeman 3D printing room.

The amplifier “boats” (see Figure 2 below) were placed into the harness to provide protection to the wires, so they were not crushed coming out of each side of the amplifiers while in the harness. The amplifier dimensions were measured using calipers, and the boats were modeled in Siemens NX where they had curved ends to protect the wires. The parts were sliced using PrusaSlicer and printed in the Hopeman 3D printing room with 50% infill.

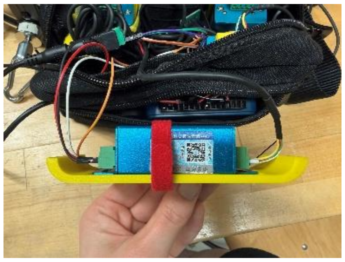


Figure 2 – Amplifier Boats

Guide Bolts

The guide bolts were the team’s solution to the frame alignment issues. These bolts would allow the frame to be mounted and bolted with less effort.

To create the guide bolts, ¼ in. (diameter) bolts were modified so that the holes in the frame (that would match the holes in the mounting plates) could easily slide into the bolts.

Using the belt sander, about ¼ in. of the bolt length was shaped into a cone. The result was a bolt with a point at the threaded end (opposite the end with the bolt head). This would help the frame slide into place easily.

Only two out of the four holes on each mounting plate had guide bolts screwed in. The other two holes were used to bolt the frame down. Additionally, floor covers were manufactured to prevent anyone in the space from stepping directly on the exposed bolts and injuring themselves.

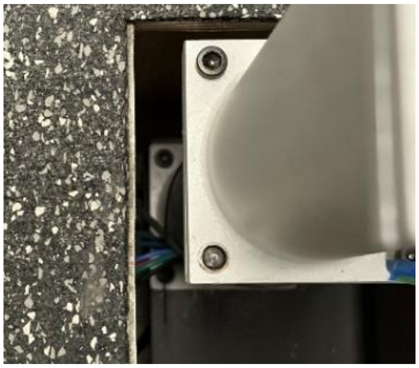


Figure 3 – Single guide bolt facing upwards after frame is attached to the frame post

Floor Covers

The holes in the floor and spiked guide bolts create a hazard for anyone in the space. The solution to this was to create floor covers out of plywood.

The holes in the floor were measured, and plywood was cut accordingly to fit the hole. The table saw was used to cut the plywood into the shape of the hole. Holes were then cut into the floor covers to fit the guide bolts. A handheld drill with a ½ in. bit was used to create these holes.

The rectangular hole in the middle of the floor covers is used as a handle to pick up the covers when the frame needs to be set in place. A handheld drill was used to make holes where the four corners of the rectangle would be, and a handheld jigsaw was used to cut out the rest of the rectangle.

Figure 4 – One of four floor covers

Frame Tubing

The Design Day frame (see Figure 5 below) was created using extra aluminum piping from the Motion Lab. The piping was cut into three three-foot tubes, two four-foot tubes, and four seven-foot tubes, using horizontal band saw. The Motion Lab also provided T-joints and four-way joints to connect the tubes together, and feet to bolt the frame to the sheet of plywood. Once the tubes were in place, a 3/16 in. Allen wrench was used to screw and secure the tubes in place.

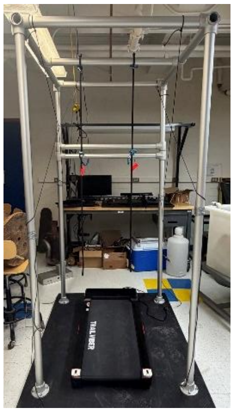


Figure 5 – Frame for design day

Plywood

To prevent the Design Day frame from moving when someone is hanging from it, the frame was bolted onto a 5 ft. x 4 ft. piece of plywood, which was cut to size using a table saw. A handheld drill with a 1/4 in. bit was used to create the four holes for each of the four poles on the Design Day frame. 1/4-20 in. bolts were then used to bolt down the Design Day frame to the plywood sheet.

Grommets

To create the integrated harness, customized to the needs of the Motion Lab, grommets were implemented to organize wiring (see Figure 6 below).

Two grommets on both sides (four grommets total for this application) of the pouch were implemented so the load cell wiring could pass in/out of the pouch without having to go through the zippered opening. Four grommets were implemented between the front and main pouch so that the amplifier wires could connect to the NI DAQ device. The NI DAQ device was placed in the front pocket, whereas the amplifiers were placed in the main pocket.

During this process, a small hole was punched into the harness using a hole puncher provided by the kit, and grommets were clamped together on the hole by a grommet tool provided in the kit.

Figure 6 – Example of grommet placement

Wiring and Cable Management

Ensuring that all cables and wires were dressed and organized well (see Figure 7 below) was necessary to ensure the success of the project. Most of the wiring to the load cell amplifiers and NI DAQ device were placed into the harness pouch to prevent these fragile wires from encountering tension, when the paracords connected to the patient were pulled on. Because the inside of the pouch is smaller than anticipated, the wires fill almost all the space inside, but are color coded to each respective load cell and amplifier to avoid confusion.

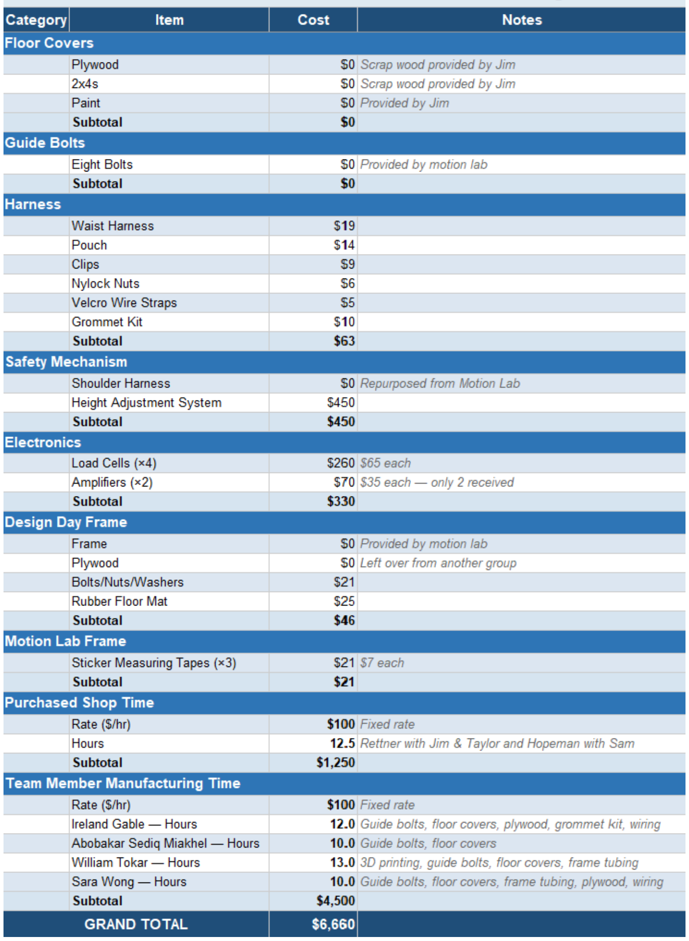
Initially, the connection to the 10V power supply used two banana cables, resulting in unnecessary extra wires inside of the pouch. However, the team was able to resolve this issue by replacing the banana cables with a breadboard where wires were soldered to prevent the wires from coming loose.

Moreover, the team also manually extended the wire of the 10V power supply so that the barrel connector could reach the newly soldered breadboard, which connects to the load cells. The Motion Lab originally had set the wiring up in a way that the banana cables would have had to go inside of the harness. Instead, extending the wire and utilizing a breadboard inside the harness pouch allowed for more flexibility in how things were arranged.

Figure 7 – Wiring and cable management system

If the system were to be scaled by 1000, different considerations and changes in manufacturing and assembly would reduce cost and build time. For example, the safety ropes would be manufactured instead of bought, because they could be created less expensively if the parts were bought individually. The group would have bought ropes, carabiners, and rope grabs. This would lower the cost from $450 to around $100. Additionally, a larger pouch would be purchased to allow for more room for the electronics. The wires inside may be subject to being crushed, so extra considerations had to be taken with the amplifier “boats" to secure the wires. Although slightly more expensive, a larger pouch would allow for more room to work with, making the system easier to assemble.

