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# MEMS 411: The Bueffer 3000

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**FL21 MEMS 411 Mechanical Engineering Design Project**

## The Bueffer 3000

The Bueffer 3000 is a volleyball setting machine design to be used for smaller club, intramural, or recreational volleyball teams that do not have a high number of trained setters. Our customer was the Washington University in St. Louis' Men's Club Volleyball team. We conducted a customer interview with one of the captains of the team and recorded what the team was looking for in a volleyball setting machine. Existing devices in the market do not properly train hitters as they do not allow for realistic timing of a set and hit. Our customer's main need was to have a device that properly trained hitters like a real setter would. From the interview, we were able to create a list of customer needs and ranked them based on most important components our customer would want in the device. We took these customer needs and created a morphological chart based on the functions the device should be able to do. The team designed various concepts and compared them using a weighted system based on interpreted customer needs. With a final design selected, engineering models were researched and evaluated to verify the physical model of the device. An initial prototype was built with the engineering models in mind. Three performance goals were set for us to achieve an acceptable product: the ball must be able to launch $\geq$ 14 ft. vertically, the ball must be able to launch $\geq$ 20 ft. horizontally, and the device must be able to deliver a ball once every 6 seconds. The prototype was refined until all aspects were adequate for our customer and met our performance goals. The final product was delivered to our customer with high remarks.

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# 1 Introduction

The sport of volleyball requires team success and cooperation. A team is only as strong as their weakest link. Therefore, the mission of The Bueffer 3000 is to develop a product that will facilitate the improvement of a hitter's technique, which is a vital skill for success. The Bueffer 3000 is a machine that will simulate a "set" or "pass" from one player to the hitter. The machine can be used to improve technique and provide repetition practice. With various avenues to achieve the end goal of launching a volleyball to a desirable trajectory, three plausible methods were explored: catapult system, sling-shot, and a pitching machine. Keeping in mind the three possible methods, safety concerns, and cost-efficiency, our customer was then interviewed and favored the sling-shot system. After consulting the customer, a higher priority was placed on the functionality and safety of the machine over aesthetics. Therefore, the updated goal became to create a volleyball sling-shot system that would be adjustable, easy to transport, and mechanically operated by a human.

# 2 Problem Understanding

## 2.1 Existing Devices

There are numerous design paths that can lead to a system that "sets" a ball to a hitter. Three methods worth exploring are a sling-shot system, baseball pitcher system, and a catapult system. Each method has various strengths and purposes, so each system was explored to determine which system would perform the desired functionality, limit potential hazards, and be easy to use.

### 2.1.1 Existing Device #1: Mega Balloon and Ball Team Launcher

Figure 1: Elastic balloon or ball launcher.

Link: https://www.catch.com.au/product/mega-balloon-and-ball-team-launcher-5076894/?offer_id=26599509&utm_source=affiliates&utm_medium=referral&utm_campaign=6040&cfclick=743d4ddabccb4a2daede733f7e0545a6

Description: The mega launcher is a current product that launches large water balloons or balls. The product requires four holders to ensure the elastic energy stored in the bands is harnessed when the ball is pulled backwards. A second individual is needed to pull the large fabric holder backwards. Upon release, the bands rapidly compress back to their initial resting state, allowing the majority of energy to be put into displacing the ball and launching it into trajectory. This system utilizes mechanical work done by humans and the energy stored in the elastic bands to launch the ball or balloon. There are hazards to be considered using such a system. If not held securely, the elastic bands can cause damage. The recoil of the fabric holder can also cause damage if the person launching the balloon or ball does not take the recoil into effect.

### 2.1.2 Existing Device #2: Jugs M1300 Combo Pitching Machine

Figure 2: Professional pitching machine with two rotating wheels.

Link: https://www.anthem-sports.com/jugs-m1300-combo-pitching-machine.html?network=g&device=c&keyword=&campaign=1622839591&adgroup=pla-560989275098&gclid=CjwKCAjwvuGJBhB1EiwA
OnwBWf11l1g_CzOK6XBBd93NqQADsNI2fIPglfuMSMlHVBoCkMMQAvD_BwE
Description: The Jugs M1300 Combo Pitching Machine launches baseballs at speeds from 20-104 miles per hour. The system utilizes the rotational motion of the top and bottom wheels to set a ball into motion. The wheels, which rotate in opposite directions, "push" the ball between the wheels so that the friction between the ball and the wheels in addition to the angular velocity of the wheels dictate the speed of the baseball. This system raises some safety hazards that must be considered during use to prevent unexpected injury. The wheels rotate at a high velocity and can pull items that come in contact with them into rotation. However, the pitching machine does have

an advantage with an adjustable launching angle to allow for multi-use and a wide, adjustable base to keep the machine held upright during use.

#### 2.1.3 Existing Device #3: Mind Ware KEVA Catapult Set

Figure 3: Desk-sized catapult system.

Link: https://www.officedepot.com/a/products/119078/Mind-Ware-KEVA-Catapult-Set-Multicolor/?utm_source=google&utm_medium=cpc&mediacampaignid=71700000086547768_14404707264&gclid=CjwKCAjwvuGJBhB1EiwACU1AiRhpDghGMvNFvgJ5odbw-R39oqPnOSSvFF2PLqyJ0ZjGb0cYoH2FMhoCpiMQAvD_BwE&gclsrc=aw.ds
Description: The KEVA Catapult Set is a simple catapult system that utilizes the elastic energy of a rubber band to pivot a lever about an axis. When the rubber band is stretched by pulling the catapult down, it exits its resting state. When the catapult is released, the rubber band rapidly compresses to its initial state. The catapult system has a stopping point located on the other side of the lever, opposite of the basket, that halts the motion of the lever. This in turn allows the ball to launch from the basket at some given angle dictated by the stopping point. This system also introduces hazards, such as the catapult rapidly accelerating and causing harm to anything or anyone in its path. On the other hand, the catapult has a sturdy base that works to prevent movement of the system.

## 2.2 Patents

### 2.2.1 Handheld water balloon catapult (US4922884A)

Link: https://patents.google.com/patent/US4922884A/en

This patent utilizes elastic bands to launch a water balloon. The sling-shot dynamics of the system provide the balloon with its energy through the re-compression towards the resting state of the elastic bands. The elastic coefficient of the bands as well as the displacement from resting state to release are the primary contributors to the balloon's motion. The static wrist structure provides the system with the necessary support. Together, the components of the balloon sling shot are fundamental for safety precautions, accuracy, and power.

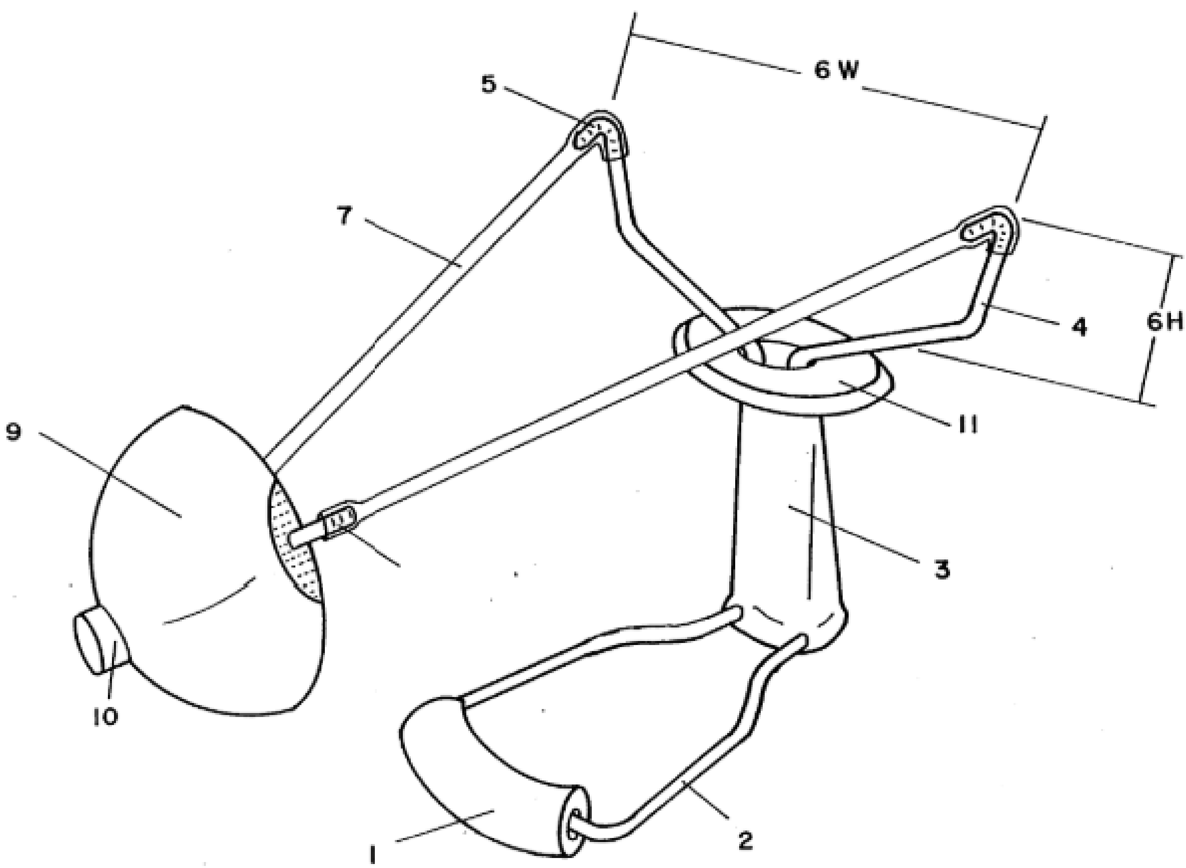



Figure 4: Patent image of water balloon slingshot.

### 2.2.2 Volleyball spiking training device (US8371964B2)

Link: https://patents.google.com/patent/US8371964B2/en

This patent suspends a volleyball at a desired height for the hitter to spike the ball. Volleyballs are loaded into a holding contraption (label 36) and fed to a loading tray which utilizes the work of gravity to reload the device after each rep. The spiking contraption is mobile, sitting on a set of four wheels, allowing it to move to a desired location with respect to the net. The height at which the ball is being suspended is also adjustable to account for various hitting heights from a pass. The system is well put together and accounts for adjustments, has a stable foundation, and has good mobility, which are three desirable components for a volleyball setting contraption.

