Redefining Health: Designing a Resistive, Omnidirectional Surface for a Gamified Fitness Experience

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Executive Summary

Traditional treadmills support unidirectional movement but fail to fully capture natural locomotion, limiting their effectiveness in rehabilitation and immersive VR experiences. Omnidirectional treadmills offer 360° motion; however, existing models have high cost, large footprints, and unnatural movement that often causes motion sickness in users. Our team created a unique omnidirectional treadmill that seeks to improve these limitations by utilizing a user-powered resistive surface comprised of free spinning balls and a hybrid braking system that employs both friction and magnetic mechanisms. This treadmill aims to allow users to move in any direction while maintaining a natural gait.

1. Problem Space: The Need for a New Treadmill

Treadmills have long had utility in a variety of applications due to their ability to create indefinite movement while keeping users in the same spot, allowing for the physiological benefits of walking and running in areas that otherwise spatially constrain travel. Such areas include small living spaces, urban settings, gyms, schools, and hospitals, among others. One notable application is rehabilitation, as walking and running are vital movements in the recovery processes of different body parts, namely the spine and legs [1]. Another application is virtual reality (VR). With the improvement of computer performance, graphics processing technology, and motion capture technology, VR technology has experienced rapid development, transforming gaming and media by connecting users to a deeply immersive environment. Treadmills allow users to physically simulate transversal through this environment. However, significant limitations in a traditional treadmill, namely only being able to support unidirectional movement, have led to further limitations in their effectiveness in these applications.

1.1 Treadmill Applications and Limitations

For walking rehabilitation, the commonly used Task-Oriented Training method requires patients to perform repetitive walking exercises (flat ground, steps, obstacle crossing), combined with balance and muscle strength training. For stroke patients, this method increased functional walking speed by 12-18% after 6 weeks of training [2]. However, as standard treadmills cannot recreate unrestricted two-dimensional movement where a user can switch directions at will, they are limited in “their usefulness for training more complex locomotor tasks”, as changing speed and direction of walking “are essential walking adaptations for efficient and safe community ambulation” [3]. In other words, standard treadmills cannot fully assist in recovery, leading rehabilitation efforts to encounter spatial concerns.

For virtual reality, users are connected to headsets that place them in a 360 degree virtual environment and that use their head movements to visually explore the environment in the same way they would look around a real setting. This makes VR a powerful tool in creating impactful immersive experiences beyond gaming, as seen in simulated museum tours, virtual classrooms, and military training exercises. VR is also used in rehabilitation to improve patient enjoyment and because immersive environmental feedback achieves multimodal integration of visual vestibular proprioception, enhancing motor learning [4]. VR-combined treadmill training increased stride length by 22% and reduced frozen gait attacks by 40% in Parkinson's disease patients [5]. The training compliance of patients in the VR gaming group increased by 58%, and the fall rate decreased by 33% after 6 months [6]. However, travel within VR is significantly limited; in most cases, the movement of an avatar, a person’s physical form within a VR environment, is controlled via a controller. Despite the fact that rotational visual feedback is synchronized with a user’s head movement, translational visual feedback is disjointed as the avatar moves while the user’s body remains stationary. This leads to a unique form of motion-sickness known as cybersickness, causing many of the same symptoms [7]. Other VR systems utilize treadmills or might allow the user to actually move within a defined boundary, but this limits the distance and direction the user is able to travel within the VR environment.

1.2 Solution: Omnidirectional Treadmill

A solution to the problems described for rehabilitation and VR is an omnidirectional treadmill – that is a treadmill that enables movement in any direction while keeping the user in the same relative position. Such a treadmill would enable complex locomotor tasks, as the user would be able to articulate their limbs in rotational manners. This kind of treadmill would also significantly increase the capability of VR as a technology by allowing for perpetual and detailed travel within an environment, at once increasing VR's potential as a training and educational tool, an immersive gaming experience, and a rehabilitation amplifier.

With Blue Goji's omnidirectional treadmill, we aim to ensure the safety of users while remaining energy efficient. There already exists an Alpha version of an omnidirectional treadmill in Blue Goji, which comprises a large rotating track that itself is composed of 30 rotating tracks arranged parallel to one another. The tracks are propelled by powerful motors and precisely controlled by sensors attached to the user's feet. However, this version requires a large area, making it inconvenient for traditional treadmill spaces such as an apartment. The motors' large use of energy and consequent effect on the environment are other concerns. As such, our team aims to create a resistive design that is user-propelled, has a small surface area, and utilizes powered braking, all while maintaining a good user experience and user safety.

2. Market Analysis: Assessing Other Omnidirectional Treadmills

2.1 Analyzing Competitors

It is difficult to create a treadable surface that is truly omnidirectional. Planar movement is significantly more complex than linear movement as it requires all six degrees of freedom in a foot, so predicting and accounting for motion in 360 degrees is a physical and computational challenge. There are a number of omnidirectional treadmills currently in development and available commercially that each approach the creation of omnidirectional movement differently. In our analysis, we examined product marketing materials, demonstrations, patents, reviews, user complaints and studies to generate a list of strengths, weaknesses, and areas of improvement with regard to cost, usability, and convenience. Products were grouped together based on the style of their approach, and the resulting categories were assessed based on their mechanical feasibility in translating to a resistive design.

One category, dubbed “X-Y motor treadmills”, encapsulates treadmills that operate by having motor-powered planar surfaces react to the user’s position and speed and move within an X-Y coordinate. Examples include Blue Goji’s alpha design, Infinadeck’s Portal treadmill, and STEPVR’s Beta treadmill [8][9]. Although successful in reproducing natural gait biomechanics in the user, these treadmills have a very large footprint, are very heavy, and are prohibitively expensive. The user position feedback mechanisms need to be precise but are a major source of lag, decreasing reliability and overall performance. Another category is “slide treadmills” and comprises omnidirectional treadmills that have users wear special shoes that allow them to “slip” on a low-friction surface while stabilized by a harness. Included are KAT VR’s KAT Walk and Virtuix’s Omni One [10]. While having a small footprint, these treadmills require a very unintuitive and unnatural motion, often causing the user to fall forward, and can only be used with their proprietary VR gear. We conducted a field test where we used this type of treadmill and further concluded that operation felt clunky and immersion could not be maintained.

A key observation across multiple products was that treadmill operation required the user to use a modified gait or non-naturalistic walking. The modifications lead to slowed movement that at times could not be done at high speeds, meaning the user is not able to run on the product [11]. In slide treadmills, the “reduced shear forces between the weight bearing foot and supporting surface” causes gait changes similar to those seen when walking on slippery surfaces. In these cases, the alterations have enough of an effect on gait biomechanics that lower limb musculoskeletal integrity may be impacted over time. Furthermore, when used with VR, such an unnatural gait can still cause cybersickness [11].

2.2 Analyzing Blue Goji’s Position in the Market

Currently, there are no omnidirectional treadmills on the market that are resistive and self-propelled. This allows Blue Goji the opportunity to create a unique and novel product that will be significantly cheaper than competitors due to the absence of expensive components like motors while maintaining a high level of performance.

3. Our Approach: Goals, Concepts and Design

3.1 Project Goals

The team aims to innovate a cost-effective, space-efficient omnidirectional treadmill that enhances VR immersion and rehabilitation efficacy. At a baseline, the device must allow omnidirectional movement and cannot utilize a motor to move. It must also improve on the most significant limitations of the current market. Key goals include:

- Affordability: Reduce production costs to broaden market accessibility.
- Compact Design: Minimize physical footprint without compromising range.
- User Experience: Mitigate motion sickness with intuitive, biomechanically aligned movement.

To further develop the project scope and goals, we created a requirement table by generating a list of specifications and detailing the standards at different criticality levels of “Must”, “Should” and “Could” to determine when each specification is met. Specifications such as functionality, durability, and manufacturability were included (Appendix 1). The ultimate goal is to build a fully functioning prototype.

3.2 Concept Selection

Eleven initial concepts were generated and evaluated based on complexity, feasibility, and alignment with project requirements. As each concept was ideated, it was then placed in a comparison matrix based on its degree of complexity and compatibility (Figure 1). Compatibility refers to how well the concepts are aligned with the defined requirements. Ideal concepts had high compatibility and low complexity. Through this, concepts were narrowed from 11 to 5. A Pugh matrix was employed to evaluate the remaining designs based on weighted criteria such as cost, motion fluidity, and technical realizability. Each concept was assessed based on how well it was predicted to perform when compared to the alpha design, whether "better", "same" or "worse" (Appendix 2). The top two designs were selected for further exploration, development, and initial prototyping: an auxetic material-based "Torus" design and a rotational ball-driven "BeyBlade" design.