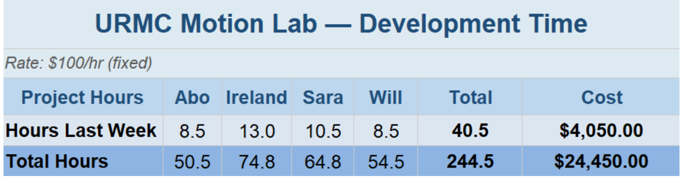
Table 1 – Purchased hardware cost, purchased shop time, team member manufacturing time



URMC Motion Lab — Bill of Materials and Manufacturing Costs

Category	Item	Cost	Notes
Floor Covers			
	Plywood	$0	*Scrap wood provided by Jim*
	2x4s	$0	*Scrap wood provided by Jim*
	Paint	$0	*Provided by Jim*
	Subtotal	**$0**	
Guide Bolts			
	Eight Bolts	$0	*Provided by motion lab*
	Subtotal	**$0**	
Harness			
	Waist Harness	$19	
	Pouch	$14	
	Clips	$9	
	Nylock Nuts	$6	
	Velcro Wire Straps	$5	
	Grommet Kit	$10	
	Subtotal	**$63**	
Safety Mechanism			
	Shoulder Harness	$0	*Repurposed from Motion Lab*
	Height Adjustment System	$450	
	Subtotal	**$450**	
Electronics			
	Load Cells (×4)	$260	*$65 each*
	Amplifiers (×2)	$70	*$35 each — only 2 received*
	Subtotal	**$330**	
Design Day Frame			
	Frame	$0	*Provided by motion lab*
	Plywood	$0	*Left over from another group*
	Bolts/Nuts/Washers	$21	
	Rubber Floor Mat	$25	
	Subtotal	**$46**	
Motion Lab Frame			
	Sticker Measuring Tapes (×3)	$21	*$7 each*
	Subtotal	**$21**	
Purchased Shop Time			
	Rate ($/hr)	**$100**	*Fixed rate*
	Hours	**12.5**	*Rettner with Jim & Taylor and Hopeman with Sam*
	Subtotal	**$1,250**	
Team Member Manufacturing Time			
	Rate ($/hr)	**$100**	*Fixed rate*
	Ireland Gable — Hours	**12.0**	*Guide bolts, floor covers, plywood, grommet kit, wiring*
	Abobakar Sediq Miakhel — Hours	**10.0**	*Guide bolts, floor covers*
	William Tokar — Hours	**13.0**	*3D printing, guide bolts, floor covers, frame tubing*
	Sara Wong — Hours	**10.0**	*Guide bolts, floor covers, frame tubing, plywood, wiring*
	Subtotal	**$4,500**	
GRAND TOTAL		**$6,660**	

Table 2 – Development time for each team member



URMC Motion Lab — Development Time

Rate: $100/hr (fixed)

Project Hours	Abo	Ireland	Sara	Will	Total	Cost
Hours Last Week	8.5	13.0	10.5	8.5	**40.5**	**$4,050.00**
Total Hours	50.5	74.8	64.8	54.5	**244.5**	**$24,450.00**

TEST PLAN AND RESULTS

The requirements and specifications created at the beginning of the project outline clear goals to meet by the end of the semester. The project can be deemed successful if these specifications are met. To design and build prototypes to meet the requirements, certain specifications were determined and confirmed by the customer (University of Rochester Motion Lab) and supervisor (Professor Muir). These specifications include

- All designed and manufactured components in direct contact with the patient would have a factor of safety of at least 2
- Device must maintain functionality when treadmill is inclined to 9 degrees
- Height variability for adjusting the clamps on the frame must be adjustable in increments of 2 inches or less
- System will allow for adjustment so the angle of a patient’s knees is no less than 90 degrees if they fall
- Frame must be able to be set up by no more than two able-bodied people.

All items in direct contact with patients were purchased from external vendors. To verify that these items met the specification of all items having a factor of safety of 2, in-depth research was done to verify that components met the project needs. This was based on the 300-pound weight limit set by the requirement of accommodating 95th percentile of people in the US based on weight. Additionally, the waist harness purchased has a strength in tension of 15 kN (3372 lbf). This also is in line with the minimum factor of safety of 2. The original factor of safety was 5, but after discussing with the sponsor, this was lowered to 2 because it would have been either too expensive or have too long a lead time. The research by the team confirmed that everything passed this specification.

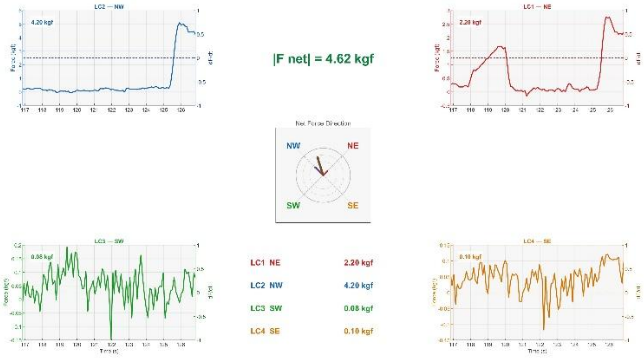
Originally, the Motion Lab estimated that the treadmill could incline to 15 degrees, but during testing it was realized that it could only go up to 9 degrees because of the motors and wiring beneath the floor in the lab. In discussion with the sponsor, this specification was changed to 9 degrees. To ensure that the device would maintain functionality when treadmill was inclined to 9 degrees (max incline the Motion Lab would use), adjustments and modifications made must not interfere with the treadmill and the bar in front of the treadmill that moves with it. This specification was mainly created to make sure that the floor coverings wouldn’t interfere with the functionality of the treadmill. This was tested by assembling everything and implementing the floor coverings and running the system. This all passed the specification.

As part of this project, there were tasks done that included streamlining and organization of components already implemented in the lab. For example, the frame at the Motion Lab was already functional, but there was an issue with attaching the clamps that the paracord pulleys were attached to. Because the device is supposed to pull people from their waist, the clamps should be at that same height on the frame. The issue was that because there was a clamp on each of the four posts of the frame, it was difficult to make sure all the clamps were at the same height. To solve this issue, measuring tape stickers were implemented on each of the four posts of the frame. This will allow the clamps to be placed at the same height on all four posts of the frame. To satisfy that it must be adjustable in increments of 2 inches or less, measuring tape stickers were purchased that were 100 cm long and had increments of as small as 1/8 inch. This system passed the specification.

Another important aspect of this project is safety. To make sure that patients were safe and would not seriously injure themselves, all safety systems considered would be designed in a way that would not allow a patient's knees to bend to a degree of less than 90 degrees. This would mean that if a patient did lose their balance, they would only fall into a slightly seated position, rather than falling all the way to the floor or being jerked in various directions. This was to ensure patient comfort. To test this, one of the team members was connected to the safety harness and the angle of their knee was measured. With the safety rope taut, the angle of the knee after "falling" was only 150 degrees. Because of this, this system passed the specification.

As stated above, streamlining and optimizing components already utilized by the Motion Lab was a vital part of this project. The final specification ensured that the proposed solution to fix the frame alignment issue would still allow a minimum of 2 able-bodied people needed to move the frame. This solution was implemented because it would not make the frame more complicated to move, which was discussed in the concepts section. Because the implemented solution was only interacting with the posts that are permanently attached to the ground and not the moveable part of the frame, this system passed the specification.

The integrated harness was also tested with the MATLAB code provided by the Motion Lab. This was to make sure that everything was hooked up properly and was providing the correct data that the Motion Lab will need to use. Additionally, the code was modified for the Design Day exhibition. The final display can be seen in Figure 8 below. Each load cell corresponds to a force graph and then the figure in the middle is an arrow that rotates and grows depending on which load cell is being pulled.



LC1 NE	2.20 kgf
LC2 NW	4.20 kgf
LC3 SW	0.08 kgf
LC4 SE	0.10 kgf

Figure 8 – MATLAB display for design day

INTELLECTUAL PROPERTY

The entire assembly of the harnesses, pouch, hardware, wiring, and paracord and safety cord attachments could be patentable. Although each individual component is not unique, combining them creates a unique solution that is novel in the perturbation device space.