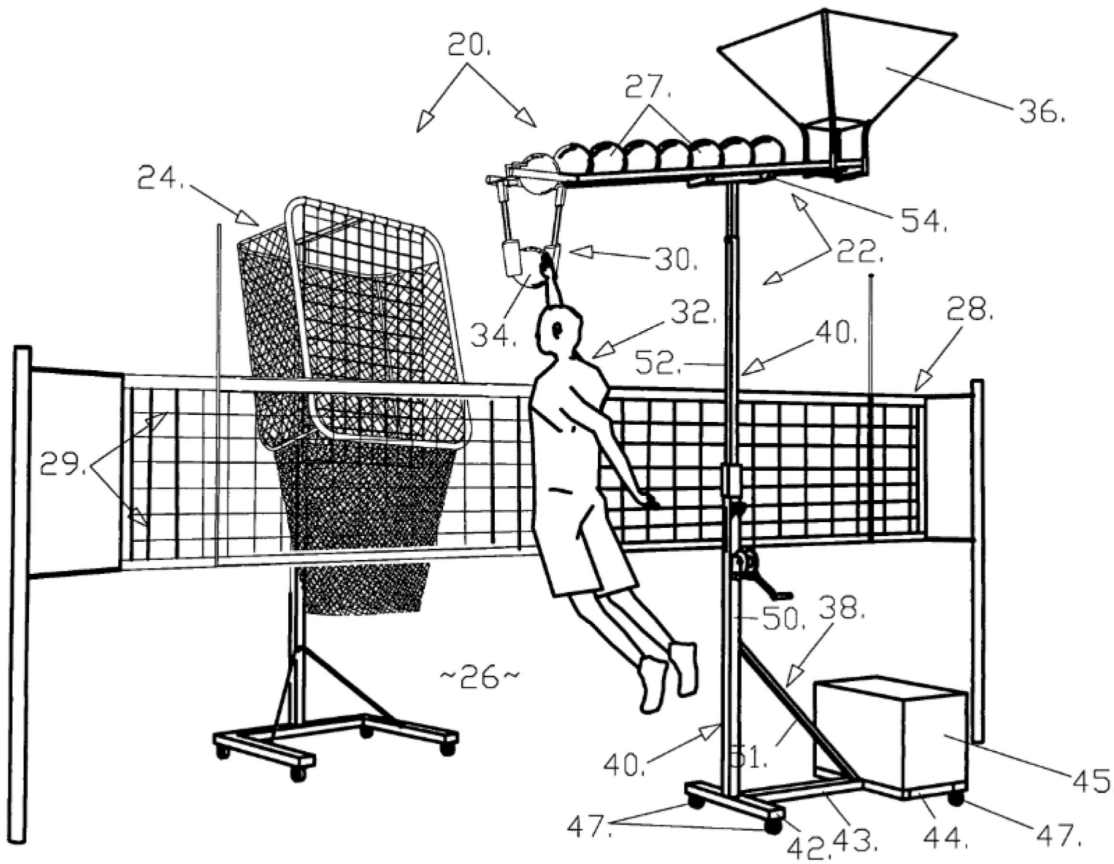



Figure 5: Suspended volleyball spiking device.

## 2.3 Codes & Standards

### 2.3.1 Standard Specification for Fitness Equipment (ASTM F2276)

This standard developed by the American Society for Testing and Materials sets specifications for the design and construction of equipment used in athletics. The standard includes instruction on design of corners, stability, edges, tube ends, supports, etc. The equipment should meet guarding, enclosure, and spacing requirements, as well as instructions for the setup and proper use of the equipment.

### 2.3.2 Playing Field Equipment - Volleyball Equipment - Functional and Safety Requirements, Test Methods ( CSN EN 1271)

This European Standard specifies the safety requirements and functional requirements of indoor and outdoor volleyball equipment. The standard can be used for two types and five classes of volleyball equipment. The standard does not apply to beach volleyball equipment or referee stands. This standard guides users on requirements for volleyball equipment they are designing.

## 2.4 User Needs

In order to determine the user needs of the volleyball setting machine, a customer was interviewed to determine the most important components the setting machine must include. The future design is intended to be based off of the customer needs to ensure satisfaction.

### 2.4.1 Customer Interview

Interviewee: Jonathan Bueff
Location: McKelvey Hall, Washington University in St. Louis, Danforth Campus
Date: September $8^{th}$, 2021
Setting: We prepared a list of questions for Jon that ranged from functionality requirements to safety concerns. It was necessary to explain possible concepts and ideas to him in order to determine which concepts would best simulate a real set. The discussion directed us to a path where functionality trumped every consideration followed by safety and mobility. The whole interview was conducted in a common space and took ∼45 min.

Interview Notes:
*When a volleyball is set to be hit, there must be some favorable trajectory of the volleyball. With that being said, we have a few questions concerning the volleyball's trajectory before it is hit. What is the optimal launch height of the volleyball?*

- About 6-7 feet above the ground. It should be a few inches above the average setter's head.

*What is the optimal height the ball travels before it is hit?*

- I would say a minimum of 8-9 feet and maximum of 14-15 feet. The ideal height would be about 14 feet.

*At what distance should the ball be hit in the air from the setter machine? This would be to simulate an actual hit and provide the hitter enough space to hit the ball without landing on the machine. For example, the ball cannot be launched directly above the machine.*

- It would be ideal to have a range of 4-15 feet from the machine as the hitting distance.

*Is it favorable for the ball to have any sort of rotation or spin when it is set?*

- The ball shouldn't have any rotation because that indicates that the ball was a double hit, so no spin would be ideal.

*Is there a preferable range of motion for the setter you would like to see? For example like being able to set backwards, forwards, etc..*

- It would be beneficial to adjust the direction of the setter whether turning it or just adjusting its launch direction. The machine would preferably shoot back, middle, and out.

*Would you like the setter machine to be lightweight? How important is weight?*

- Weight is not super important. If it needs to be heavier to meet the functionality, I would say weight is not a priority to minimize. If it is heavier, it just needs to be able to move out of the way if a hitter runs into it.

*Are there any safety precautions you would like prioritized?*

- If it is heavy, padding around the sides would be beneficial. It would also be nice to not have to worry about sharp edges. The situation in which this would be used is primarily for hitting drills and not ones where people would be running around and diving.

*The rate at which the ball is launched has the potential to be automatic or manual. With that being said, the feed system can be automatic or human powered. What do you think would be most beneficial?*

- It would be nice to have control over the launch rate. I think a human powered system would be the best solution. It would allow for manual control of launching the ball. It probably would also reduce possible errors if it was automatic.

*We have a few concepts in mind including a slingshot system, a catapult system, and rotational wheel launching system. It is early in the design process, but we were curious to hear your take on these concepts.*

- So I think the most optimal systems would be either the slingshot or wheel system. To me the catapult system seems a little odd. The slingshot system and wheel system definitely have safety concerns though.

*Would you like the setter to be portable? How important is portability?*

- Portability in terms of moving it shorter distances would be ideal. We don't need it to be folded up and packed into like a bag, but maybe having wheels on it to roll it into a corner or something would be great.

*What specific characteristics would be most desirable for a setting machine? Can you rank the importance of these characteristics?*

- In my opinion, I believe functionality would be the most desirable characteristic of a setting machine. Obviously, safety precautions need to be considered, and including a mobility aspect would be ideal, but functionality is a priority.

### 2.4.2 Interpreted User Needs

Based on the interview, we were able to determine some of the basic needs our machine must incorporate in order to meet the user's needs. Ranking the needs of the user, functionality is the priority followed by safety and mobility. With this information, the following needs were determined and ranked based on importance.

Table 1: Interpreted Customer Needs

| Need Number | Need | Importance |
|---|---|---|
| 1 | An optimal launch height of 6-7 feet | 3 |
| 2 | An optimal peak trajectory height of 9-14 feet | 5 |
| 3 | An optimal hitting distance of 4-15 feet from the setting machine | 5 |
| 4 | No rotation or spin on the ball | 5 |
| 5 | Manual feed rate and consistency | 4 |
| 6 | Mobility to move and store the machine | 5 |
| 7 | Padding around the structure for safety precaution | 2 |
| 8 | Should shoot back, middle, and out | 4 |
| 9 | Strong support so it does not tip easily | 4 |
| 10 | Easy to use | 4 |
| 11 | Reduce hazards such as sharp edges | 5 |
| 12 | Launching mechanism should have a large range of motion | 4 |
| 13 | Lock the launching mechanism into place for consistent sets | 4 |
| 14 | Allows for various set types | 5 |

## 2.5 Design Metrics

The design metrics are meant to provide target thresholds and ideal thresholds for the final product. Based off of the customer needs, the table below quantifies and qualifies the needs desired by the customer. As concept generation and production progresses, communication with the customer may introduce more specifications and thresholds.

Table 2: Target Specifications

| Metric Number | Associated Needs | Metric | Units | Acceptable | Ideal |
|---|---|---|---|---|---|
| 1 | 1 | Height of launch | ft | 6-7 | 6.5 |
| 2 | 2 | Peak set height | ft | 9-15 | 12 |
| 3 | 3 | Hitting distance from machine | ft | 4-15 | 10 |
| 4 | 4 | Rotation upon release | rad/sec | $2\pi$ | 0 |
| 5 | 8 | Weight-efficient | lb | 100 | 75 |
| 6 | 11 | Sharp edge test in 16 CFR 1500.49 Code of Federal Regulations (CFR) Consumer Product Safety Commission | binary | Pass | Pass |