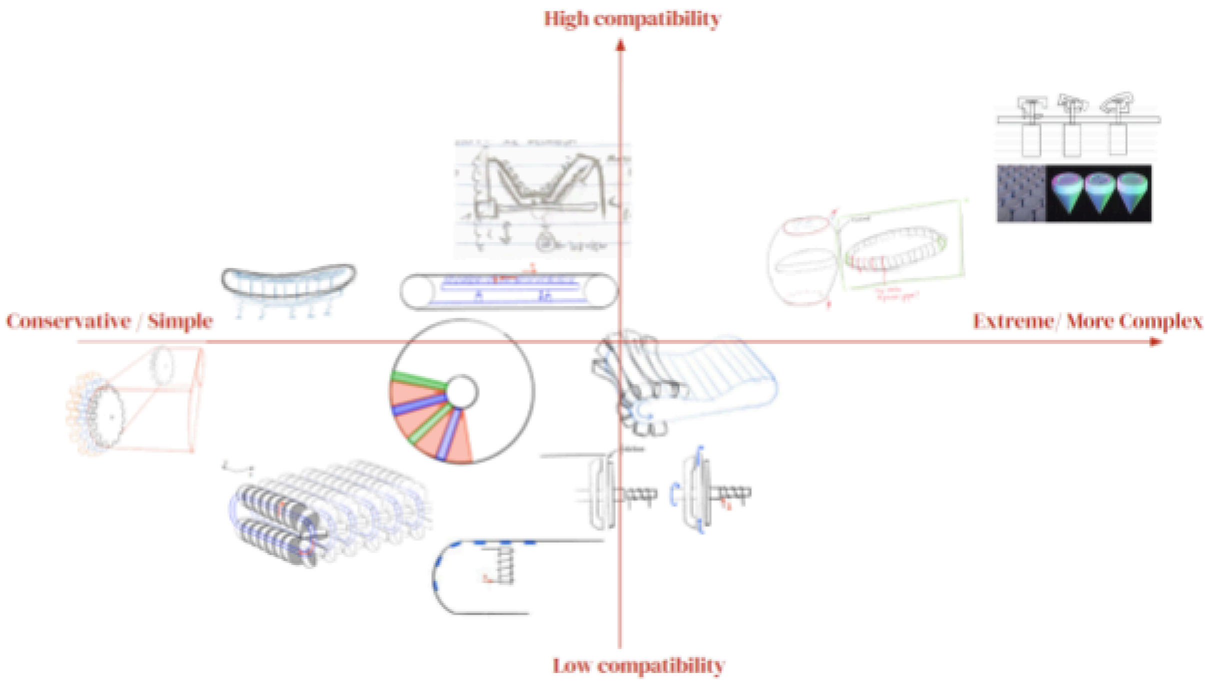

Figure 1. Compatibility and complexity comparison for concept designs.

3.2.1 Torus Design

This design drew inspiration from the bases of slide omnidirectional treadmills. Instead of having a curved, conical shape, a torus shape would be used. The reasoning was that a sphere with a track around it would give the simplest form of omnidirectional movement desire. However, as a sphere would result in excessive height, we explored whether a torus shape, with the ability to accommodate various geometries, could be a more compact alternative. The track would wrap around this shape, and the user would walk in the middle in any direction.

The idea was implemented in CAD for further development and to understand how the supposed parts would be fixed (Figure 2). Notably, in the Pugh matrix, the feasibility criterion was rated as "worse" for this idea; for it to function, the track needed to be able to constantly adapt to the torus shape. It needed to be made of a material that would be able to extend and come to rest during the functioning of the treadmill. We considered auxetic materials: metamaterials with a negative Poisson's ratio that expand in both directions when pulled in one direction. After investigating various existing auxetic material shapes with different properties, we tested the ones that could stretch in a curve like the torus's outer edge.

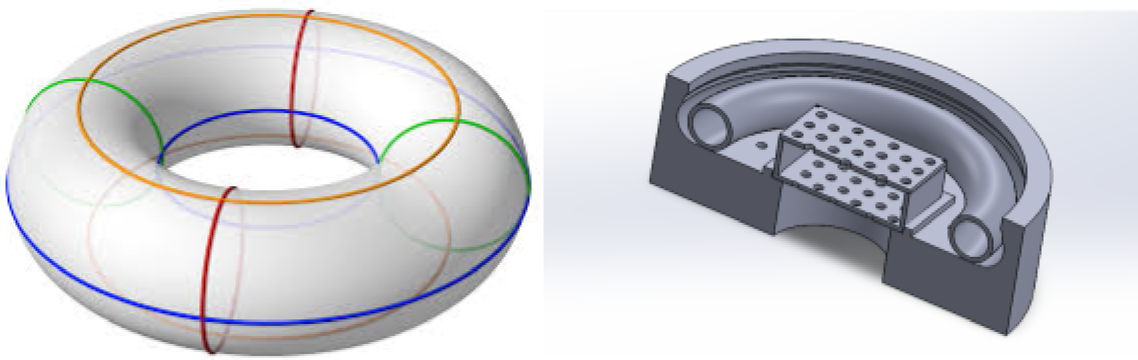

Figure 2 : Torus shape and conceptual CAD cross-section

3.2.2 BeyBlade Design

This design was inspired by the results of the field test to create a user powered running interface. (Figure 3). The frame is slanted at an angle with an interface consisting of many free-spinning steel balls. The user, first standing in the middle, places their foot onto the slant, and the rolling balls combined with the slant angle causes the foot to naturally return to the middle. Since the balls are encased in a way that allows rotation, the user would be able to walk in all directions, reaching omnidirectional movement. Stopping the motion of the balls would require an active braking system done through friction from direct contact or magnetic resistance.

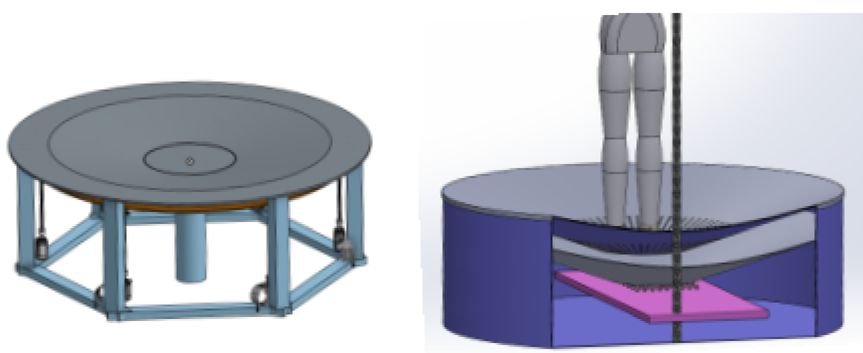

Figure 3. BeyBlade design conceptual CAD models

3.3 Initial Prototyping and Concept Evaluation

For the Torus Design, initial prototypes were created to understand the best way to design the auxetic material. To create auxetic materials, rubber was cut into hexagons meant to be placed modularly, and different auxetic patterns were laser cut into them (Figure 4). A small 3D-printed part was used as the torus shape. Different small motion phases that extended and compressed the track were created and the ability to make the structure return to the resting phase were tested. After a few experiments, we concluded the material was too fragile, as after several cycles of testing, some of the attachments in the pattern broke apart. Additionally, because the material was stable in both the contracted and expanded phase, it was extremely difficult to get the material to transition between them, leading to broken connections in every attempt. The experiment showed that using auxetic materials raised more concerns than solutions, so after further investigations and discussion with our advisors, we came to the conclusion that the idea would not be suited for our given timeline.