Currently, patent number US8246354B2 outlines a perturbation device with a treadmill and frame as one piece. The treadmill will disturb the gait in this specific iteration, instead of a pulling force via paracords. However, the descriptions of the device found in the patent do not focus on how the patient will be kept safe if the gait disturbance causes them to fall. The Motion Lab's perturbation device will allow fall prevention to occur safely while in use, and it will pull patients at the hips rather than trip them on the walking platform.

SOCIETAL AND ENVIRONMENTAL IMPLICATIONS

Perturbation devices will allow for further study of biomechanics, human kinematic motion, balance training, fall prevention, and rehabilitation. The perturbation device will be useful for physical therapists, doctors, or biomedical engineers when dealing with patients who are elderly, injured, or have head trauma. Particularly, the Motion Lab intends to use perturbation devices in physical therapy offices in the future.

By improving the Motion Lab's current perturbation device, the safety and robustness of the system will be improved, allowing the patient to feel comfortable when their gait is disturbed. Additionally, recovery for patients will be accelerated, which will allow the Motion Lab to help more people in the long term.

This creation and use of the perturbation device will result in a relatively minor environmental footprint. The device requires electricity due to the 10V power supply to the load cells, connection to a computer, treadmill, and VR. At the Motion Lab, the motors, which will wind the paracords, also require power. However, since the device will likely only be connected to power when patients are present, it should not have a significant impact on the environment.

RECOMMENDATIONS FOR FUTURE WORK

Given more time, further implementation of VR, including motion tracker markers on the feet, would be a priority. Currently, the Motion Lab uses motion trackers in conjunction with force plates to assess how a patient's foot lands when their gait is disturbed. The Motion Lab could further immerse the patient by providing an environment with obstacles in VR that could track the patient's full-body movement. If there had been room for cameras, access to Motion Lab's motion trackers, and more time, this could have been implemented on Design Day.

The guide bolts solution to the frame alignment, as decided by the team, currently solves the problem at hand, allowing the frame to line up with the mounting plates easier. However, an even more efficient solution could be implemented, since the frame alignment with the guide bolts takes at least five minutes with two people. See Figure 10 for other solutions to the frame alignment issue, which could have been implemented with more time on the project.

Additionally, the cable management inside the fanny pack on the harness could be improved. The fanny pack implemented was one that would not be too bulky on the patient, have loops that can easily be attached/unattached, and have multiple pockets, as requested by the Motion Lab. However, due to fanny pack's smaller size, the wires intended to be neatly packaged into the fanny pack are packed tight, without much empty space, to ensure that the fanny pack can zip closed. The wires and load cells are color coded to prevent further confusion, but to perfect the packaging, the wires and amplifiers should have more room to ensure that wiring is clear.

ACKNOWLEDGMENTS

Thank you to the Motion Lab – Zachary Farnam, Dr. Ram Haddas, Dr. Ronald Wood, and Brian Morey for all their help and guidance throughout this semester. Also thank you to Professor Chris Muir, Jim Alkins, Chris Pratt, Sam Kriegsman, and Elizabeth Martin for their help with purchasing, manufacturing, and anything else that was needed for the project. This project could not have been done without the help of these people.

REFERENCES

[1] Vital and Health Statistics. (2025, June). CDC. https://www.cdc.gov/nchs/data/series/sr_03/sr03-050.pdf

[2] Zhang, J., Li, J., Zhao, C., Wang, K., & Lv, C. (2025). *Structural design, accuracy analysis, and mechanical calibration of a small two component docking mechanism for large loads in space*. Scientific Reports. https://www.nature.com/articles/s41598-025-88757-z.pdf

[3] Hibbeler, R. C. (2022). *Engineering mechanics: Dynamics* (15th ed.). Pearson. https://www.pearson.com/en-us/subject-catalog/p/engineering-mechanics-dynamics/P200000003398/9780137514717

APPENDIX A – CONCEPT SELECTION

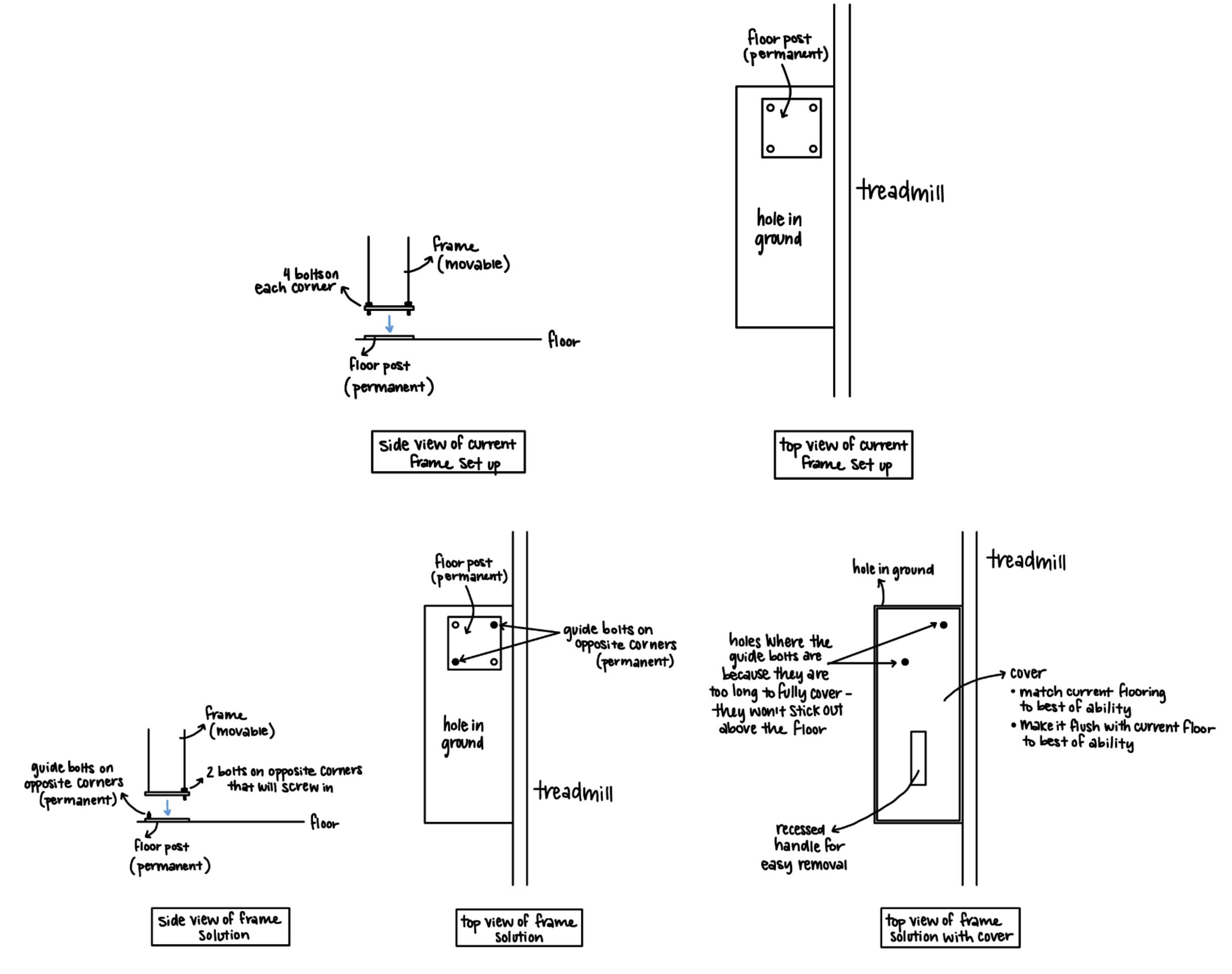
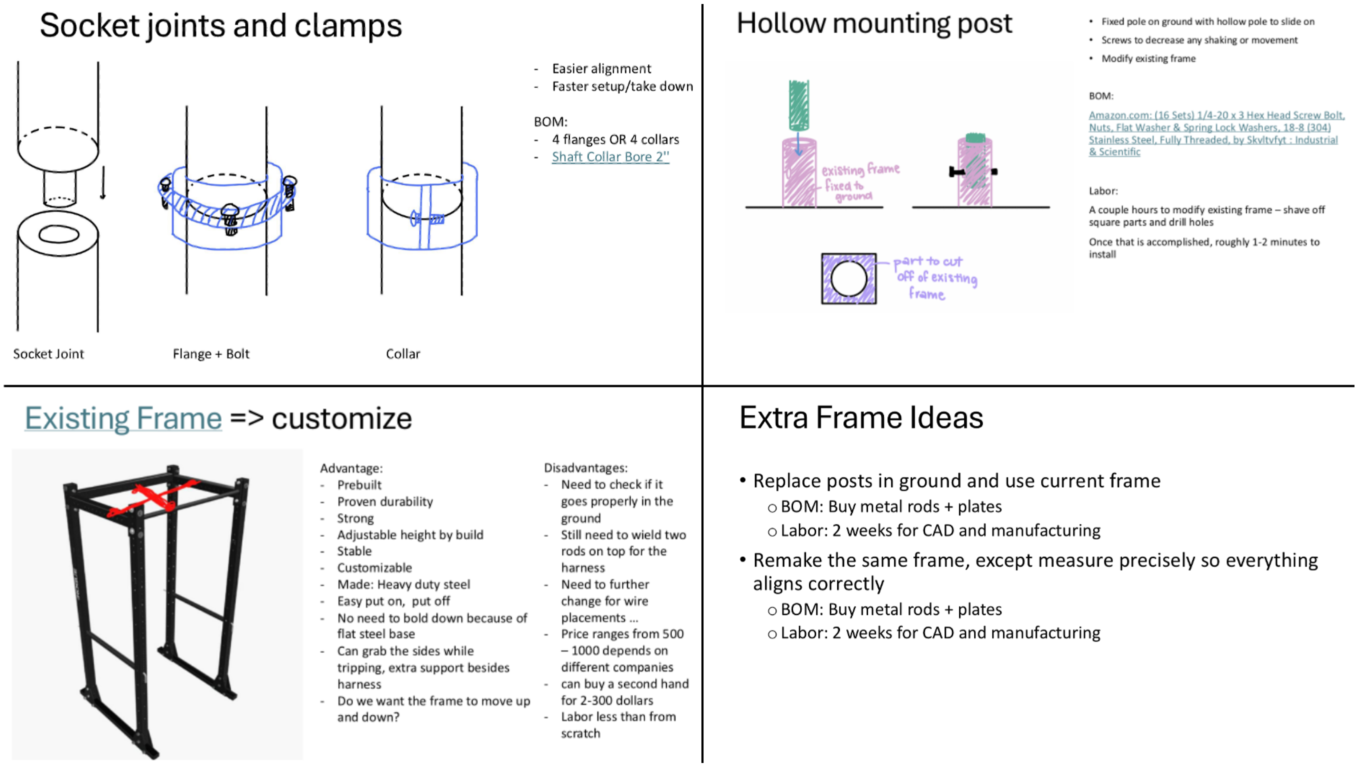