## 2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

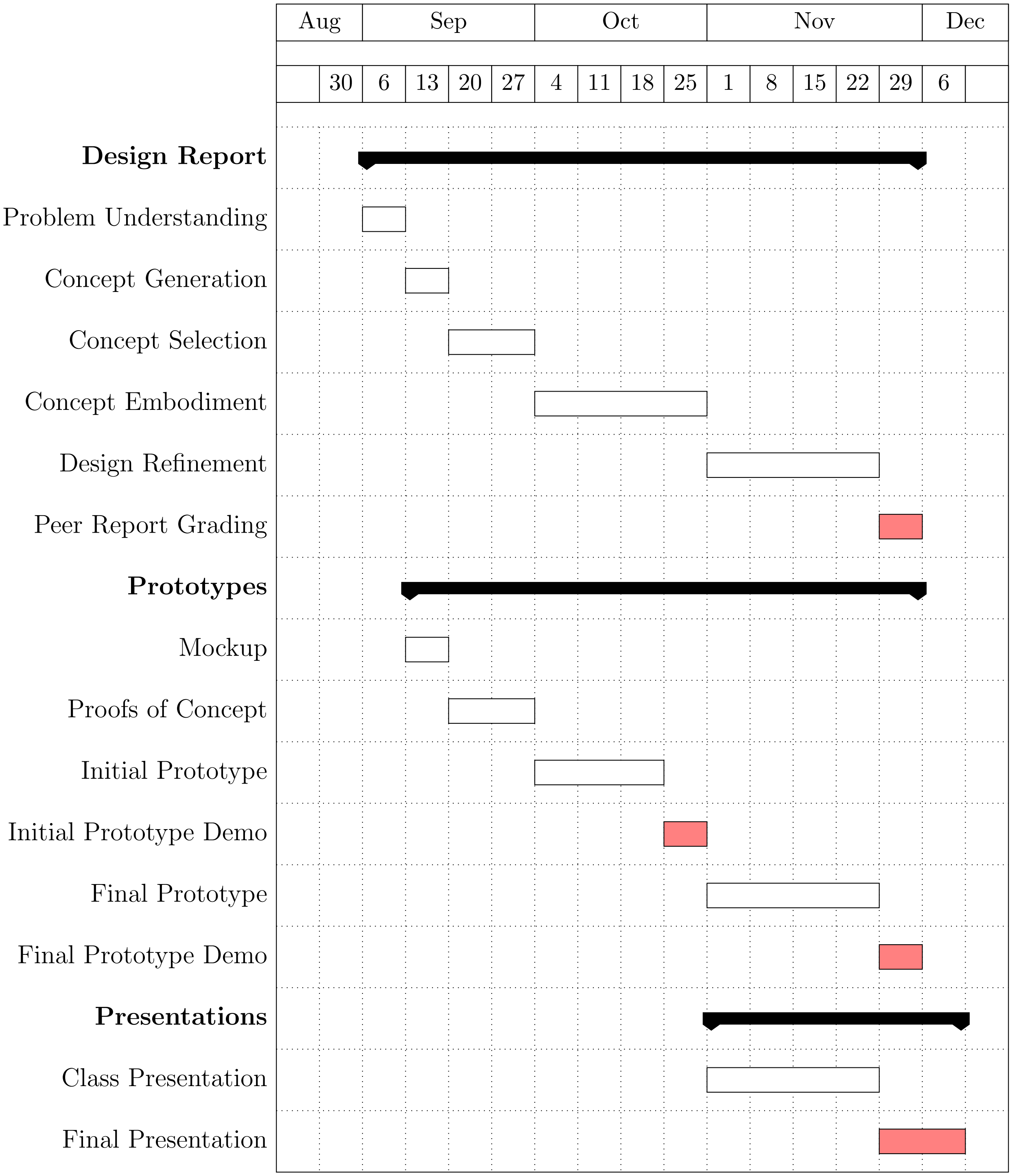



Figure 6: Gantt chart for design project

# 3 Concept Generation

## 3.1 Mockup Prototype

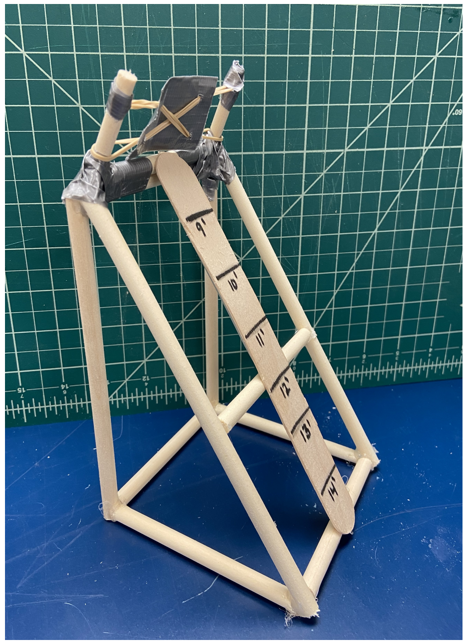



Figure 7: Mockup prototype isometric view

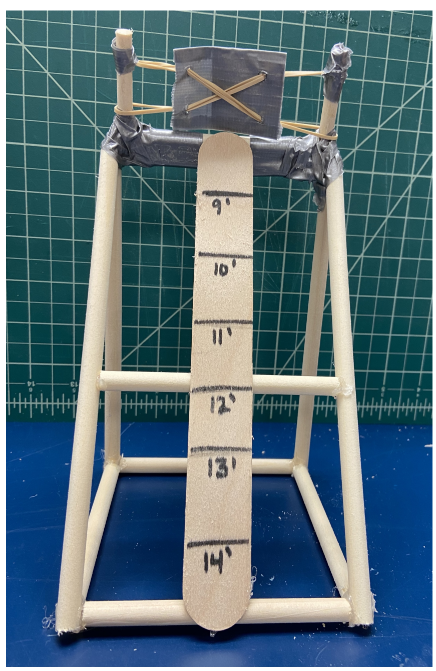



Figure 8: Mockup prototype front view

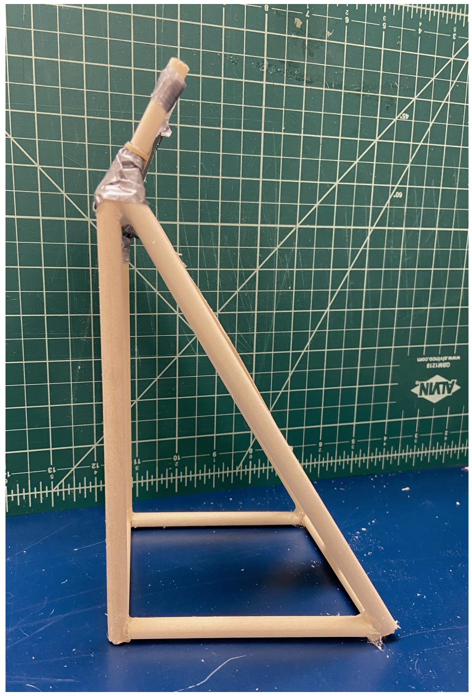


Figure 9: Mockup prototype side view

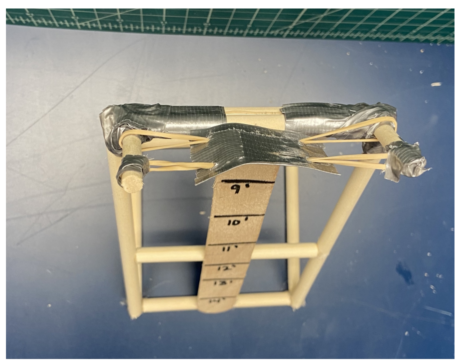


Figure 10: Mockup prototype top view

Designing the mockup prototype illuminated a number of challenges that may be encountered during the design process. We concluded that the base of our setting machine must be heavy and capable of supporting a reasonable force. The exerted force will vary with direction but should be aligned along the same plane regardless of direction. Therefore, the support in the system should prevent failure along this given launch plane. In addition to exploring the possible locations for extra support, we were challenged with devising a method to adjust the launch angle. There are several viable solutions, so further prototyping and experimentation will determine the most effective launch angle adjustment method. Aside from the support testing and launch angle adjustment testing, the fundamental concepts we have hypothesized thus far seem to be pliable and effective methods to set a volleyball. Further experimentation will provide insight into the effectiveness of our current design.

### 3.2 Functional Decomposition

The following functions were derived from the interview with our customer. Such needs for the device are essential to creating a machine that realistically sets a volleyball in accordance with the rules of the sport and reliably benefits the team.

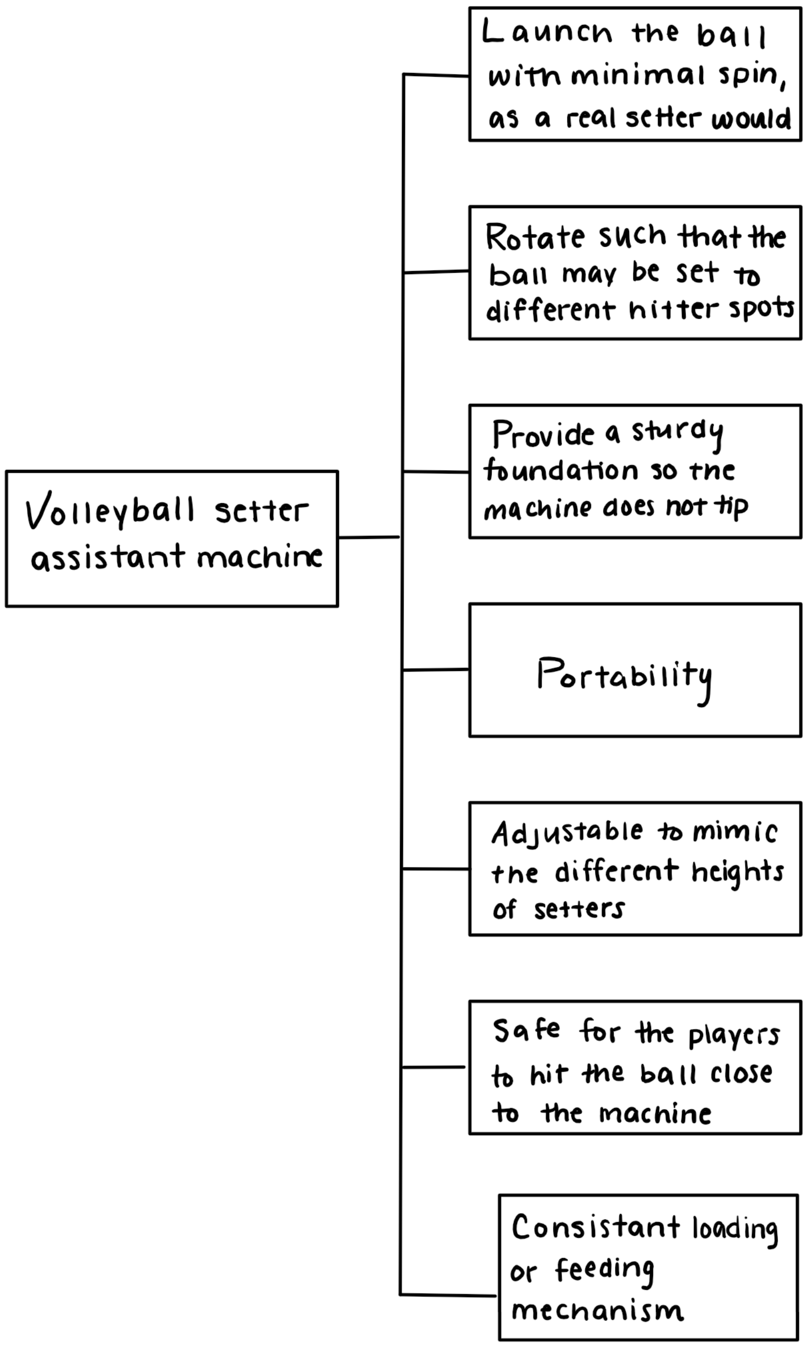



Figure 11: Function tree for The Bueffer 3000, hand-drawn and scanned

## 3.3 Morphological Chart

The morphological chart explores the various ways the functional needs could be fulfilled. These range of options were then explored in the alternative design concepts.