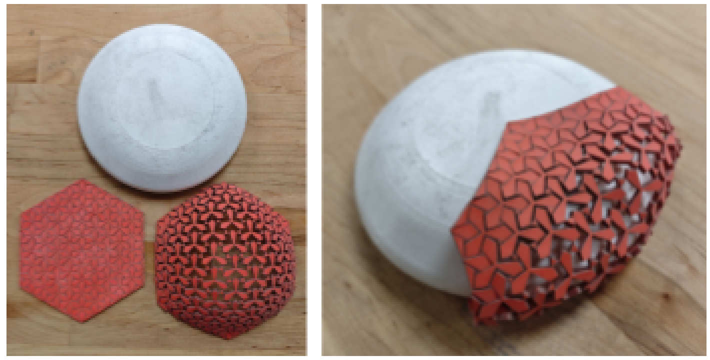

Figure 4: Laser cut auxetic material

For the Beyblade Design, two potential braking system ideas were generated. The feasibility and user friendliness of the friction braking system and magnetic braking system were investigated, with the criteria for assessment being the system's ability to completely stop a ball when a large force was applied. Testing platforms were 3D printed and used with two different ball sizes, 10mm and 18mm in diameter (Figure 5). Friction braking was tested on both ball sizes. The magnetic

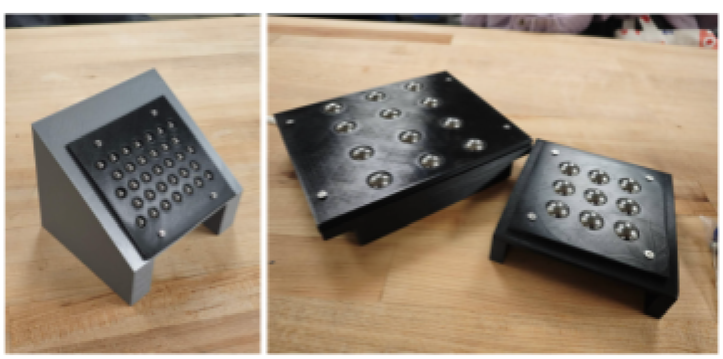

Figure 5: Friction test for 10mm (left), friction and magnetic test for 18mm (right).

braking test was done only with the 18mm balls since the magnetic force is too small for the 10mm balls.

By putting different friction pads underneath the balls and compressing it with another surface, the friction system could be tested through several stages of compression achieved by adjusting the distance between the upper platform and the lower surface using the screws (Figure 6). Polyurethane foam sheet, natural rubber, 40A durometer rubber and 60A durometer rubber were tested on 10mm balls. 18 mm balls had the same testing but without the polyurethane foam sheet since it performed poorly in the first testing. Test results show that 40A, 60A and natural rubber are suitable for 10mm balls; 60A and natural rubber are suitable for 18mm balls. Natural rubber performs the best in both cases (Appendix 3).

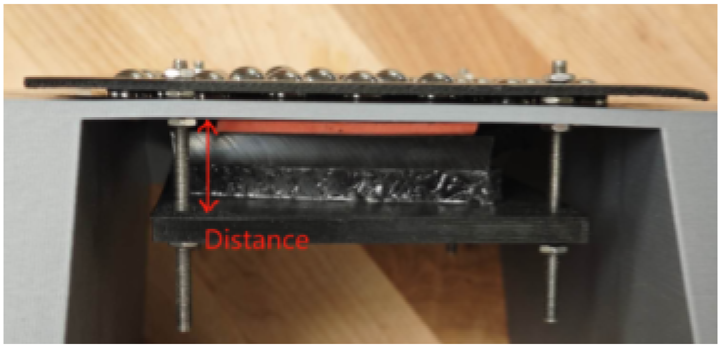

Figure 6: Distance to adjust friction pad compression level

For the magnetic braking system, two design ideas were proposed as a way to apply resistance to the steel spheres: disc magnets could be raised and lowered with their distance from the spheres affecting their pull, or electromagnets could be used with a varying current to affect their pull. Initially, the required magnet strength was calculated to be around 120 N (Appendix 4). 100N and 150N solenoid electromagnets and one 26 lbf disc magnet were initially tested by placing them directly under the 18mm ball (Figure 7). The electromagnets performed better than the disc but did not completely stop the ball's rotation as expected (Appendix 5). It was determined that this is due to how the geometry of the balls interact with a magnetic field, making the magnet pull strength weaker than its max rating.

Figure 7: Magnet resistance testing

A simulation study was conducted using FEMM software to optimize the designs by analyzing how the magnetic field propagates and influences the spheres. The system was modeled by defining the different materials involved, namely air, steel (for the sphere), and the solenoid coil of the electromagnet. Key parameters such as the number of coil turns, wire thickness, and solenoid dimensions were carefully set based on the real electromagnet specifications. Through these simulations, it is observed that the magnetic field propagates more efficiently over flat surfaces compared to spherical geometries (Appendix 6), since the lines of the magnetic field are closer between two flat surfaces than the spherical configuration. Additionally, it was found that increasing the number of coil turns (N) led to a significant enhancement in magnetic attraction force (Appendix 7). Based on these results, a design decision was made to increase the physical diameter of the electromagnets to improve their interaction with the treadmill surface and enhance system performance. However, the ball's position relative to the surface of the magnet correlates to the ball's position in the magnetic field, ultimately affecting the pull it experiences. Upon review and adjustment in calculations, more powerful electromagnets (250N, 500N and 800N) were tested. The 800N magnets covered all 9 of the balls in the test prototype, however, as predicted by the simulations, only 5 of 9 balls were completely stopped, with the rest being able to rotate somewhat. Regardless, the electromagnet was effective in stopping the user's movement, calling into question whether the criteria of stopping every ball was too strict.

The strengths and weaknesses of each braking system was compared. The friction braking system could easily conform to a curved shape and was cost effective, as the rubber material is significantly cheaper than purchasing a sufficient number of electromagnets. However, the friction braking system relied on stepper motors: although the distance can be precisely controlled, the friction pad would need to cover all balls at once, leading to slow and inexact application and an increase in the device's height to accommodate the motors' inclusion and movement, in turn raising structural integrity issues. In using electromagnets, the magnetic braking system allowed quick and precise control of brake strength through current control and led to a significantly shorter treadmill profile. However, they were costly per unit and consistency varied based on the ball's location within the magnetic field (Appendix 8). As their braking performances were similar, it was determined that a hybrid braking system could be used: the magnetic system would be used in the center, where the user would spend most of their time, and the friction system would be used on the sides, which are already higher in height than the center due to being curved. This allowed the device to maintain a shorter profile while balancing costs. Furthermore, as the friction pads are expected to wear out more quickly over time than the magnets, positioning the friction system on the side reduced the wear the pads experienced while also allowing for a modular design and easy pad replacement. Thus, having a hybrid braking system would extend durability.

In deciding the final concept to fully prototype, the testing results, as well as consideration for what design would allow for omnidirectional movement not powered by motors and intuitive motion were considered. It was with these considerations that the BeyBlade design was ultimately chosen.

4. Final Design and Prototype

The full prototype is not intended to be the final version of the product. Rather, it is meant to be a fully operational, large-scale demonstration that serves as a proof of concept for the key facets of the original design. Consequently, several boundaries were set to limit the prototype's scope, namely time, budget, and a maximum size specification. These constraints, among others that arose throughout the final prototyping process, meant that some initial expectations, such as the ability to run, could not be met. As such, subsequent design decisions prioritized the prototype and its completion, with noted areas of improvement reserved for future iterations of the project.

4.1 Frame and Supports

4.1.1 Frame Design and Material Selection

The initial frame design was a curved shape that would require complex and costly manufacturing processes such as 3D metal printing, sand casting, or metal casting to create. There was also a structural concern as placing supports would have proven to be difficult with the curvature. Given these constraints, we brainstormed with our advisors and several technicians in Jacob's Hall. Having the feeling of being able to walk in any direction seamlessly was the most important design criteria, so the curve was

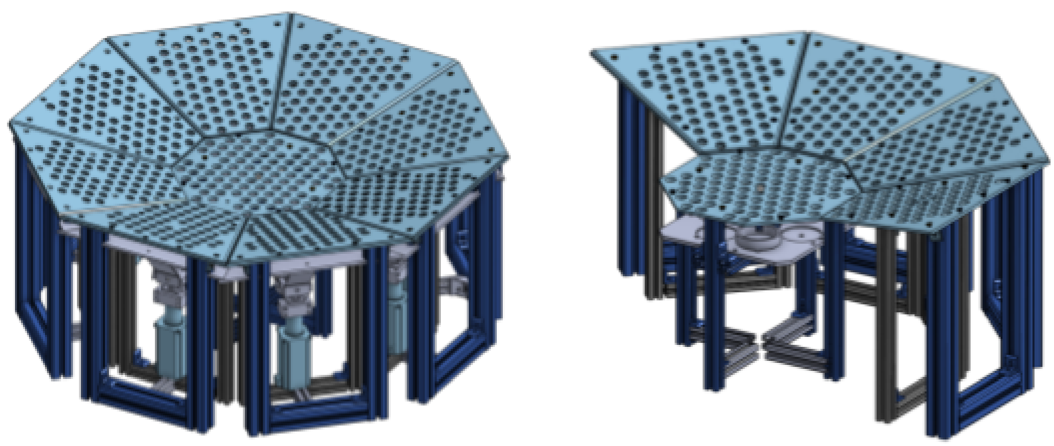

Figure 8: Octagonal base frame design, later modified to four side plates

mimicked by having angled flat metal side plates welded around an octagonal base plate (Figure 8). This positioning mimics a curved feel, allowing the user to transition between different directions without much deterrence. This design also makes manufacturing simpler and cheaper. Each plate consists of a top and bottom half with spherical cutouts that enclosed the balls when the halves were screwed together. The plates would be supported by multiple T-slot extrusion bars that are leftovers from the Alpha design.