Figure 9: Frame Mounting Solution
Top image is original frame alignment and bottom image is improved solution decided based on selection matrix.



Socket joints and clamps

- Easier alignment
- Faster setup/take down

BOM:
- 4 flanges OR 4 collars
- Shaft Collar Bore 2''

Hollow mounting post

- Fixed pole on ground with hollow pole to slide on
- Screws to decrease any shaking or movement
- Modify existing frame

BOM:

Amazon.com: (16 Sets) 1/4-20 x 3 Hex Head Screw Bolt, Nuts, Flat Washer & Spring Lock Washers, 18-8 (304) Stainless Steel, Fully Threaded, by Skyltyfyt : Industrial & Scientific

Labor:

A couple hours to modify existing frame – shave off square parts and drill holes

Once that is accomplished, roughly 1-2 minutes to install

Existing Frame => customize

Advantage:
- Prebuilt
- Proven durability
- Strong
- Adjustable height by build
- Stable
- Customizable
- Made: Heavy duty steel
- Easy put on, put off
- No need to bold down because of flat steel base
- Can grab the sides while tripping, extra support besides harness
- Do we want the frame to move up and down?

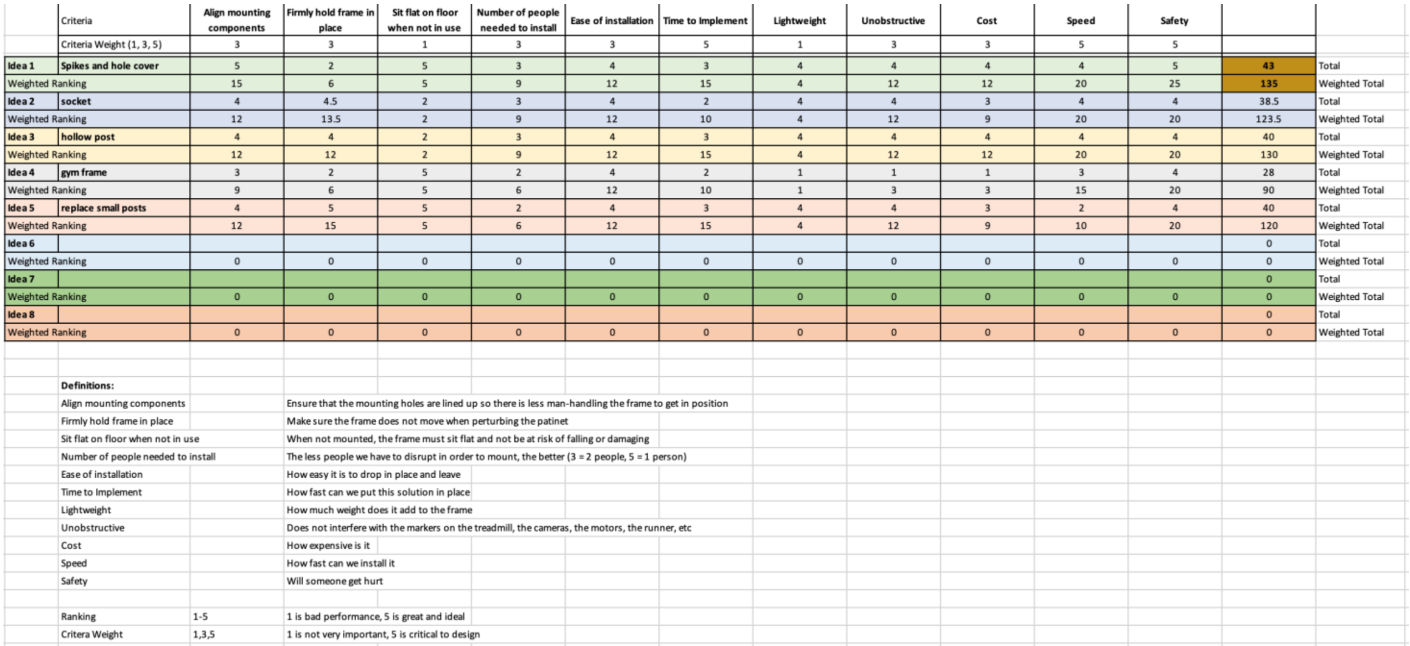
Disadvantages:
- Need to check if it goes properly in the ground
- Still need to wield two rods on top for the harness
- Need to further change for wire placements ...
- Price ranges from 500 – 1000 depends on different companies
- can buy a second hand for 2-300 dollars
- Labor less than from scratch

Extra Frame Ideas

- Replace posts in ground and use current frame
  - BOM: Buy metal rods + plates
  - Labor: 2 weeks for CAD and manufacturing
- Remake the same frame, except measure precisely so everything aligns correctly
  - BOM: Buy metal rods + plates
  - Labor: 2 weeks for CAD and manufacturing

Figure 10: Preliminary Frame Mounting Concepts
Examples of frame ideas seen below in the selection matrix

Table 3: Frame Mounting Concept Selection Matrix
Including definitions of each criterion