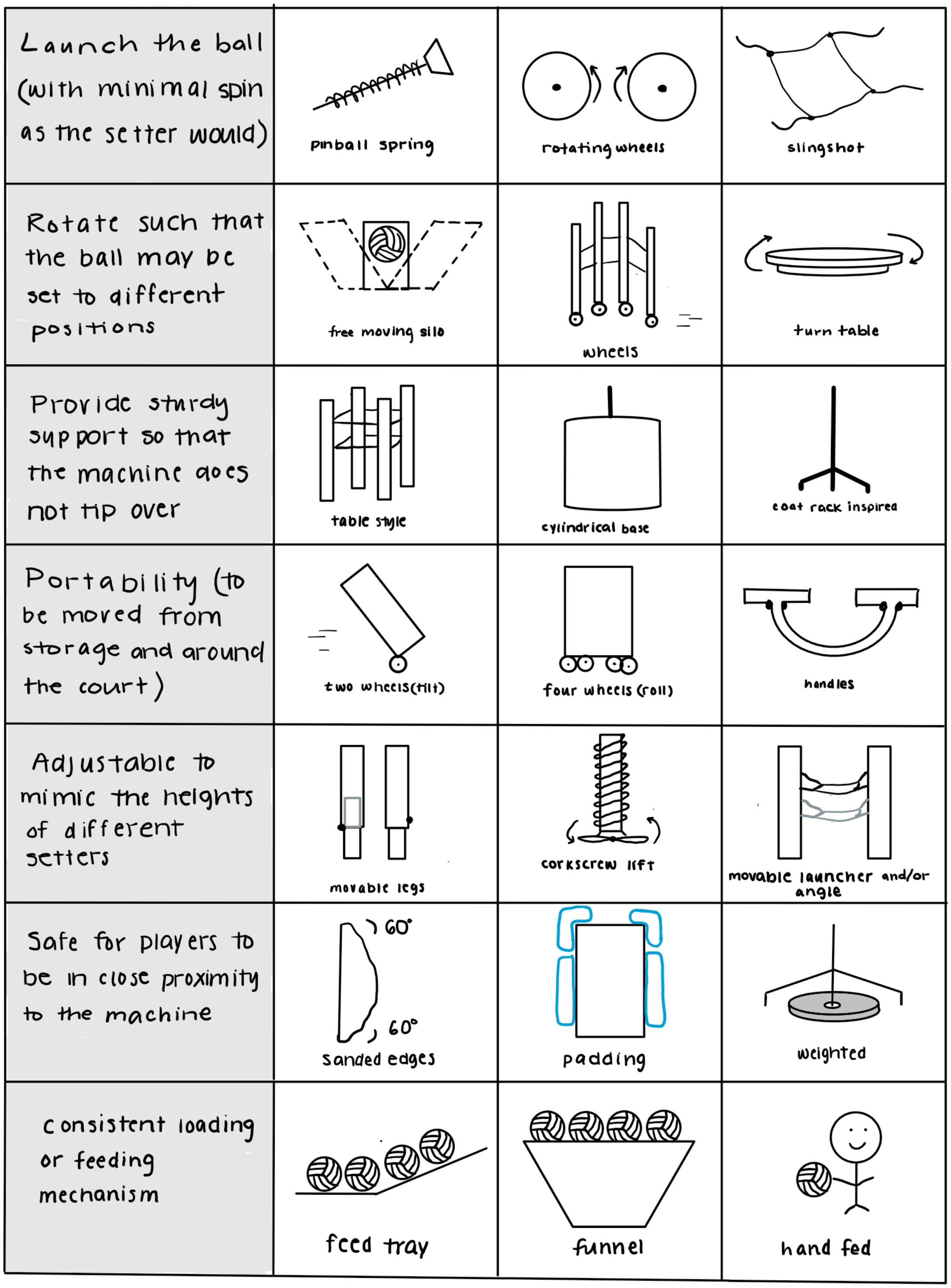



Figure 12: Morphological Chart for the Bueffer 3000

## 3.4 Alternative Design Concepts

### 3.4.1 Fork Launcher

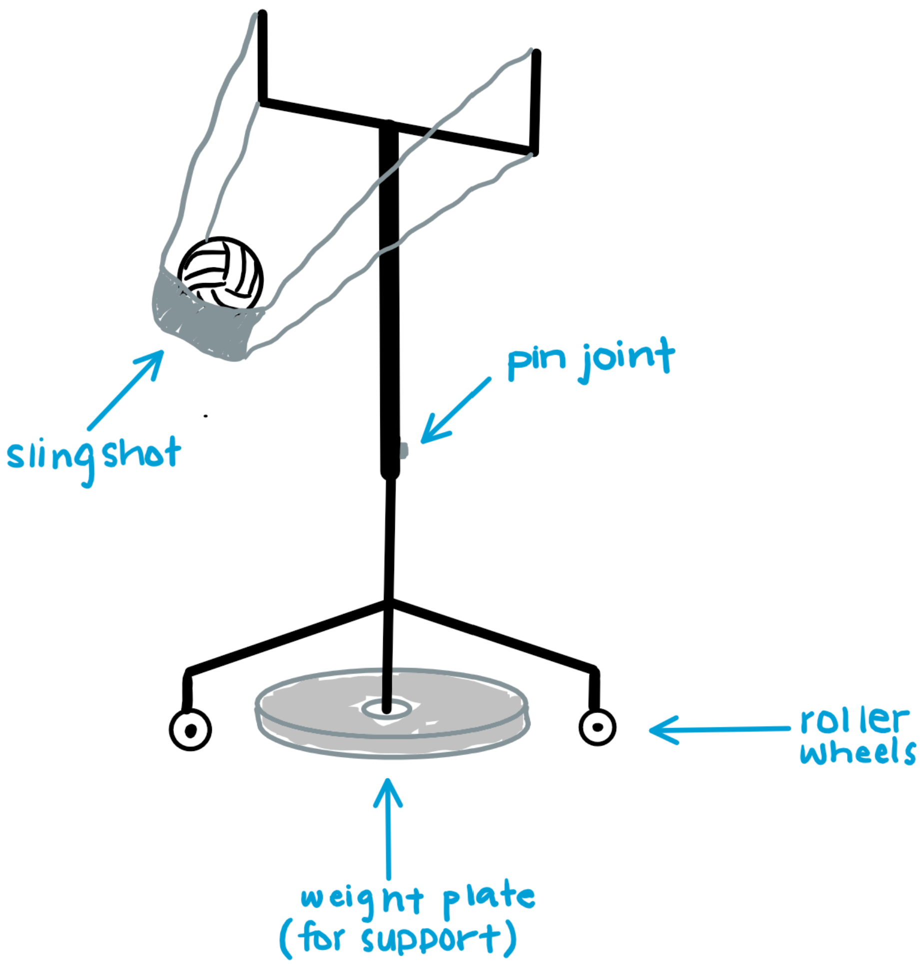



Figure 13: Sketches of Fork Launcher concept

<u>Solutions from morph chart</u>:

1. Coat rack inspired structural support
2. Slingshot to launch volleyballs
3. Wheels to mobilize machine
4. Wheels to rotate machine
5. Pin joint to adjust height
6. Weights for stability
7. Manually fed and operated

Description: A pronged, coat-rack inspired body for the machine provides stable support to the mechanism. The central vertical pole is comprised of two pieces connected by a pin joint to allow for height adjustments as needed. The slingshot launching mechanism is manually fed and operated, though a storage device could be constructed around the central pole. Wheels are attached to each of the base legs so that the device can be easily moved to and from storage and around the court. The wheels will be equipped with breaks so that the device remains stationary when needed. The wheels also serve to rotate the machine such that the volleyballs may be launched in the appropriate direction of the hitters. A weight is mounted at the bottom of the machine in order to provide additional stability and safety so that it does not tip over when in use.

### 3.4.2 Wooden Support Launcher

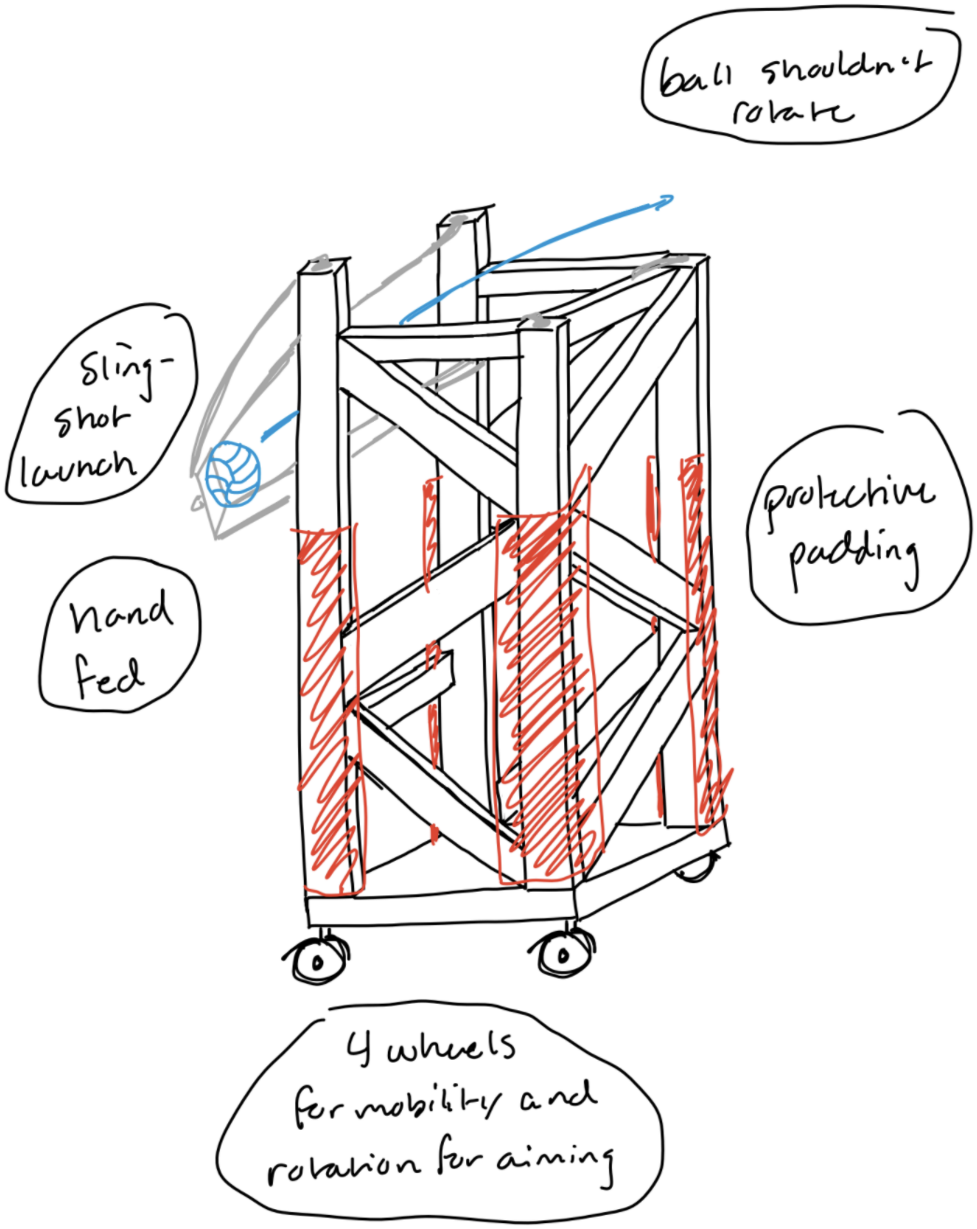



Figure 14: Wooden Support Launcher

<u>Solutions from morph chart</u>:

1. Based on slingshot method
2. Directionality addressed by 4-wheel rotational base
3. Table style structure
4. Contains 4 wheels for mobility

5. Movable launcher or angle
6. Contains padding as safety precaution
7. Manually fed and operated

Description: The Wooden Support Launcher boasts an extra supportive frame to prevent failure. The excessive support also adds weight to the system which should also prevent it from tipping over when the slingshot is pulled. Sitting on a platform with wheels makes it easy to move the Wooden Support Launcher and also adjust its angle of launch simply by rotating it to the desired direction. The system is manually loaded (aka hand fed) and manually powered allowing for adjustable force and therefore adjustable launch parameters (height, distance, etc.). Upon launch, the ball is expected to have minimal rotation due to the slingshot motion, but this will have to be further investigated during experimentation. Lastly, the padding around the perimeter of the Wooden Support Launcher addresses some of the safety concerns with this given design.

### 3.4.3 The Beast

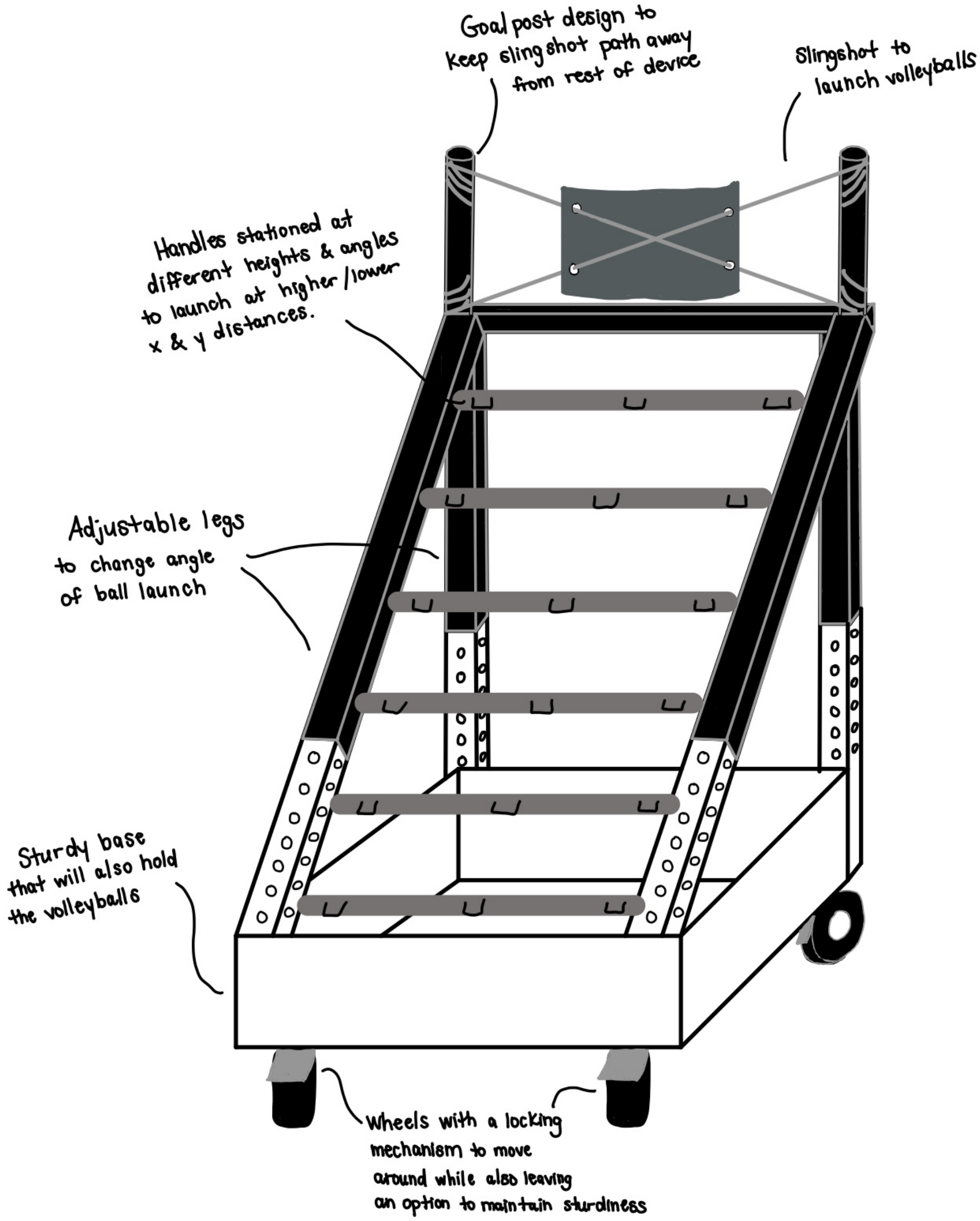



Figure 15: Sketch of The Beast volleyball launcher concept.

Solutions from morph chart:

1. Slingshot to launch the ball
2. Wheels to rotate and move the machine around
3. Rectangular table-style base to provide support and ensure that the machine does not tip over.
4. Multiple horizontal bars at different heights on the machine with handles on each bar so that the slingshot can be moved and launched to different heights and angles.

5. Adjustable legs to mimic heights of different setters and change launch angles.
6. Rounded metal edges so that no injury will come from players running into the machine.
7. Hand fed loading mechanism.

Description: The Beast features a sleek and functional volleyball setter design. It wields four sturdy, adjustable, metal legs to adjust launch angle and height in addition to a lower ball carrier, a goalpost-slingshot launch design, and numerous angled handles to adjust the height and angle of the launched projectile. The Beast is manually powered and fed, so it can be used at any location. The angled handles function as both a guide for where to launch the slingshot as well as a potential locking mechanism for the slingshot for more consistent sets. The edges of the legs will be rounded to ensure that there are no injuries if a player accidentally runs into The Beast. Wheels on the bottom of The Beast make it portable and easily stored.

### 3.4.4 Volleyball Setter 2021

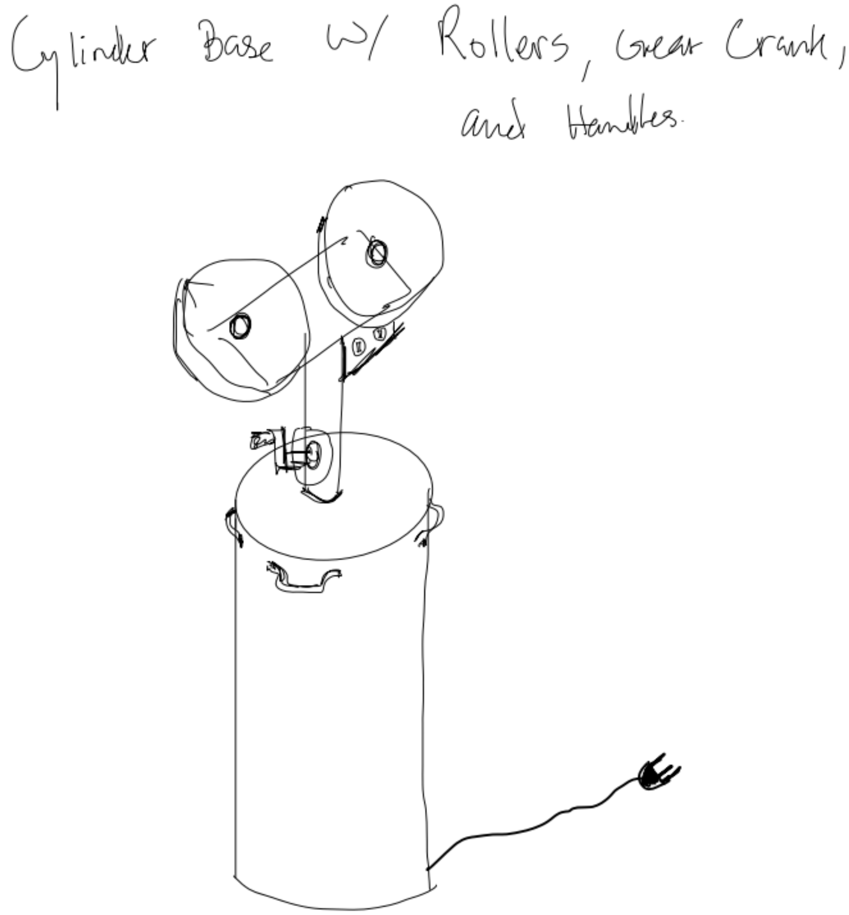



Figure 16: Volley Setter 2021

Solutions from morph chart:

1. Ball rollers with adjustable speeds
2. Contains handles for carrying machine around
3. Ball roller can rotate around on pole
4. Can be manually fed or automatically fed with attached ball cage
5. Rollers can be set at same speed to mitigate ball rotation
6. No sharp edges from cylindrical design, but warning label for hugh speed rollers should be added
7. Height can be adjusted by gear crank

Description: The Volley Setter 2021 is a state of the art volleyball setting machine. The automatic rollers allow the user to easily adjust the speed using a dial, and the angle of the set ball by raising or lowering the roller heads. The central pole can rotate freely, allowing the user to turn the machine 360 degrees to hit any hitting position. The height the sets are coming at can also be adjusted via the gear crank located on the central pole. The centralized weight distribution and cylindrical design boast a high quality of safety as the machine is much less likely to tip over or cut users. The handles allow user(s) to move the machine to any appropriate location.