Plate material was selected based on mechanical properties, manufacturability, cost, and ease of assembly. For mechanical properties, toughness, yield strength and a high elastic region were the most important criteria. In order to understand the stress the frame would experience, a worst case finite element analysis (FEA) was performed (Figure 9). When walking, people can generate up to 1.5 times their body weight [2]. Considering a maximum user weight of 300 lbs, we placed a 600 lb force to represent the max weight the structure may see. Given that this is a design that involves human safety, the safety factor should be relatively high. Ultimately, we decided to have a safety factor of at least 2.5. According to the results of the FEA, the maximum stress was found to be 38.5 MPA, and given our safety factor, we narrowed down materials to those with a yield strength of at least 40 MPA. Ceramics were further eliminated due to their brittle nature and low impact strength. Considering part manufacturability was also important as the parts are large and require threading and precise tolerances. We considered various plastics, but due to the low yield strength, need for threading, and limitations in printing sizes, we decided to eliminate plastics as an option. This left us with metal as the final option, namely aluminum and steel. The final determinate in the material selection was the cost. Ordinarily, aluminum's yield strength would be too low, but there are several grades such as Aluminium 6061 that meet our strength requirements. The other options were various grades of steel, mostly all which met the strength requirements. Since strength was not an issue, we ultimately chose the cheaper option of Aluminium 6061.

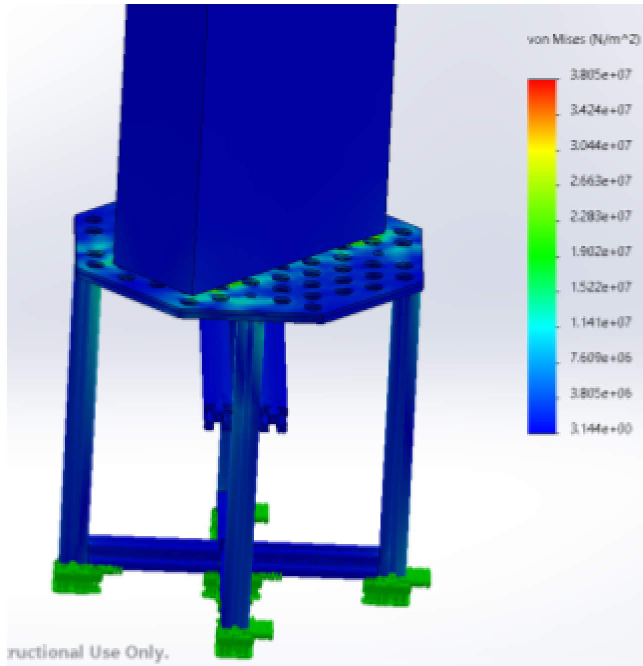

Figure 9: Base plate FEA

4.1.2 Buckling concern of T-Slot framing

Since the plan was to repurpose the T-slot bars into supports for the plates, a major concern was buckling. Each side plate is supported by two vertical 25 mm steel bars in the middle and two vertical 40mm bars at the end. Multiple cross bars were placed as supports between the vertical bars in order to preemptively mitigate buckling. A buckling analysis was done in order to verify the rigidity of the structure (Figure 10). A loading force of 300 lbs was placed on one beam to

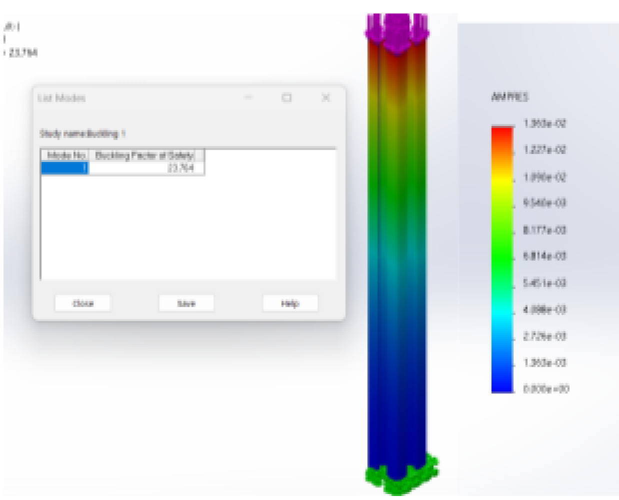
Figure 10. FEA of the beam showed FoS of 23.764

simulate the worst case scenario. The results showed the frame design is structurally sound and does not pose a concern in buckling or bending (FEA). Further, frame integrity will not be reliant on the strength of the welding between plates.

4.1.3 Frame Construction: Manufacturing, Welding, T-Slot Machining, and Teflon Coating

The spherical cutouts were used to allow the balls to freely spin while being restrained, but to achieve such a shape, the plates would have to be machined through computer numerical control (CNC) machined. To ensure the balls would be able to roll properly, we discussed with our advisors and with the technicians in Jacobs' Hall to determine a sufficient tolerance for the cutouts, ultimately deciding on 0.13 mm, a free running fit according to ISO standards. We reached out to a manufacturer for a CNC quote as the plates were too large to do in-house but found that the costs of doing all eight side plates went beyond our budget. After discussion and exploring other options, we made the decision to complete the project with only four side plates. To weld the bottom halves of the frame plates together, we connected with the mechanicians in Hesse Lab. We designed and built a wood fixture and four metal bracket fixtures were made to hold the bottom plate halves in place for the welding (Appendix 9). The T-Slots were cut to the required length as well (Appendix 10).

The engineers in Jacobs' raised the concern that the friction between the steel balls and the aluminum interface might be too high, preventing the balls from rotating over time. Various options were considered in order to reduce the friction including superfinishing the balls and frames, creating a custom insert made of a low friction material like ceramic, or adding a low–friction coating of Teflon or diamond-like carbon (DLC). Given the sheer scale of design changes it would require, custom inserts were eliminated. Although diamond-like carbon would not wear off over timelike Teflon, it is significantly more

Figure 11: Teflon spray coating process

expensive, so was also ruled out. We received a quote from a manufacturer for professional Teflon coating, but the cost and lead time far exceeded our budget and timeline. As a result, we opted to manually coat the plates ourselves, applying two coats of Dupont non-stick Teflon spray (Figure 11).

It was discovered that during the weld, the plates had warped slightly. Due to this, the top halves of the plate did not lay as flat as intended, causing them to pinch some of the balls and impede their rotation. Increasing the cutout tolerance with a dremel has somewhat improved ball rotation.

4.2 Braking System Design

4.2.1 Friction Braking system

After finalizing the frame design, our next focus was developing the braking mechanisms to apply controlled resistance to the balls. To apply friction to the ball rollers, we calculated that a device would need to deliver a sufficient linear force of 3300N (Appendix 11). This narrowed the options down to either a linear actuator or a lead screw. Ultimately, we selected a lead screw due to spatial constraints and the high cost of actuators that had the required stroke length and force output. Once we sourced a suitable lead screw, we explored ways to synchronize the applied linear force using an Arduino and electrical circuit boards. The friction braking system design was then developed based on the lead screw structure, comprising a custom connector to mount the lead screw to the frame, a friction plate embedded with natural rubber as selected through material testing, a support system for the friction plate, and another connector linking the support to the lead screw (Figure 12) (Appendix 10).