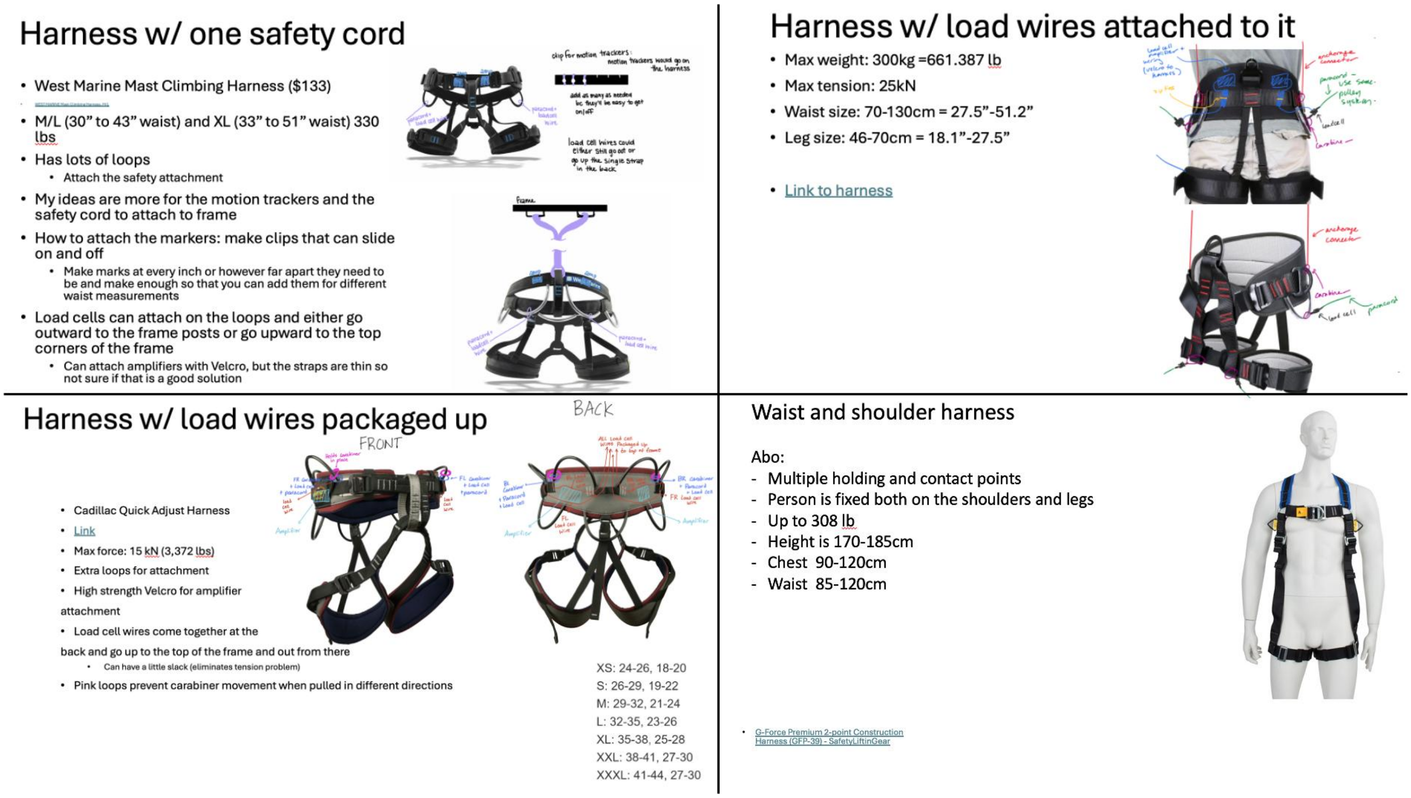


	Criteria	Align mounting components	Firmly hold frame in place	Sit flat on floor when not in use	Number of people needed to install	Ease of installation	Time to Implement	Lightweight	Unobstructive	Cost	Speed	Safety		
	Criteria Weight (1, 3, 5)	3	3	1	3	3	5	1	3	3	5	5		
Idea 1	**Spikes and hole cover**	5	2	5	3	4	3	4	4	4	4	5	**43**	Total
Weighted Ranking		15	6	5	9	12	15	4	12	12	20	25	**135**	Weighted Total
Idea 2	**socket**	4	4.5	2	3	4	2	4	4	3	4	4	38.5	Total
Weighted Ranking		12	13.5	2	9	12	10	4	12	9	20	20	123.5	Weighted Total
Idea 3	**hollow post**	4	4	2	3	4	3	4	4	4	4	4	40	Total
Weighted Ranking		12	12	2	9	12	15	4	12	12	20	20	130	Weighted Total
Idea 4	**gym frame**	3	2	5	2	4	2	1	1	1	3	4	28	Total
Weighted Ranking		9	6	5	6	12	10	1	3	3	15	20	90	Weighted Total
Idea 5	**replace small posts**	4	5	5	2	4	3	4	4	3	2	4	40	Total
Weighted Ranking		12	15	5	6	12	15	4	12	9	10	20	120	Weighted Total
Idea 6													0	Total
Weighted Ranking		0	0	0	0	0	0	0	0	0	0	0	0	Weighted Total
Idea 7													0	Total
Weighted Ranking		0	0	0	0	0	0	0	0	0	0	0	0	Weighted Total
Idea 8													0	Total
Weighted Ranking		0	0	0	0	0	0	0	0	0	0	0	0	Weighted Total

Definitions:

Align mounting components		Ensure that the mounting holes are lined up so there is less man-handling the frame to get in position
Firmly hold frame in place		Make sure the frame does not move when perturbing the patinet
Sit flat on floor when not in use		When not mounted, the frame must sit flat and not be at risk of falling or damaging
Number of people needed to install		The less people we have to disrupt in order to mount, the better (3 = 2 people, 5 = 1 person)
Ease of installation		How easy it is to drop in place and leave
Time to Implement		How fast can we put this solution in place
Lightweight		How much weight does it add to the frame
Unobstructive		Does not interfere with the markers on the treadmill, the cameras, the motors, the runner, etc
Cost		How expensive is it
Speed		How fast can we install it
Safety		Will someone get hurt
Ranking	1-5	1 is bad performance, 5 is great and ideal
Critera Weight	1,3,5	1 is not very important, 5 is critical to design

Figure 11: Harness Solution
Improved solution decided based on selection matrix.



Harness w/ one safety cord

- West Marine Mast Climbing Harness ($133)
- M/L (30” to 43” waist) and XL (33” to 51” waist) 330 lbs
- Has lots of loops
  - Attach the safety attachment
- My ideas are more for the motion trackers and the safety cord to attach to frame
- How to attach the markers: make clips that can slide on and off
  - Make marks at every inch or however far apart they need to be and make enough so that you can add them for different waist measurements
- Load cells can attach on the loops and either go outward to the frame posts or go upward to the top corners of the frame
  - Can attach amplifiers with Velcro, but the straps are thin so not sure if that is a good solution

Harness w/ load wires attached to it

- Max weight: 300kg =661.387 lb
- Max tension: 25kN
- Waist size: 70-130cm = 27.5”-51.2”
- Leg size: 46-70cm = 18.1”-27.5”

- Link to harness

Harness w/ load wires packaged up

- Cadillac Quick Adjust Harness
- Link
- Max force: 15 kN (3,372 lbs)
- Extra loops for attachment
- High strength Velcro for amplifier attachment
- Load cell wires come together at the back and go up to the top of the frame and out from there
  - Can have a little slack (eliminates tension problem)
- Pink loops prevent carabiner movement when pulled in different directions

XS: 24-26, 18-20
S: 26-29, 19-22
M: 29-32, 21-24
L: 32-35, 23-26
XL: 35-38, 25-28
XXL: 38-41, 27-30
XXXL: 41-44, 27-30

Waist and shoulder harness

Abo:
- Multiple holding and contact points
- Person is fixed both on the shoulders and legs
- Up to 308 lb
- Height is 170-185cm
- Chest 90-120cm
- Waist 85-120cm

- G-Force Premium 2-point Construction Harness (GFP-39) - SafetyLiftinGear

Figure 12: Preliminary Harness Concepts
Examples of harness ideas seen below in the selection matrix

Table 4: Harness Concept Selection Matrix
Including definitions of each criterion