# 4 Concept Selection

## 4.1 Selection Criteria

| | Sets ball with no rotation | Sturdy Base | Adjustable launch height/angle | Safety | Ease of Use | | Row Total | Weight Value | Weight (%) |
|---|---|---|---|---|---|---|---|---|---|
| Sets ball with no rotation | **1.00** | 1.00 | 1.00 | 1.00 | 9.00 | | 13.00 | 0.26 | 25.88 |
| Sturdy base | 1.00 | **1.00** | 1.00 | 3.00 | 9.00 | | 15.00 | 0.30 | 29.86 |
| Adjustable launch height/ angle | 1.00 | 1.00 | **1.00** | 0.33 | 5.00 | | 8.33 | 0.17 | 16.59 |
| Safety | 1.00 | 0.33 | 3.00 | **1.00** | 7.00 | | 12.33 | 0.25 | 24.55 |
| Ease of use | 0.11 | 0.11 | 0.20 | 0.14 | **1.00** | | 1.57 | 0.03 | 3.12 |
| | | | | | | | | | |
| | | | | | **Column Total:** | | **50.23** | **1.00** | **100.00** |
| | **ONLY change the lower-left triangle of the matrix** | | | | | | | | |
| | **The right 3 columns will be automatically calculated** | | | | | | | | |

Figure 17: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

## 4.2 Concept Evaluation

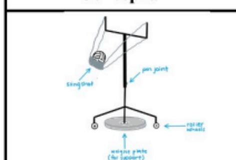
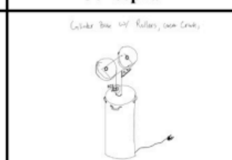
| **Alternative Design Concepts** | | **Concept #1** | | **Concept #2** | | **Concept #3** | | **Concept #4** | |
|---|---|---|---|---|---|---|---|---|---|
| | |  | |  | |  | |  | |
| **Selection Criterion** | **Weight (%)** | **Rating** | **Weighted** | **Rating** | **Weighted** | **Rating** | **Weighted** | **Rating** | **Weighted** |
| Sets ball with no rotation | 25.88 | 4 | 1.04 | 4 | 1.04 | 4 | 1.04 | 2 | 0.52 |
| Sturdy base | 29.86 | 3 | 0.90 | 4 | 1.19 | 4 | 1.19 | 1 | 0.30 |
| Adjustable launch height/ angle | 16.59 | 4 | 0.66 | 2 | 0.33 | 5 | 0.83 | 4 | 0.66 |
| Safety | 24.55 | 2 | 0.49 | 4 | 0.98 | 3 | 0.74 | 3 | 0.74 |
| Ease of use | 3.12 | 4 | 0.12 | 3 | 0.09 | 3 | 0.09 | 3 | 0.09 |
| | **Total score** | **3.210** | | **3.637** | | **3.889** | | **2.310** | |
| | **Rank** | **3** | | **2** | | **1** | | **4** | |

Figure 18: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

## 4.3 Evaluation Results

The results from the Analytical Hierarchy Chart show that the most important feature of our volleyball setter machine is a sturdy base at 29.86%. The next most important feature at 25.88% is the optimization of a non rotating launch. At 24.55%, the next most important feature is safety. The adjustable launch angle and height comes in next on a list of importance at 16.99 %. The last feature, the ease of use, was only weighted 3.12%. Given the outcome of the hierarchy chart, we were able to prioritize selected criteria base our models off these results.

The results from the Concept Evaluation strongly support concepts 2 and 3 but not concepts 1 and 4. Concept 3 was awarded the highest score overall for a number of reasons. The concept has the sturdiest base and can easily be transported in similar fashion to a cart due to the 4 wheels underneath the base. The structure of both concept 2 and 3 seems to provide adequate support throughout, especially where excess support is necessary. However, concept 3 is much more stable when subject to the angled forces associated with launching the volleyball. Concepts 1 and 4 lack the stability necessary to function safely and properly. Analyzing the adjustability of the launch angle, concept 3 has the most optimal and adjustable launch angle while concepts 1 and 4 follow. In terms of safety, concept 2 covers the majority of the safety concerns, but concept 3 can easily be adjusted to accommodate for more safety concerns simply by the addition of padding and safety precaution notes. Lastly, all concepts score fairly even across the board for simplicity of use, but the ease of use can be improved by adding instructions and graphics for operational direction. Concept 3 contains many advantageous components that suit the needs of a functional, easy to use, safe volleyball launcher.

## 4.4 Engineering Models/Relationships

### 4.4.1 Model 1: Kinematics

In physics classes, we calculate criteria of projectiles based on the kinematic equations. Once the volleyball is launched, it becomes a projectile for which we can calculate key components, given initial conditions. These components include the velocity and angle of launch. As shown in Fig. 19 and Eq. 1, Eq. 2, Eq. 3, and Eq. 4, the known height ($\Delta y$) and distance ($\Delta x$) can be used to calculate the velocity and angle required to satisfy the height/distance requirements. Since both of the height and distance values need to be adjustable based on the user and hitter, we can use these calculations to add user guides to the machine.

$$V = V_0 t + \frac{1}{2} a t^2 \tag{1}$$

$$\Delta x = \left( \frac{V + V_0}{2} \right) t \tag{2}$$

$$\Delta x = V_0 t + \frac{1}{2} a t^2 \tag{3}$$

$$V^2 = V_0^2 + 2a(\Delta x) \tag{4}$$

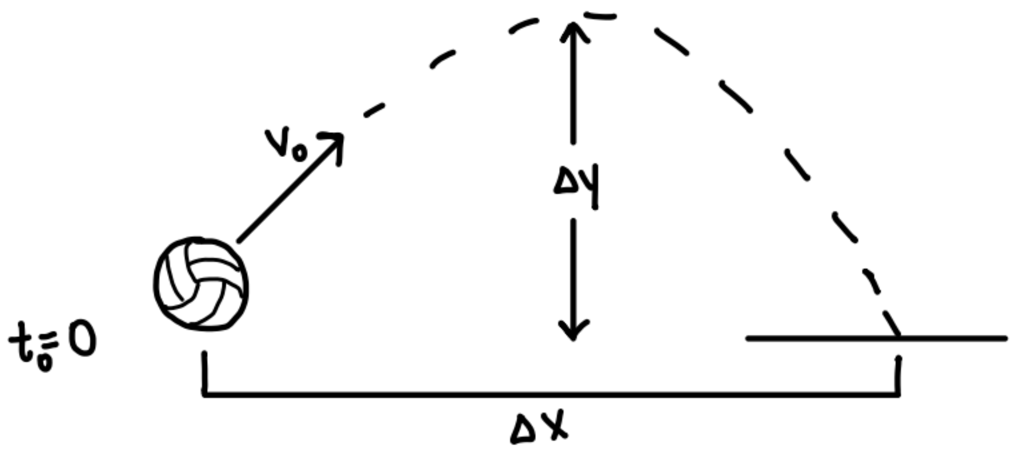



Figure 19: The path of the launched volleyball, modelled as a projectile, where $\Delta y$ is the maximum height and $\Delta x$ is the maximum horizontal distance. The horizontal distance at which the hitter would hit the volleyball is $\frac{\Delta x}{2}$.

### 4.4.2 Model 2: Work-Energy Principles

The work energy theorem helps us solve for the amount of work we will need to get the ball to reach a certain velocity. Since we will know the heights and distances our volleyball will need to reach, we will be able to use kinematics in section 4.4.1 to calculate the velocity required to reach those heights and distances. Once the velocity is calculated, we can use work-energy principles to calculate the amount of work the user needs to put into the slingshot, as shown in Fig. 20.

Figures out the work needed to get a ball to a certain velocity from slingshot:

$$W = \frac{1}{2} m v_f^2 - \frac{1}{2} m v_i^2$$

Our ball starts from rest so $v_i = 0$:

$$W = \frac{1}{2} m v_f^2$$

Now we can plug in realistic values for the ideal speeds of the ball to see how much energy is necessary to apply on the slingshot bands to acheive that speed.


Figure 20: A schematic of the work energy theorem involving our volleyball setter.

### 4.4.3 Model 3: Static Force Analysis

In truss problems, we use the method of sections to find external forces on the structure of trusses. We can model our volleyball setter machine as a truss, as shown in Fig. 21. By doing this, we will be able to find the reaction forces at the base that result from pulling back on the slingshot. The known values in this model will be the input force (easily attainable from the work-energy principles in section 4.4.2), and the locations of the forces ($x_1$, $x_2$, $x_3$, and $y_1$). The values we will be solving for are the reaction forces $A_x$, $A_y$, $B_x$, and $B_y$ on the locked wheels. These values will provide useful information as we navigate the requirements for no tipping.

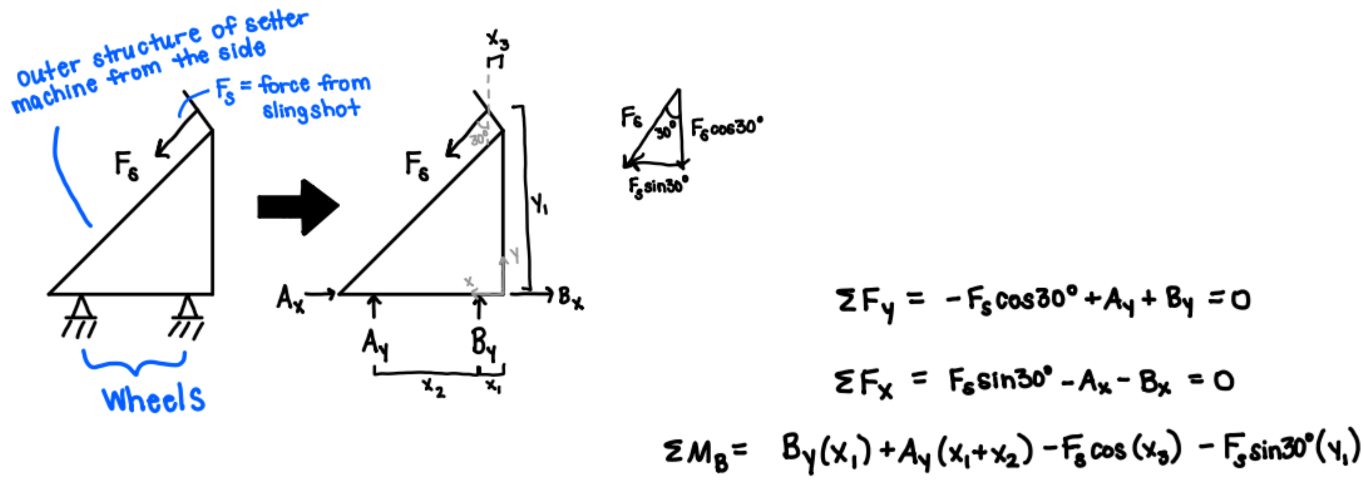



Figure 21: Side view of the volleyball setter machine modelled as a truss. Newton's 2nd Law is used to sum the forces in the x and y directions in addition to summing the moments.