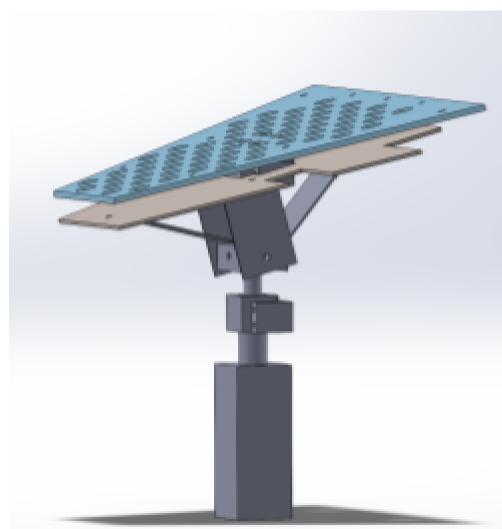

Figure 12: Friction Braking System CAD

Machining the custom connectors in metal required either costly outsourcing or an in-house process that was complex and time-consuming. Fortunately, as most of the force applied to the connectors would be compressive and therefore insignificant, we were able to 3D-print the connectors and use heat-set inserts to provide the threaded hole for bolt connection. For the friction plate, minimizing bending was prioritized to ensure even friction force across the ball rollers—critical for both user experience and safety. Although stainless steel offered higher stiffness, we opted for aluminum. It had sufficient rigidity while being much lighter, which allowed the lead screw to deliver more of its force directly into braking rather than spending it lifting the heavy plate, thus enhancing system performance. The plate was manufactured using a waterjet cutter at Jacobs Hall, offering both precision and cost-effectiveness through in-house manufacturing. Creating the support system was particularly difficult; each lead screw required three uniquely angled supports to match the 15° slope of the main frame. We fabricated these by cutting aluminum sheets to the correct lengths and bending them using lab equipment with an accuracy of ±1°. Getting the angles as accurate as possible was crucial to adhere to the slope of the design and ensure evenly distributed applied friction.

By thoroughly planning every step and maintaining tight coordination between design and fabrication, we were able to avoid unforeseen issues and achieve a smooth and efficient assembly process (Figure 13). The rubber sheet is glued to the foam sheet then placed on the supporting frame. The lead screw is connected with the stepper motor using a 10mm to 8mm coupler, then the stepper motor is constrained on the supportive beams using brackets to prevent it from rotation.

For the electrical control system, the stepper motors are connected with stepper motor drivers and controlled using an Arduino board. The motor drivers are connected to a 24 power supply to support the motors' motion (Figure 14). By adjusting the command in the computer from "none" "low" "high" resistance, the

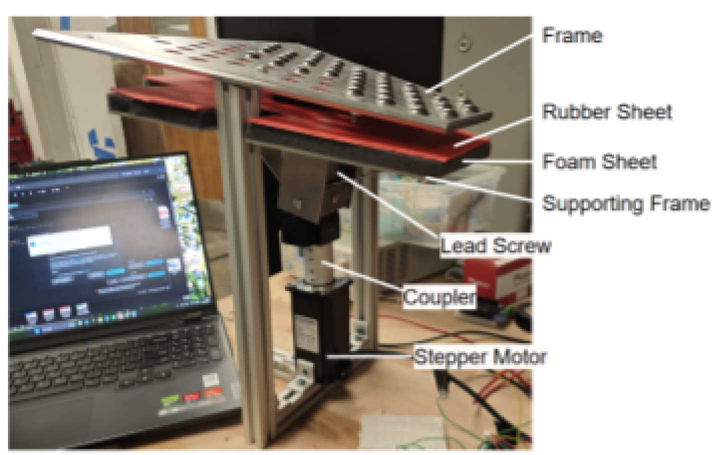

Figure 13: Friction Braking Assembly

stepper motor can rotate to move the connector on the lead screw upwards. The friction pad then compresses on the bottom frame, adding resistance to the balls.

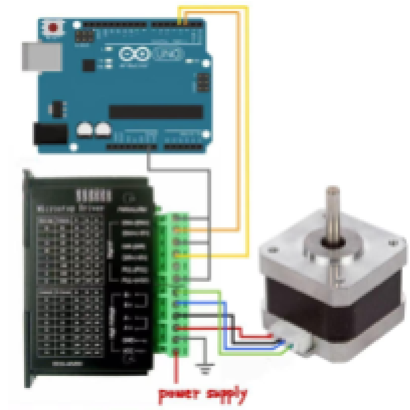

Figure 14: Wiring diagram for lead screw & stepper motor control system.

4.2.2 Electromagnetic Braking System

One concern was how to fix the electromagnets to the main frame without designing something too complex to manufacture while taking into account the availability and price of the materials. After a few iterations by brainstorming and reviewing designs with our advisors, we ended up with a support bed design (Figure 15). The bed would hold the magnets and be fixed to a T-slot bar (Appendix 10). The electromagnets originally chosen were sold out, so magnets of higher strength but larger diameter (50 mm vs 65 mm) had to be used, reducing the number of magnets that could fit on the bed to six and impacting the overall magnetic field. As seen in the previous testing, the balls in the base plate will experience

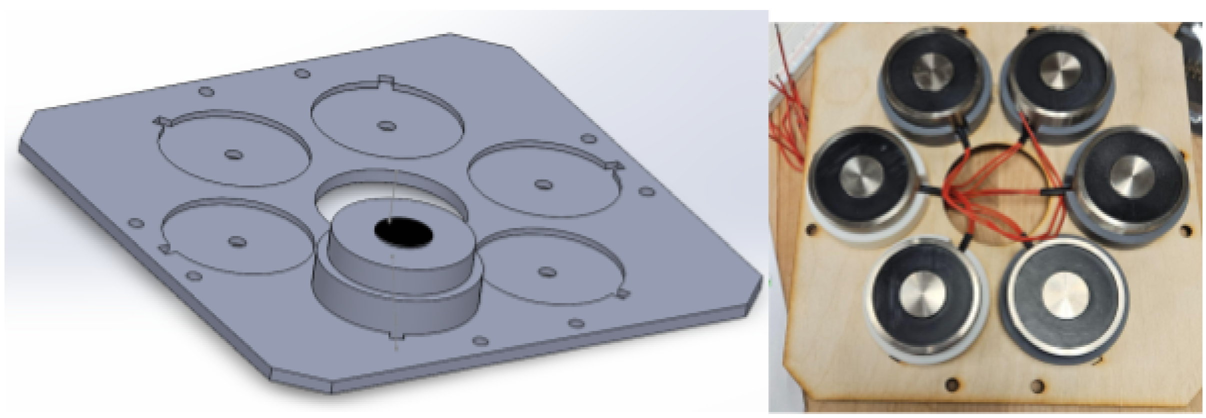

Figure 15: Magnet Brake support bed CAD (left) and wood manufacture (right)

different pull forces based on their location within the magnetic field. However, six magnets are believed to be sufficient enough to stop the user's movement. Wood was chosen as the support bed material due to its machinability, accessibility and price. Two boards were laser cut and then glued together (Figure 15). A housing for each electromagnet was added to first prevent burning the wood if the electromagnets reach too high a temperature, and second prevent the magnet from spinning and unscrewing through a keyed notch. The housings are SLA-printed in heat-resistant resin.

Users should be able to control the extent to which the magnetic brakes are applied; as such, users need to be able to manipulate the current sent to the magnets to affect their pull strength. A control system was designed where a potentiometer with a dial sends a signal to an Arduino microcontroller, which in turn sends a pulse width modulation signal to a metal–oxide– semiconductor field-effect transistor (MOSFET) (Figure 16). Based on that signal, the MOSFET will turn on and off at a certain rate, with the rate determining how much voltage the electromagnet receives, ultimately affecting its performance. With this configuration and the magnets placed in parallel, turning the potentiometer dial affects how much resistance the magnets apply to the balls. The circuit was first simulated in TinkerCAD and tested using breadboards before being soldered to perfboards (Appendix 12). For users to try adjusting the brake themselves, the potentiometer was placed on a separate board and placed beside the treadmill; the other board was affixed to the wooden magnet bed.