	Criteria	Body coverage	Complexity to Put On	Adjustable for all sizes	Load Cell Location	Accessibility of Amplifiers	Location of wires from patient to PC	Weight	How many do we need to buy to fit everyone	Permenant Load Cell AMP capability	Time to Implement	Speed	Cost	Safety		
	Criteria Weight (1, 3, 5)	3	3	5	3	5	1	1	3	3	5	3	5	5		
Idea 1	**Harness w/ one safety cord**	4	4	2	3	3	3	3	2	4	3	4	3	2	**40**	Total
Weighted Ranking		12	12	10	9	15	3	3	3	12	15	12	15	10	**131**	Weighted Total
Idea 2	**Harness w/ load wires attached to it**	3	4	3	2	4	3	3	1	4	3	4	4	2	40	Total
Weighted Ranking		9	12	15	6	20	3	3	6	12	15	12	20	10	143	Weighted Total
Idea 3	**Waist and Shoulder Harness**	3	2	4	1	2	3	3	1	4	3	3	2	2	33	Total
Weighted Ranking		9	6	20	3	10	3	3	6	12	15	9	10	10	116	Weighted Total
Idea 4	**Harness w/ load wires packaged up**	4	4	2	4	4	3	3	1	4	3	4	2	2	40	Total
Weighted Ranking		12	12	10	12	20	3	3	6	12	15	12	10	10	137	Weighted Total
Idea 5	**Separate waist and shoulder harness**	5	2	3	5	4	4	2	1	4	2	2	2	5	41	Total
Weighted Ranking		15	6	15	15	20	4	2	6	12	10	6	10	25	146	Weighted Total
Idea 6															0	Total
Weighted Ranking		0	0	0	0	0	0	0	0	0	0	0	0	0	0	Weighted Total
Idea 7															0	Total
Weighted Ranking		0	0	0	0	0	0	0	0	0	0	0	0	0	0	Weighted Total
Idea 8															0	Total
Weighted Ranking		0	0	0	0	0	0	0	0	0	0	0	0	0	0	Weighted Total

Definitions:		
Body coverage		Will the markers be blocked (1 = yes, 5 = no)
Complexity to Put On		How hard is it to put on a patient (1 = what Katie had to do 2/6, 5 = velcro)
Adjustable for all sizes		Can people fit (1 = only one body type, 5 = one size fits ALL)
Load Cell Location		Load cell wire location (1 = paitent tripping on slack, 5 = wireless)
Accessibility of Amplifiers		How easily we can plug into the PC / calibrate zero and gain (1 = sewn into fabric, 5 = externally accessable)
Location of wires from patient to PC		Where do the wires go after leaving the harness (1 = patient trips, 5 = wireless)
Weight		
How many do we need to buy to fit everyone		
Permenant Load Cell AMP capability		
Time to Implement		How fast can we make this work / get to testing in lab 2 (1 is never, 5 is tomorrow)
Speed		How fast can we put it on the patient (1 = 20 minutes, 5 = 30 seconds)
Cost		How expensive is it? (1 = $$$$$, 5 = free)
Safety		Will someone get hurt? (1 = death trap, 5 = baby proof)
Ranking	1-5	1 is bad performance, 5 is great and ideal
Critera Weight	1,3,5	1 is not very important, 5 is critical to design

APPENDIX B – STRUCTURAL FEA ANALYSIS

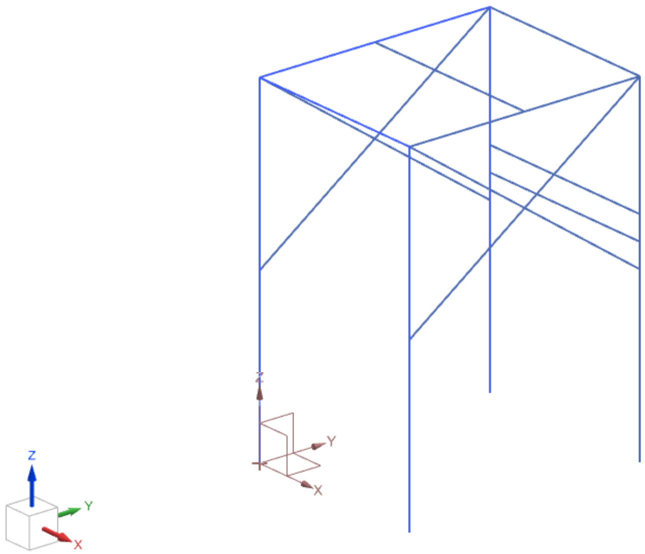


Figure 13: Simplified CAD model of the frame used on Design Day, created with line features. This was created specifically to run a finite element analysis on the frame.

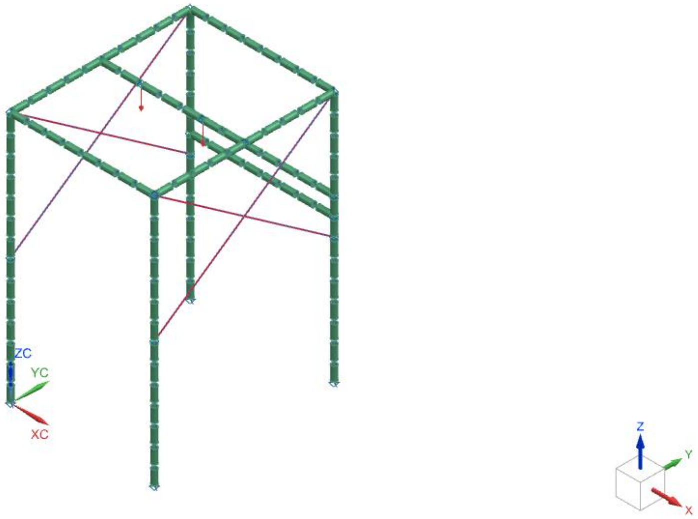


Figure 14: Finite element model of the simplified frame CAD model seen in Figure 13.

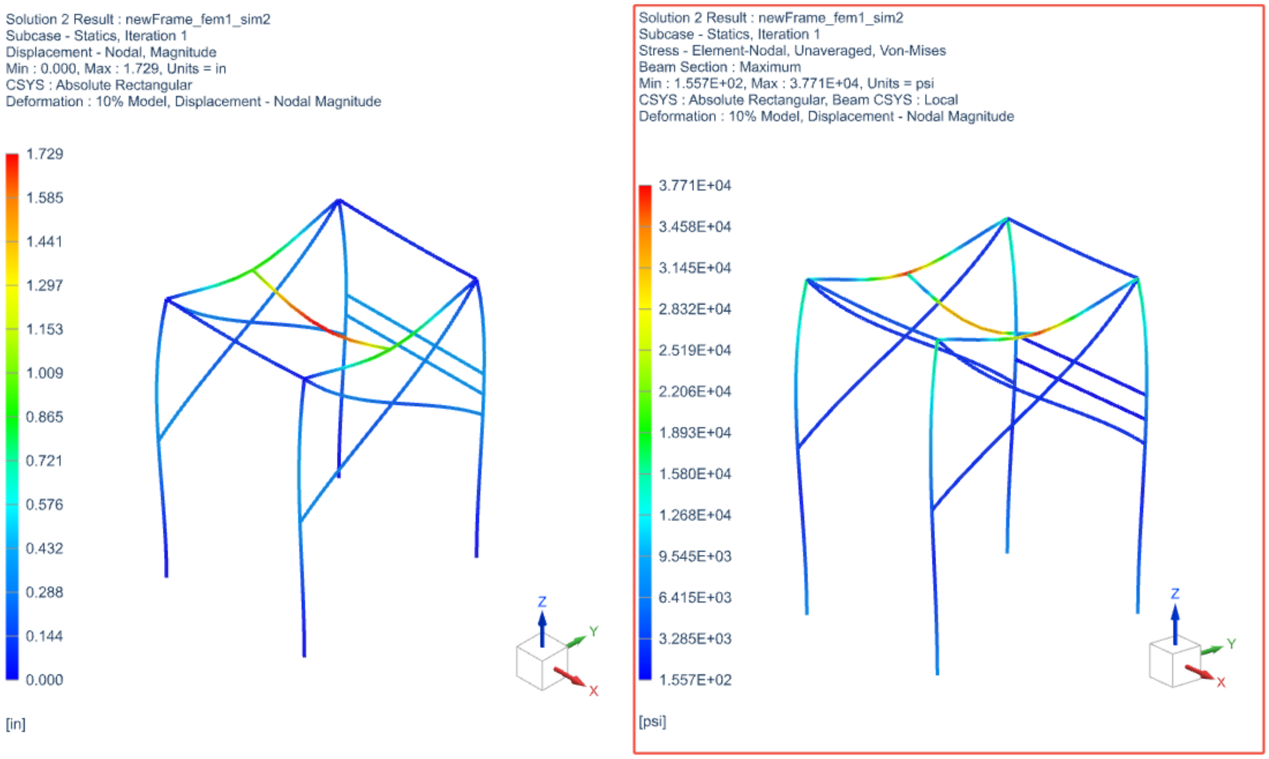


Figure 15: Linear statics solution results of the finite element model seen in Figure 14. The left result is the displacement, and the right result is the element-nodal stress.