# 5 Concept Embodiment

## 5.1 Initial Embodiment

The initial prototype of the Bueffer 3000 was made from 7 planks of wood and consisted of a triangular design with a slingshot shooting mechanism, much like the top half of the current design seen in Fig. 23. The slingshot shooting mechanism was chosen because the customer preferred a slingshot over other shooting mechanism options primarily for simplicity of use. The triangular design was chosen due to the optimized force distribution it offered in comparison to other design options. As shown in Fig. 22, when compared to a rectangular and circular design, a triangular design allowed for less wood to be used while preventing tipping by ideal force distribution throughout the device.

After the construction of the initial prototype, the Bueffer 3000 was tested to determine its ability to complete three performance goals. The three goals are as follows:

(1) The device can launch ≥10 balls in 1 minute.
(2) The device can launch balls at elevation angles of 30 degrees, 80 degrees, and at least two intermediate angles.
(3) The device can launch balls that reach ≥14 ft above the top of the device, and (in a different

launch) land $\geq$20 ft away from the base of the device.

The first goal was achieved by measuring the time it took to launch consecutive volleyballs. Having just one volleyball added time from collecting the ball once it was launched to using hat same volleyball to reload and launch again. With that being said, the first goal was achieved using this method. We were able to launch the volleyball, collect it, reload it in the bueffer 3000, and launch it again all under 6 seconds therefore completing our first prototype goal.

The second goal was easy achieved due to our design. The angle of launch can be adjusted to any degree between 0 to 90 degrees. This allows for versatility and easy adjustment to obtain an optimum launch angle. We tested the initial prototype at both 30 and 80 degrees and had no trouble with the launch. Given the ability to adjust to any angle, we tested our prototype at two more angles to showcase its versatility.

The third goal focused primarily on optimal measurements of a launch. In order to launch the ball 14 feet above the top of the device, we had to prioritize the launch angle and power. Launching the ball at approximately 10 degrees, we were able to observe a peak altitude greater than 14 feet above the top of the prototype. In a separate launch, we had to prioritize power and a launch angle closer to 45 degree in order to maximize the launch length from the base of the launcher. In doing so, we were able to achieve a launch that landed greater than 20 feet from the device.

After completing the initial prototyping stages, a base was added to increase the weight of the machine and add a level of usability that would allow the customer to stand at an upright position instead of bending to launch each volleyball as seen in Fig **??**. The increased elevation by adding a base also better represents a realistic set which would occur at a similar elevation. Since one of the customer's needs is for the machine to be portable, the dimensions remained at 27 inches by 30 inches by 72 inches. Since most door frames are 36 inches by 80 inches, the Bueffer 3000 should fit through all doors necessary to fit into the gym.

Figure 25 showcases the materials used in the construction of the Bueffer 3000. Items 1-5 consist of wooden 2x4 planks ranging in length from 23to 36 inches. Item 6 are i-hooks that are used to fasten the elastic bands to the wooden structure. Hooks were chosen here to allow the slingshot to reach its full range of motion while keeping the path of the slingshot out of direct contact with the wooden structure. This helped to ensure that the volleyball would not get caught up in the ball carrier and would come out of the carrier in the desired direction of launch. The remainder of the items in the bill of materials seen in Fig. 24 are the wood screws used to hold the structure together, the 3D printed ball holder, and the slingshot's elastic bands. It is worth mentioning that the 3D printed ball holder was designed to be slightly larger than the diameter of a volleyball to minimize the chances of the volleyball getting stuck during launch.

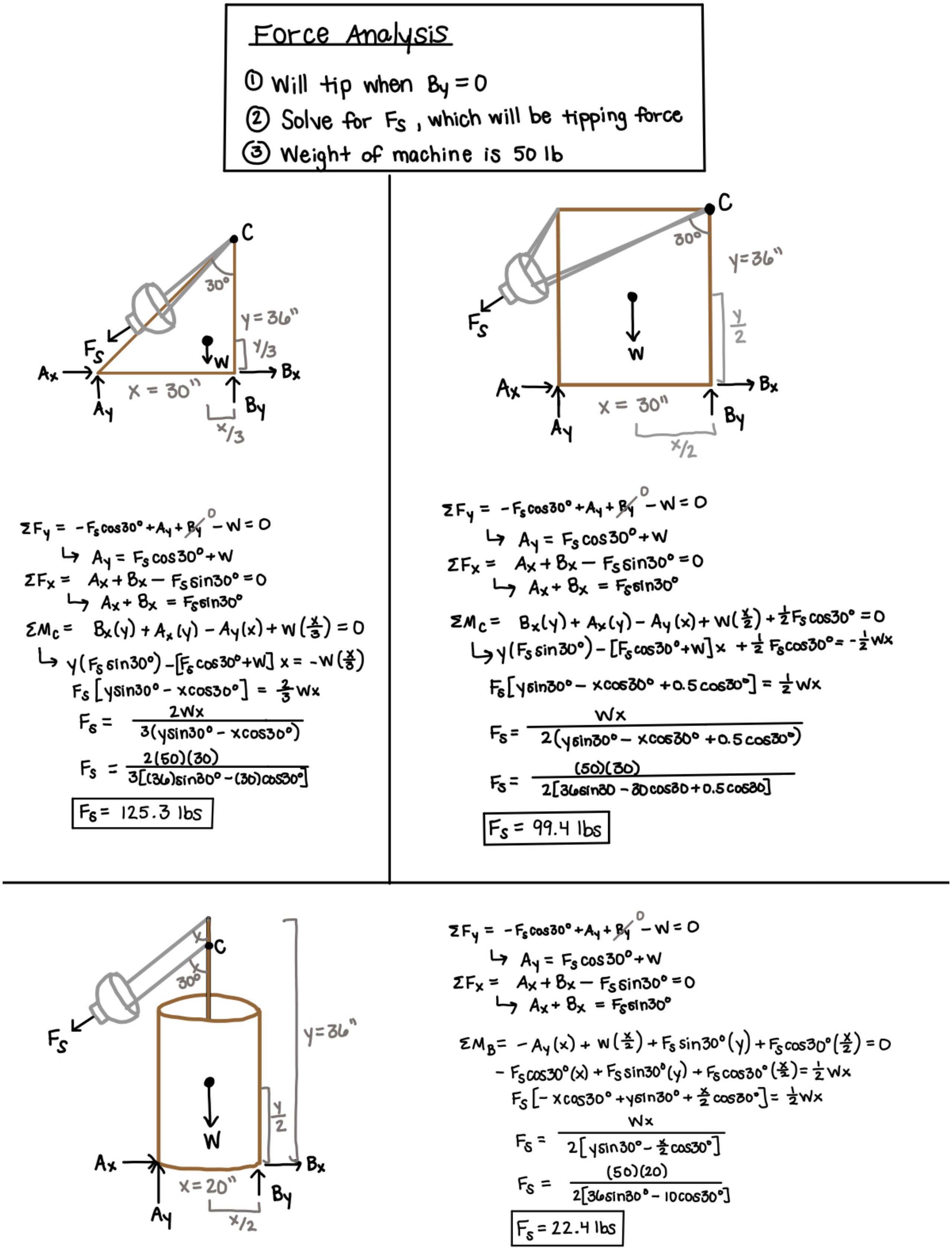



Figure 22: External force analysis of all viable design options.

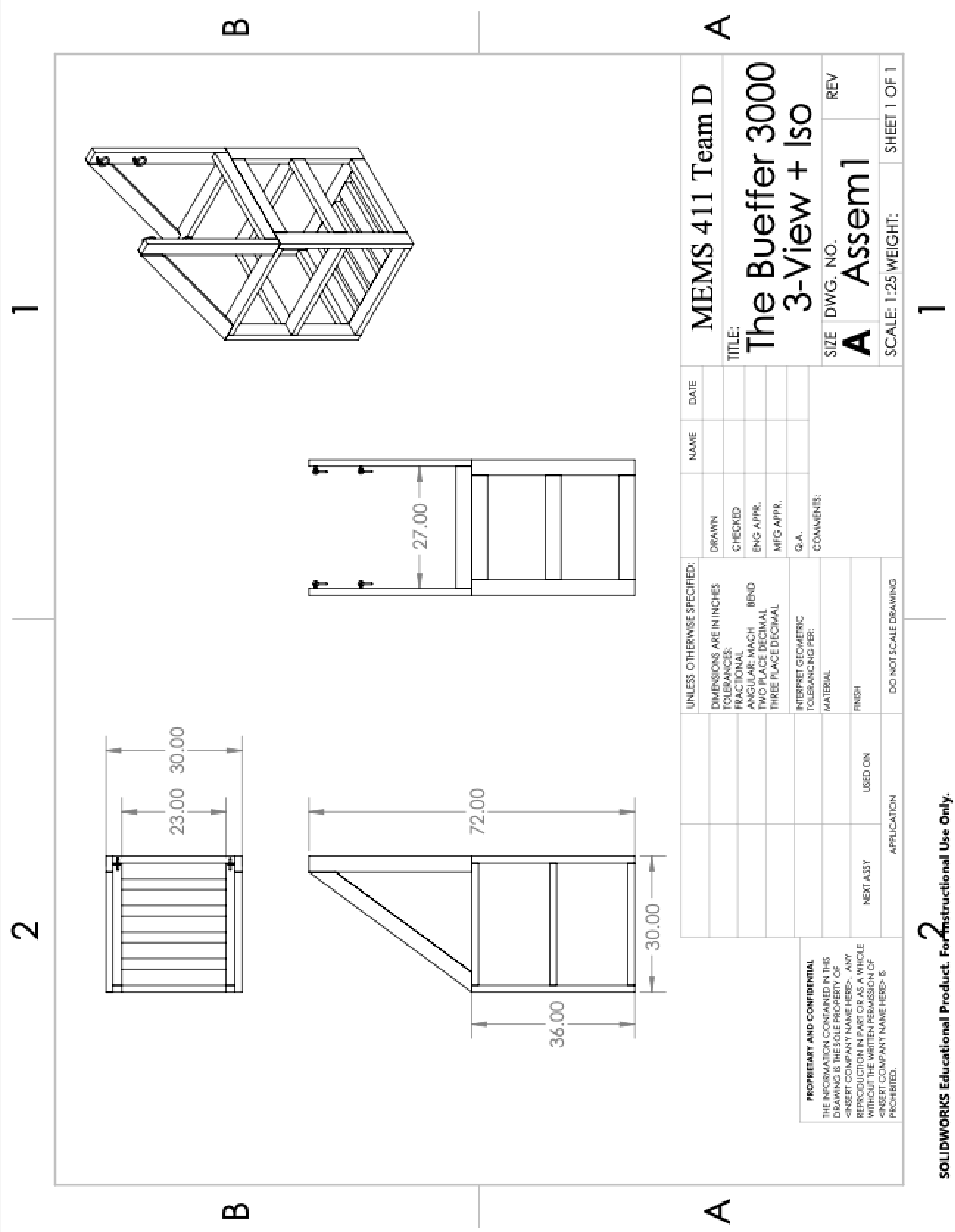



Figure 23: Assembled projected views with overall dimensions

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | XXX | 36in. 3X4 plank | 4 |
| 2 | XXX | 27in. 3X4 plank | 7 |
| 3 | XXX | 23in. 3X4 plank | 10 |
| 4 | XXX | Angled 3X4 support | 2 |
| 5 | XXX | Vertical 36in 3X4 planks with rings | 2 |
| 6 | 9587T35 | Screw-In Holder for 2" Item Diameter | 4 |
| 7 | XXX | 2.5in. wood screws | 30 |
| 8 | XXX | 3.5in. wood screws | 30 |
| 9 | XXX | 3D printed ball holder | 1 |
| 10 | XXX | elastic bands | 4 |