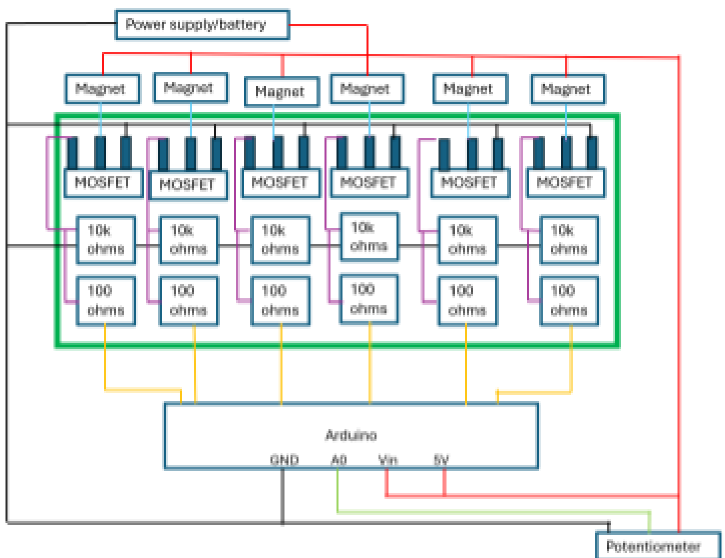

Figure 16: Magnet system control circuit diagram

5. Assessment of Final Prototype

5.1 Full Prototype Assessment

After each braking system was assembled and tested, the entire system was assembled together and assessed for performance (Figure 17). Due to the incomplete state of the treadmill system, we were not permitted to physically stand or walk on the prototype. This restriction was mainly due to safety concerns, as the system was not fully enclosed and lacked all necessary structural components to support a user's weight should they fall. Since the user might "slip" on the rolling surface when on the treadmill, this was a serious hazard. This limitation significantly affected our ability to conduct walking testing to determine whether the prototype could achieve natural user movement, a key goal of our omnidirectional treadmill. However, based on early testing with scaled-down prototypes and individual subsystem experiments, we observed promising behavior that suggested the potential for natural movement. While these results were encouraging, the full effectiveness without real user interaction can not be confirmed.

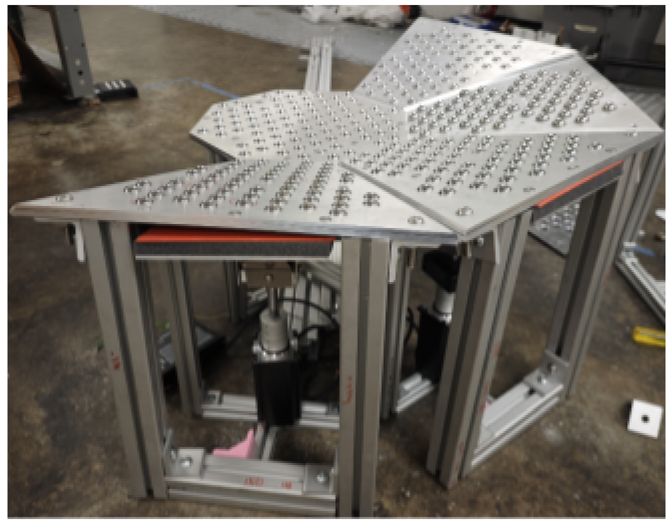
Figure 17: Full prototype assembly with hybrid brakes

Despite the testing constraints, a grading system is developed to objectively evaluate the prototype across the same 14 metrics featured in the Pugh Chart to see if we had succeeded in our project goals (Table 1). Each criterion was rated on a scale from 1 (poor) to 5 (excellent), reflecting the assessment based on observations, component testing, interaction done by sliding hands and feet on the surface, and analysis of partial system integration. To account for metrics that had greater importance and priority than others, the scores were multiplied by a corresponding weighting factor. The two categories marked with a dash (–), were left unscored because they required full user interaction to accurately assess.

Certain limitations in the design and building process directly impacted performance in specific areas. For instance, shock absorption and weight resistance were constrained by the material selections and prototyping resources. The low water resistance score reflected our use of open electrical components and non-sealed connections, especially at the ball roller joints. Despite these limitations, we believe the prototype succeeded in several key areas. It demonstrated strong modularity, allowing individual subsystems to be independently replaced or upgraded theoretically due to segmented assembly design.

Table 1: Evaluation Metric Score

Evaluation Metric	Metric Weight Factor	Score (Unweighted)	Score (Weighed)
Modularity	1	5	5
Overall dimensions	1	3	3
Surface Grip	2	4	8
Maintenance	2	2	4
Shock absorption	2	3	6
Weight resistance	2	3	6
Water Resistance	2	1	2
Ease of use	3	3	9
Precision of omnidirectional movements	3	-	-
System responsiveness	2	-	-
User safety	3	2	6
Initial Manufacturing cost	1	4	4
Repair cost	1	3	3
Simplicity	3	4	12
Possibility to work	3	5	15
Total		**42 (out of 65)**	**83 (out of 130)**

The overall structure matched our target dimensions, and the surface roller grip provided sufficient resistance under unloaded testing. Most importantly, our team was able to prove the conceptual feasibility of the hybrid braking system and roller-driven omnidirectional motion system, giving us confidence in the potential for future development.

In summary, while the prototype could not be fully tested under real user conditions, it served as a successful proof of concept. It validated many of our design decisions, highlighted areas for improvement that we have learnt many lessons from, and provided a strong foundation for further iterations.

5.2 Braking System Assessment

The performance of the braking systems were qualitatively evaluated through controlled foot drag tests on the inclined treadmill platform. The adjustments are achieved through vertical positioning of the friction braking interface and regulation of the current supplied to the electromagnets. Users demonstrated significant discrimination of resistance gradients, thereby validating the efficacy of our design concepts.

There were still some limitations of the friction braking system. When individual balls were tested using hands to assess their performance separately, it was observed that some balls did not experience full resistance as expected. This issue was attributed to the unexpected deformation of the frame caused by the welding process. Despite the overall satisfactory performance of the system, if more precise friction control is to be achieved in the future, it is necessary to consider enhancing the quality of the welding process or selecting alternative materials for the frame construction. The use of stronger materials could potentially reduce frame deformation and improve the consistency of resistance for each ball. For the magnet braking system, it was difficult to adjust the T-slot supporting the magnet bed to be as close to the balls as possible to ensure the balls experienced the maximum pull. A more optimal design with precise dimensioning could ensure the magnets are placed in the correct spot. Furthermore, while the magnets caused sufficient resistance to many of the balls, as we were unable to fully test walking on the treadmill, it is unclear if enough balls were stopped to cease user movement. Using the smaller magnets as originally intended would likely create a more effective field that stops more balls.

Currently, both braking systems are operated independently. We are in the process of combining the braking systems so that the resistances they apply both correspond to the potentiometer's dial at the same time. Successful completion of this task would further underscore the feasibility of a hybrid system.

6. Discussion and Future Work

Throughout the project, we made several key compromises due to constraints in budget, space, and available manufacturing resources. For example, we chose to segment the overall surface of the treadmill into flat planes rather than create a smooth concave surface to save significant manufacturing cost. We 3D-printed connectors instead of machining them from metal, which saved time and money but reduced long-term durability. The magnetic braking system was only partially implemented at the base when ideally it would be implemented throughout the entire treadmill, prompting us to use the hybrid solution. Most significantly, we were unable to test the system under real user load due to safety concerns. Had we been able to build and test the full system as intended, we believe the prototype would have demonstrated a smooth user experience with desired responsiveness, user feedback, and movement precision. A fully enclosed and reinforced structure would have enabled proper load testing, allowing us to fine-tune the braking system and roller control for natural, intuitive movement. With more time and resources, we could have also improved maintainability and robustness such as exploring ways to dust and waterproof the treadmill surface, pushing the system closer to a deployable, real-world prototype.

After testing the device, we were able to get a better understanding of how the parts interact and how we can improve the quality of the design. While testing the rotation of the balls we noticed that the balls were able to roll but they were not able to spin like we intended. This is partly due to the fact that we had to manually coat the teflon but it was also due to other factors including the ball procurement, plate finish, and final coating. During experimentation, different balls rolled differently; this was due to the fact that the supplier shipped them in plastic bags and some of the plastic melted on the balls affecting the smoothness. We also noticed that the finish of the plates was rough and sometimes not up to tolerance specification, which affected the friction. Finally we saw that the manual Teflon coating had little effect and a teflon or diamond-like carbon coating at the supplier level will be necessary.

The project's future would continue with the research and designs we accumulated throughout the year. The hardest part of this project was getting an initial idea and finding relevant science/information needed to solve problems. With our completed prototype alongside our calculations, future teams will have an easier time of getting started. All data is stored in a shared Google Drive folder and Onshape.