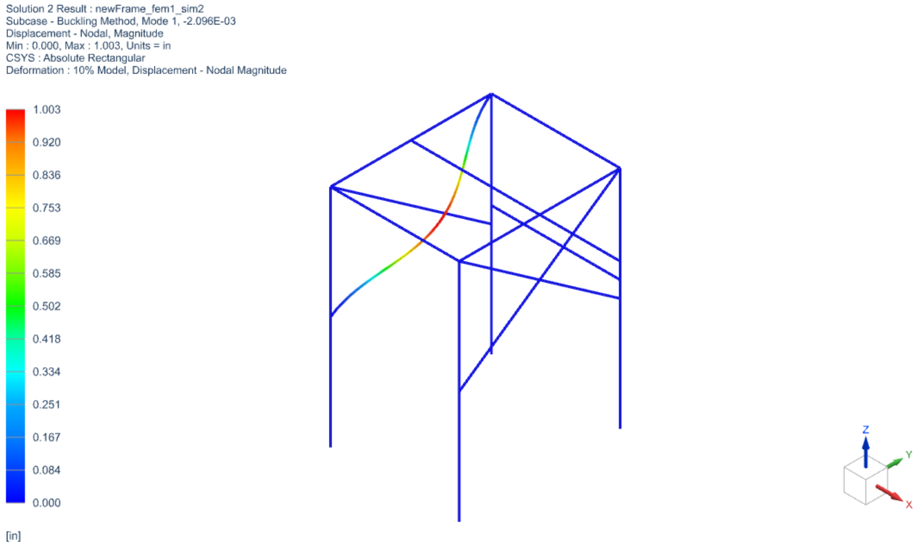
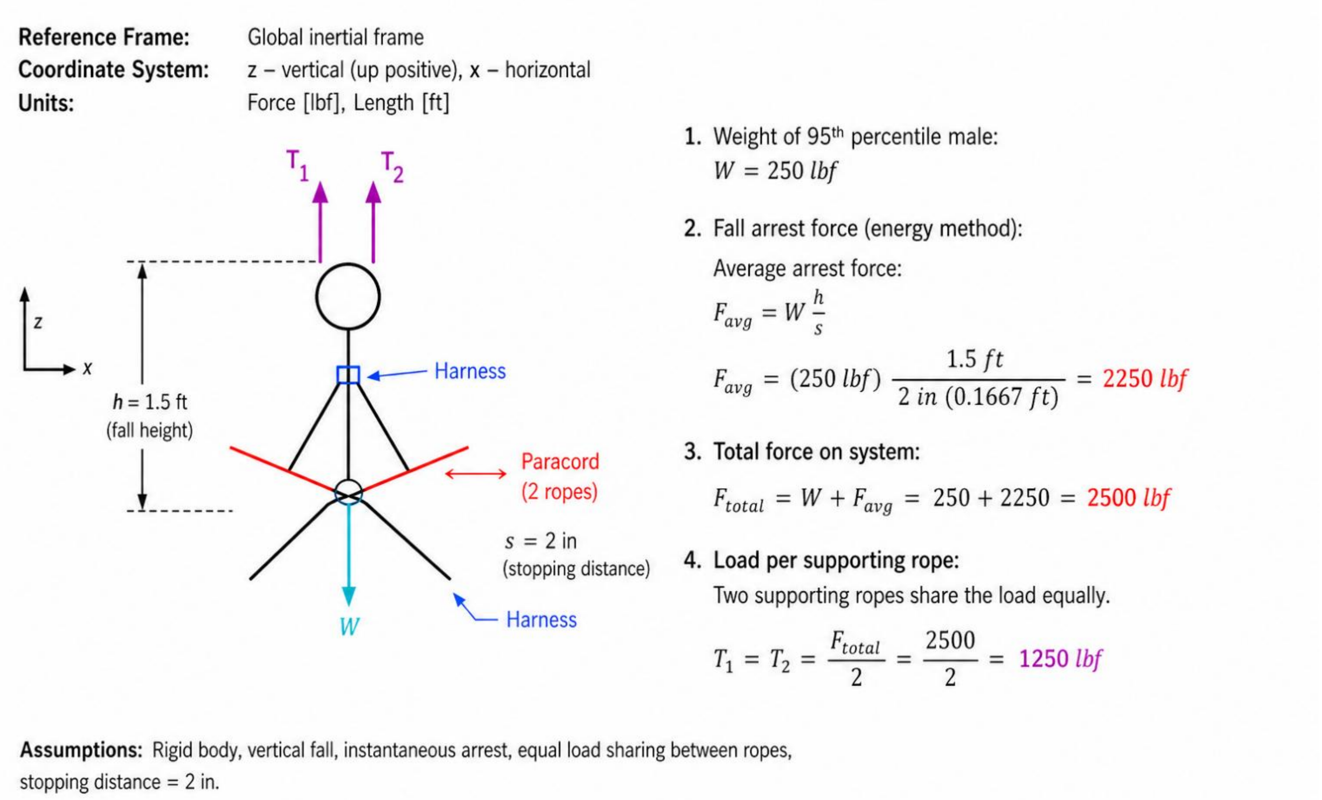


Figure 16: Buckling solution (Mode 1) displacement result of the finite element model seen in Figure 14.

APPENDIX C – FUNDAMENTAL STATICS ANALYSIS



Reference Frame: Global inertial frame
Coordinate System: z – vertical (up positive), x – horizontal
Units: Force [lbf], Length [ft]

1. Weight of 95th percentile male:
   $W = 250\ lbf$
2. Fall arrest force (energy method):
   Average arrest force:
   $F_{avg} = W\,\frac{h}{s}$
   $F_{avg} = (250\ lbf)\ \frac{1.5\ ft}{2\ in\ (0.1667\ ft)} = 2250\ lbf$
3. **Total force on system:**
   $F_{total} = W + F_{avg} = 250 + 2250 = 2500\ lbf$
4. **Load per supporting rope:**
   Two supporting ropes share the load equally.
   $T_1 = T_2 = \frac{F_{total}}{2} = \frac{2500}{2} = 1250\ lbf$

Assumptions: Rigid body, vertical fall, instantaneous arrest, equal load sharing between ropes, stopping distance = 2 in.

Figure 17: Safety cord tension analysis of a 95th percentile male falling 1.5 ft [3]

APPENDIX D – WIRING DIAGRAM

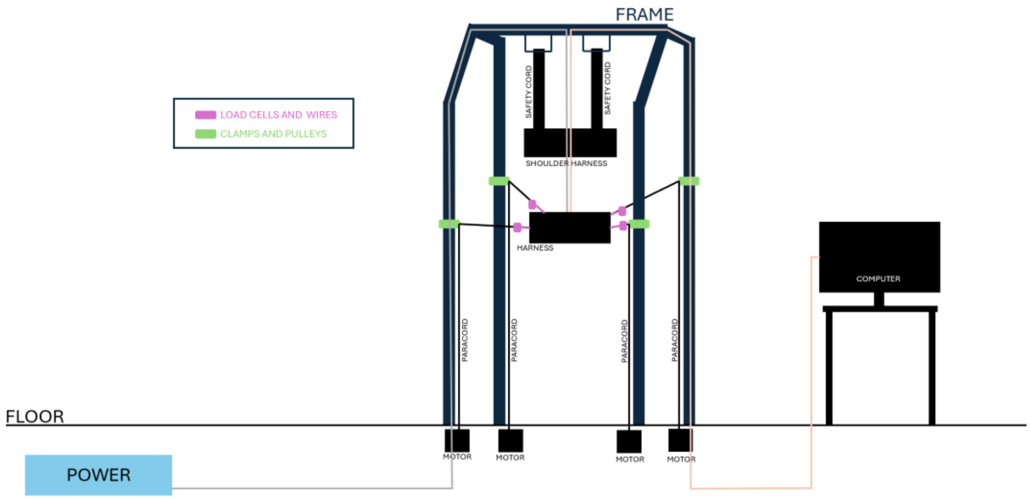


Figure 18: Overall wiring diagram. See Figure 19 below for detailed wiring inside the harness.