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Report Writing Deliverable

Ki-Hoon Lee : 3.2.1 Torus Design, 4.2.1 Friction Braking system, 5.1 Full Prototype Assessment, 6. Discussion and Future Work

Sarah Chinedu Nwakudu : 1. Problem Space, 2: Market Analysis, 3.1: Project Goals, 3.2: Concept Selection, 3.3 Initial Prototyping and Material Selection 4. Final Design and Prototyping, 4.1.3. Frame Construction, 4.2.2 Electromagnetic Braking System, 5. Assessment of Final Prototype, Editing

Sebastien Guerif: 3.2.1 Torus Design, 3.3 Initial Prototyping and Concept evaluation 4.2.2 Electromagnetic Braking system

Xavier Johnson : 3.2.2 Beyblade Design 4.1.1 Material Selection 4.1.2 Buckling concern of T-slot framing, 4.1.3 Frame Construction: Manufacturing, Welding, T-Slot Machining, and Teflon Coating 6. Discussion & Future Work

Yuxin Ye : 1. Problem Space 3.1 Project Goals, 3.2 Concept selection, 3.3 Initial Prototype and Material Selection 4.2.1 Friction braking system (assembly & control) 5. Assessment of final prototype

Printed name: Sarah Nwakudu Signature:

Printed name: Yuxin Ye Signature:

Printed name: Sebastien Guerif Signature:

Printed name: Ki-Hoon Signature:

Printed name: Xavier Johnson Signature: Xavier Johnson

Appendix

Appendix 1. Project Specifications

Specification	Must	Should	Could
Operation	Resistive		
Functionality	Can walk naturally	Able to run	Can walk and stop freely
	For 220 lb users	>220lbs users	Not noisy
Durability		Lifespan of 10 years	Minimal maintenance
Aesthetics	1x1 ft to 2x2 ft surface	Prototype of this dimension	Less bulky and thinner than previous design
Safety	No body parts come into contact with surface		Can use without a harness
	Zero to minimal slip of the user from surface		
Maintenance		Easy maintenance: easily accessible screws etc. (Avoid last treadmill assembly & disassembly problem)	Modular design so if a section of the treadmill is faulty / unresponsive, it can be replaced
Manufacturability	Proof of concept build		Easy to assemble with as many accessible and available parts.
			Minimize use of bespoke parts

Appendix 2. Pugh Chart for Design Selection

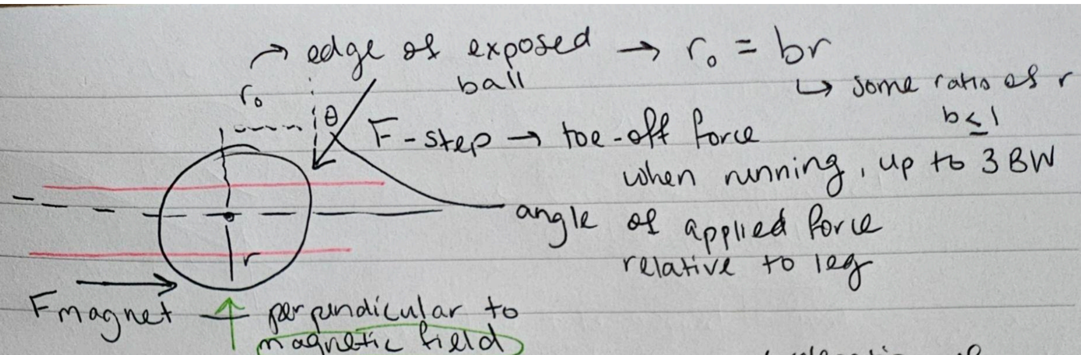
			Baseline	Alternatives				
Topics	Criteria	Weight	Previous Year Project	Disney Treadmill	Rollers Track	Torus Shape	Pizza Design	BeyBlade Arena
Shape	Modularity	1	Same	Better	Better	Same	Better	Better
	Overall dimensions	1	Same	Better	Same	Better	Worse	Same
Surface	Surface Grip	2	Same	Worse	Worse	Same	Worse	Worse
	Maintenance	2	Same	Worse	Better	Worse	Same	Better
	Shock absorption	2	Same	Worse	Same	Worse	Same	Worse
Resistance	Weight resistance	2	Same	Worse	Worse	Better	Worse	Worse
	Water Resistance	2	Same	Worse	Better	Better	Better	Better
Functionability	Ease of use	3	Same	Better	Worse	Same	Better	Same
	Precision of omnidirectional movements	3	Same	Worse	Worse	Better	Worse	Worse
	System responsiveness	2	Same	Worse	Worse	Better	Worse	Better
	User safety	3	Same	Better	Same	Better	Worse	Worse
Cost	Initial Manufacturing cost	1	Same	Worse	Better	Same	Same	Same
	Repair cost	1	Same	Worse	Better	Worse	Worse	Better
Complexity	Simplicity	3	Same	Worse	Same	Worse	Better	Better
Feasability	Possibility to work	3	Same	Same	Worse	Worse	Same	Same
	Better		-	4	5	6	4	5
	Same		-	1	4	4	4	4
	Worse		-	10	6	5	7	5
	Weighted Better		-	8	7	13	9	11
	Weighted Same		-	0	0	0	0	0
	Weighted Worse		-	20	15	11	14	12
	Overall Score		**0**	**-12**	**-11**	**2**	**-5**	**-1**

Appendix 3. Friction Braking System Initial Prototype Testing

Table 2. Friction Test

Test #	Ball size	Brake Material	Distance (mm)	Results
Test 1	10mm	Rubber durometers = 40A	12.15	Hardly rotate
Test 2			13.23	Rotate with resistance
Test 3			14.29	Rotate freely
Test 4		Rubber durometer = 60A	12.45	Hardly rotate
Test 5			12.95	In between
Test 6			13.04	Rotate with resistance
Test 7		Natural Rubber	15.12	No rotation
Test 8			16.52	Rotate with resistance
Test 9		Foam Sheet	16.33	Rotate with small resistance
Test 10			24.56	Rotate
Test 11	18mm	Rubber durometers = 40A	13.51	Rotate with large resistance
Test 12			14.21	Rotate with resistance
Test 13		Rubber durometer = 60A	13.64	Hardly rotate
Test 14			13.98	Rotate with resistance
Test 15		Natural Rubber	10.52	No rotation
Test 16			11.25	Rotate with resistance

Appendix 4. Magnet Strength Calculation for Initial Prototype Testing



$\tau = I\alpha \rightarrow \tau = \frac{2}{5}mr^2\alpha \qquad \alpha = \frac{a}{r}$ → deceleration of runner

$$\tau = I\frac{a}{r} = \frac{2}{5}mr^2\frac{a}{r}$$

$F_{magnet}\cancel{r} - F_{step}\cos\theta\, b\cancel{r} = \frac{2}{5}m\cancel{r^2}\frac{a}{\cancel{r}}$ → radius of ball does not affect brake performance directly

$$F_{magnet} = \frac{2}{5}ma + F_{step}\, b\cos\theta$$

$F_{step} = F_{input} / \underbrace{\#\text{ of balls per foot}}$ (ball of foot)

~~ball radius will affect this~~

$$\boxed{F_{magnet} = \frac{2}{5}ma + \frac{F_{input}}{\#\text{ balls}}\, b\cos\theta}$$

assume avg deceleration is $5\ m/s^2$, ball mass is 0.1 kg, F_{input} is 3BW, & # of balls is 5 balls, b is 0.75, ~~&~~ $\theta = 0$

$$F_{magnet} = \frac{2}{5}(0.1)(5) + \frac{3BW}{5}(\cancel{\cos\theta}\ 1)(0.75)$$

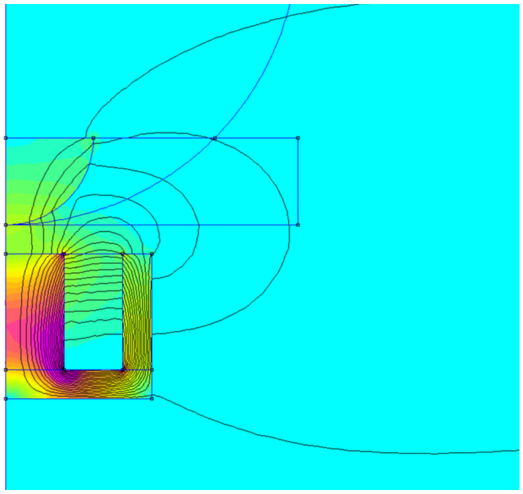
$$F_{magnet} = 0.2 + 0.45BW\cancel{\cos\theta}$$

Appendix 5. Magnetic Braking System Initial Prototype Testing

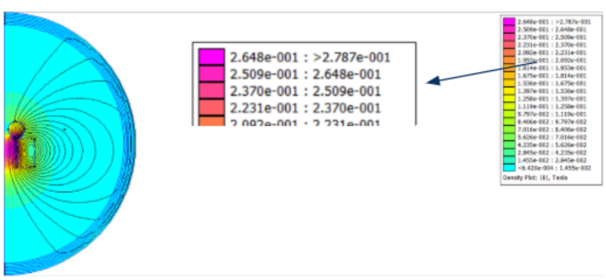
Table 3. Magnet Test

Test #	Magnet Specification	Results
Test 1	12V 100N 30 x 22mm Electric Lifting Magnet Electromagnet Round Electromagnet Solenoid Lifting Cylinder Electromagnet	A lot of resistance but still rotates
Test 2	12V DC 150N Electric Lifting Magnet Electromagnet Solenoid Lift Holding 30mmx22mm	A lot of resistance but still rotates
Test 3	26 lbf max pull, Magnetized Through Thickness, 3/16" Thick, 15/16" OD	Rotates fairly easily

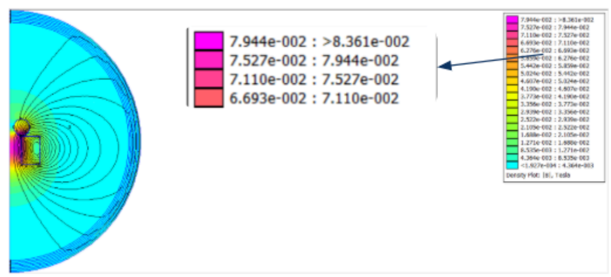
Appendix 6. Magnetic Field Over Flat Surfaces



Appendix 7. Magnetic Attraction Force Regarding Different Coil Number (N)

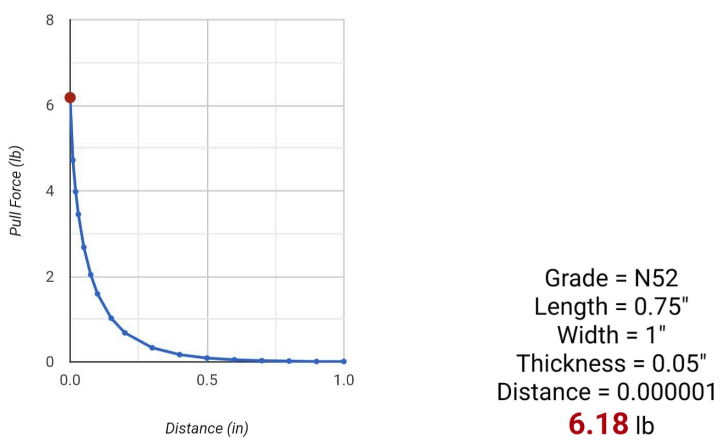


Magnetic field intensity with N= 10000

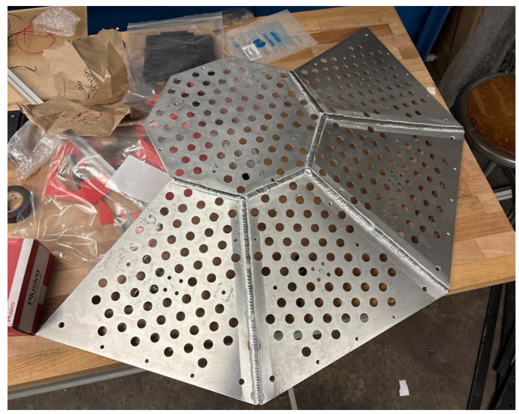


Magnetic field intensity with N= 3000

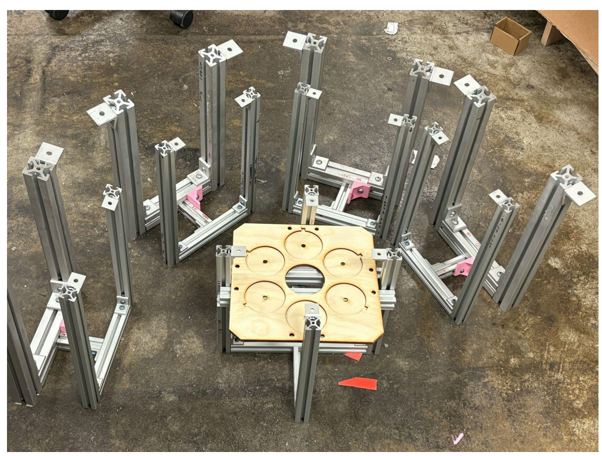
Appendix 8. Electromagnetic Pull Force Variation with Different Distance



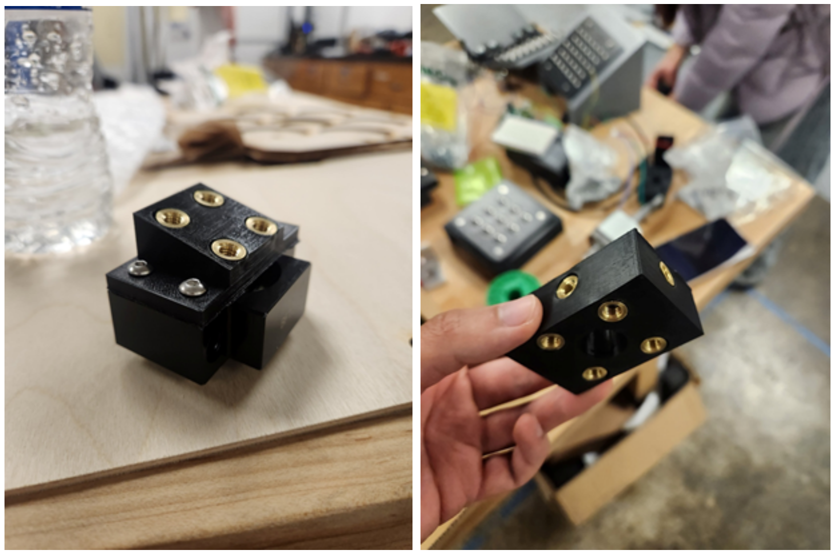
Appendix 9. Wood Fixture For Frame Welding



Appendix 10. Components Manufacturing



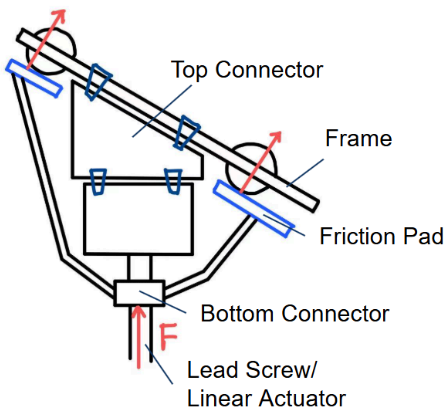
T-slots Cutting



Connectors Made Using Heat-Set Inserts

Friction Pad & Support Manufacturing

Appendix 11. Force/ Torque Calculation for Linear Actuator/ Stepper Motor



Friction Coefficient: $\mu = 0.3$

Pressure needed to make a ball stop: $P \approx 16\,kPa$

Contact Area for balls: $A = 4\pi r^2/4 = 0.001\,m^2$

Friction force: $f_{pad} = 62\,balls \times PA = 1000\,N$

Vertical force needed: $F = f_{pad}/\mu \approx \underline{3300\,N}$ Linear Actuator

If using lead screw, max torque needed for stepper motor:

$$T_R = \frac{Fd_m}{2}\left(\frac{L+\pi f_{lead} d_m sec(\alpha)}{\pi d_m - f_{lead} l sec(\alpha)}\right) \approx \underline{6\,N \cdot m}$$ Stepper Motor

d_m - mean diameter

f_{lead} - coefficient of friction for lead screw,

l - lead (5 mm)

α - lead screw angle.

Appendix 12. Circuit Simulation for Magnetic Braking System