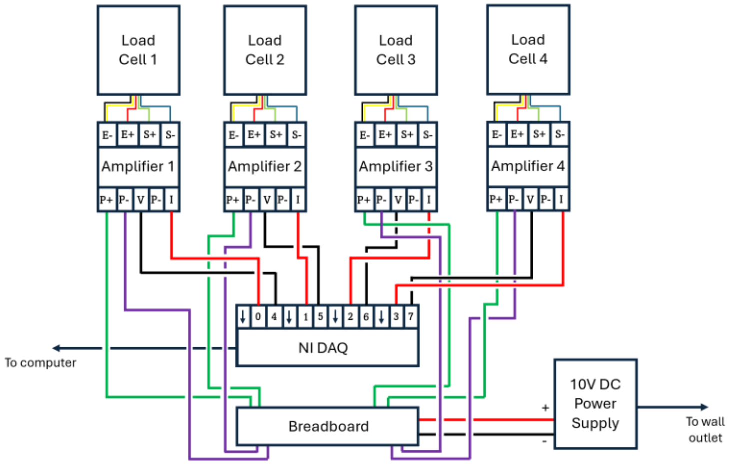
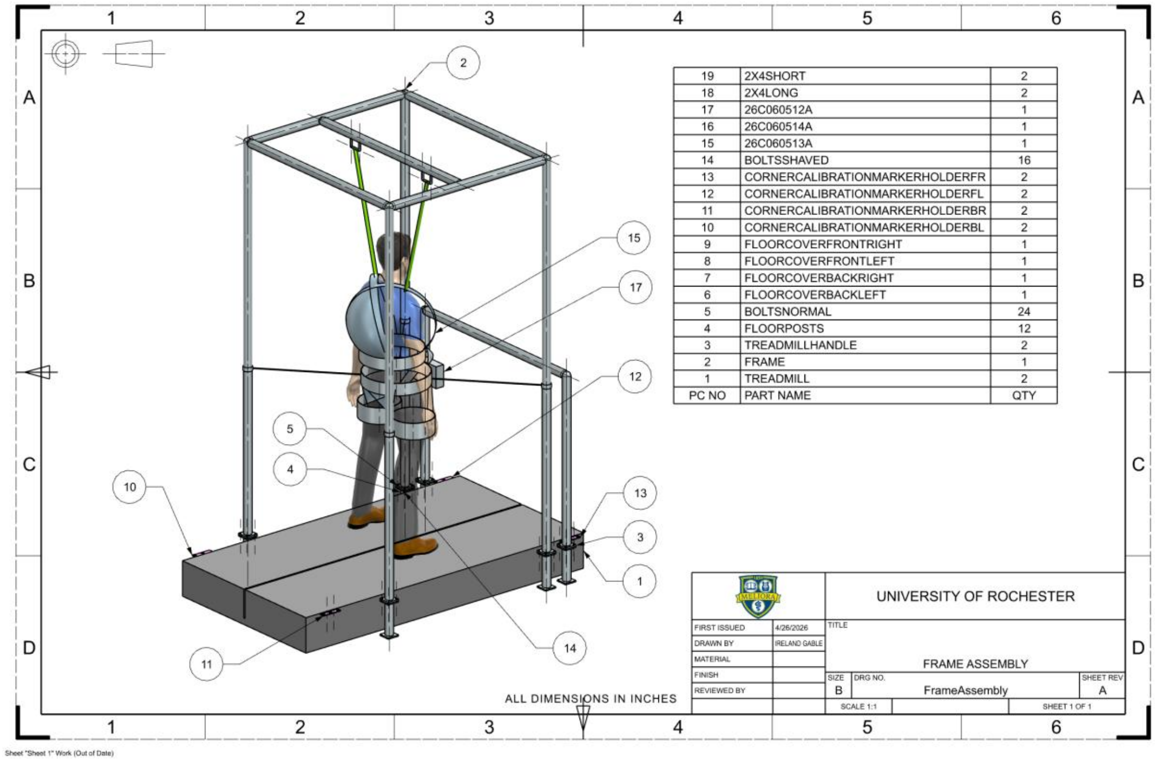


Figure 19: Detailed wiring diagram inside the waist harness.

Table 5: Electronics Bill of Materials

Item	Price	Comments
Waist Harness	$19	
4 Load Cells	$260	$65 each
4 Amplifiers	$140	$35 each
NI DAQ	$0	From Motion Lab
10V Power Supply	$0	From Motion Lab
Wires	$0	From Motion Lab
Breadboard	$0	From Sam K.
Total	$419	

APPENDIX E – ASSEMBLY DRAWING AND BILL OF MATERIALS



PC NO	PART NAME	QTY
19	2X4SHORT	2
18	2X4LONG	2
17	26C060512A	1
16	26C060514A	1
15	26C060513A	1
14	BOLTSSHAVED	16
13	CORNERCALIBRATIONMARKERHOLDERFR	2
12	CORNERCALIBRATIONMARKERHOLDERFL	2
11	CORNERCALIBRATIONMARKERHOLDERBR	2
10	CORNERCALIBRATIONMARKERHOLDERBL	2
9	FLOORCOVERFRONTRIGHT	1
8	FLOORCOVERFRONTLEFT	1
7	FLOORCOVERBACKRIGHT	1
6	FLOORCOVERBACKLEFT	1
5	BOLTSNORMAL	24
4	FLOORPOSTS	12
3	TREADMILLHANDLE	2
2	FRAME	1
1	TREADMILL	2

UNIVERSITY OF ROCHESTER

FIRST ISSUED	4/26/2026	TITLE: FRAME ASSEMBLY
DRAWN BY	IRELAND GABLE	SIZE: B
MATERIAL		DRG NO.: FrameAssembly
FINISH		SHEET REV: A
REVIEWED BY		SCALE 1:1
		SHEET 1 OF 1

Figure 20: Frame assembly drawing.

Table 6: Complete Bill of Materials

URMC Motion Lab — Bill of Materials

Category	Item	Cost	Notes
Floor Covers			
	Plywood	$0	*Scrap wood provided by Jim*
	2x4s	$0	*Scrap wood provided by Jim*
	Paint	$0	*Provided by Jim*
	Subtotal	**$0**	
Guide Bolts			
	Eight Bolts	$0	*Provided by motion lab*
	Subtotal	**$0**	
Harness			
	Waist Harness	$19	
	Pouch	$14	
	Clips	$9	
	Nylock Nuts	$6	
	Velcro Wire Straps	$5	
	Grommet Kit	$10	
	Subtotal	**$63**	
Safety Mechanism			
	Shoulder Harness	$0	*Used motion lab's*
	Height Adjustment System	$450	
	Subtotal	**$450**	
Electronics			
	Load Cells (×4)	$260	*$65 each*
	Amplifiers (×2)	$70	*$35 each — only 2 received*
	Subtotal	**$330**	
Design Day Frame			
	Frame	$0	*Provided by motion lab*
	Plywood	$0	*Left over from another group*
	Bolts/Nuts/Washers	$21	
	Rubber Floor Mat	$25	
	Subtotal	**$46**	
Motion Lab Frame			
	Sticker Measuring Tapes (×3)	$21	*$7 each*
	Subtotal	**$21**	
3D Printing			
	Corner Calibration Markers (×4)	$0	PLA provided by school
	Amplifier Boats (×4)	$0	PLA provided by school
	Motor Spools (×4)	$0	PLA provided by school
	Subtotal	**$0**	