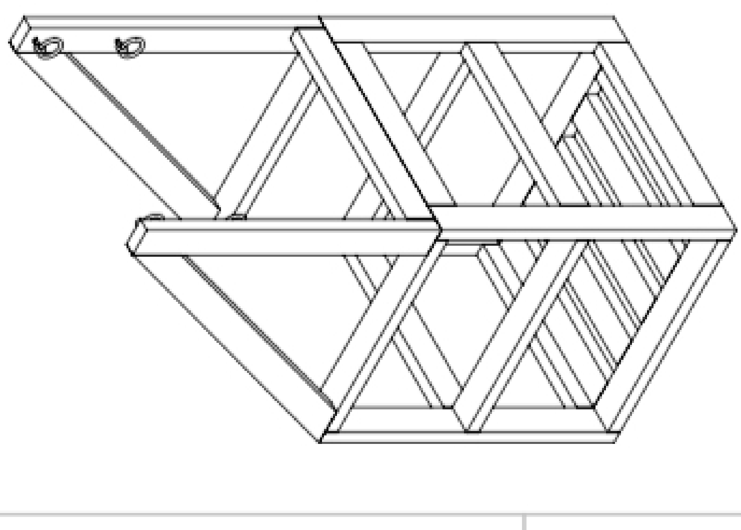



Figure 24: Assembled isometric view with bill of materials (BOM)

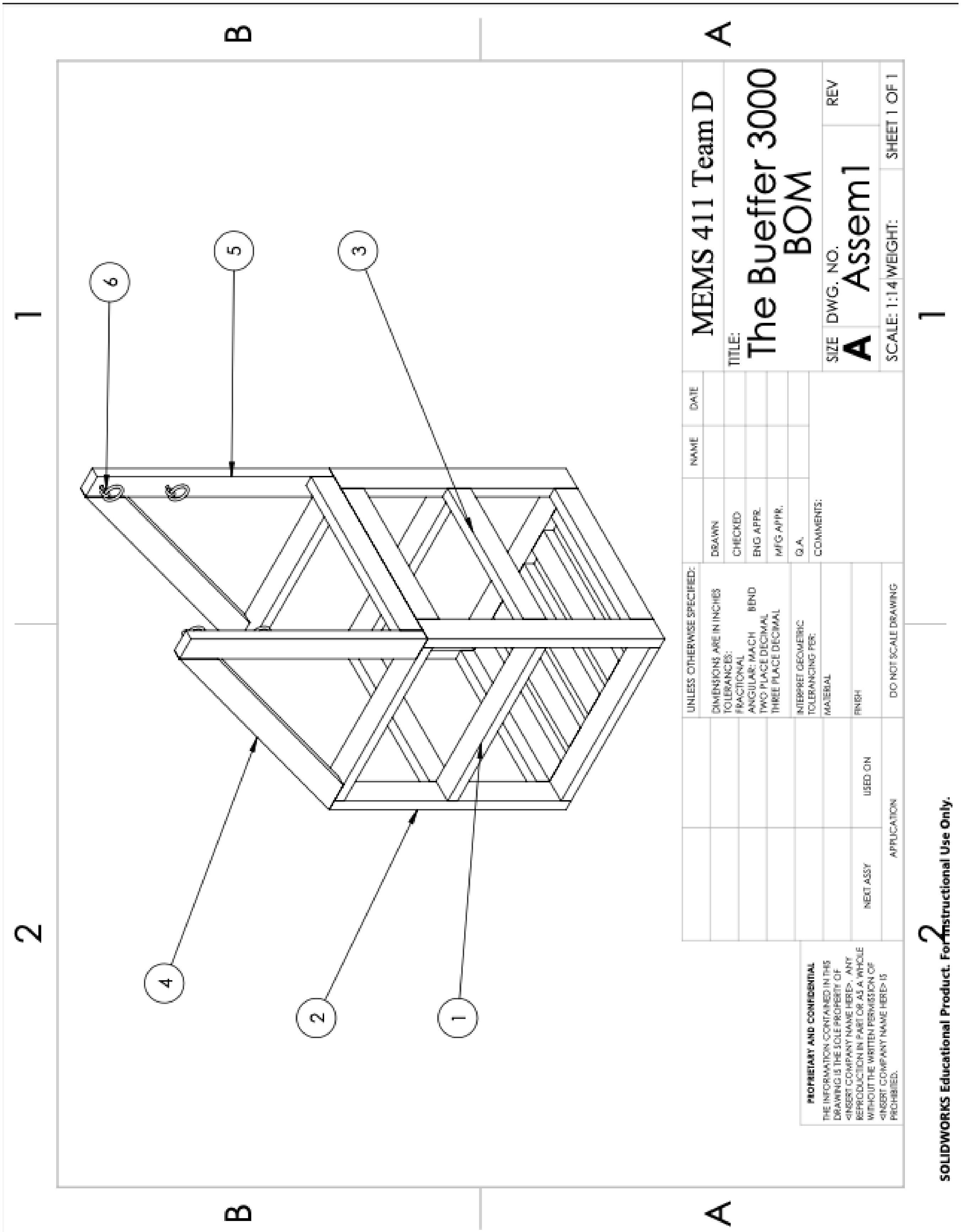



Figure 25: Exploded view with callout to BOM

## 5.2 Proofs-of-Concept

Our Proof-of-Concept design resembled a scaled down version of the initial prototype. Constructed of wood and designed to distribute force in a similar fashion, the success of our Proof-of-concept motivated the majority of our ideas and designs in the initial prototype. More specifically, we found great success with the ability to optimize the launch angel and power with fixed, elastic bands, so we intended in incorporating this idea into our initial prototype. Also, the we learned that a fabric ball holder was less ideal due to its flexibility and inability to provide a stable grip on the ball for launching. This motivated us to design a cup for the ball that was used in out initial prototype. Lastly, it should be noted that our Proof-of-Concept has been reliable for the current prototype that we have constructed, and we expect this to hold true for our final design which includes the addition of a base.

## 5.3 Design Changes

When comparing our initial prototype to the selected concept, there are many more similarities than differences. Both designs utilize a triangular structure for support and allow for the attachment of elastic bands as a method for launching the ball. As a mode of transportation, wheels were used in our selected concept but will not be implemented until the next prototype. Both models allow for volleyballs to be stored in the bottom of the structure which allows for a faster reload and launch time. All aspects of launching are manually controlled in both designs from the power to the angle of launch. Lastly, it is worth noting that the models and calculations relevant to the selected concept apply to the initial prototype and future designs as well.

Some of the primary differences between the selected concept and the initial prototype include the wheel placement and the volleyball holder. In the initial concept, 4 wheels were to be placed underneath the design to provide a solution to portability, but in the initial concept, wheels were not included. However, in the upcoming design, two wheels will be used to provide portability but also stability when in use. Additionally, the volleyball holder in the selected concept was a fabric holder which was not ideal due to its inability to secure the ball during launch as discussed above. Therefore, the new holder was 3D printed to provide a more secure hold of the ball as it is launched. This design proved to be very efficient and will be implemented into future designs. With that being said, testing our prototype exposed a few minor flaws that will be adjusted for the future model of the holder. The first flaw was the cup diameter which should be very close to the diameter of a volleyball but not much greater than an inch of the diameter in order to prevent the ball from getting stuck in the cup on launches at greater angles. Additionally, the handle on both 3D printed launchers fractured during testing, so we plan to incorporate additional handle support or resort to a more durable option such as a fabric handle.

There are also other factors we intend to include in our design that were wither neglected in the prototype, selected concept, or both. For the future design, we intend on including padding to limit the risk of injury when using the machine. Additionally, notes on how to properly work the machine and a list of safety concerns will be added to the device so any user can safely operate the launcher. As mentioned above, we are still testing the durability of current handle prototypes which will be finalized in the future design. We speculate that tipping may become an issue under incorrect use of the machine, so we intend to incorporate features such as added mass to the bottom of base in the future design. It is also worth noting that the elastic bands used to facilitate the launch have yet to be finalized for the future design, but we intend on minimizing length to reduce backfire. With all things considered, our future design will incorporate many of the desired features from the selected concept and initial prototype while using the knowledge acquired during testing to optimize safety, functionality, and portability.

# 6 Design Refinement

## 6.1 Model-Based Design Decisions

Three engineering principles were used in the decision making process for the Bueffer 3000: kinematic principles, work-energy principles, and static force analysis. These three engineering principles guided the design decisions made during the design and construction processes. The effected components include the slingshot (launch velocities and launch forces), ball holder, machine height, and machine weight.

### 6.1.1 Launch Velocities

To determine the required launch velocities, kinematic principles were examined. Of the four kinematic equations defined in the Concept Selection section, only the second equation was used. From customer interviews, the ideal launch height ($\Delta y$) and distance ($\Delta x$) were known for angles of $\theta = 30°$ and $\theta = 80°$. Using the customer's needs, the velocities required to hit these criteria at launch ($V_0$) were calculated in Fig. 26. The frame that was analyzed here was launch to $\Delta y$, which means that the final velocity ($V$) is equal to 0 since this is an inflection point and the ball changes direction here. The required launch velocity at an angle of 30° was found to be 12 ft/s, while the required launch velocity at an angle of 80° was found to be 14.62 ft/s.

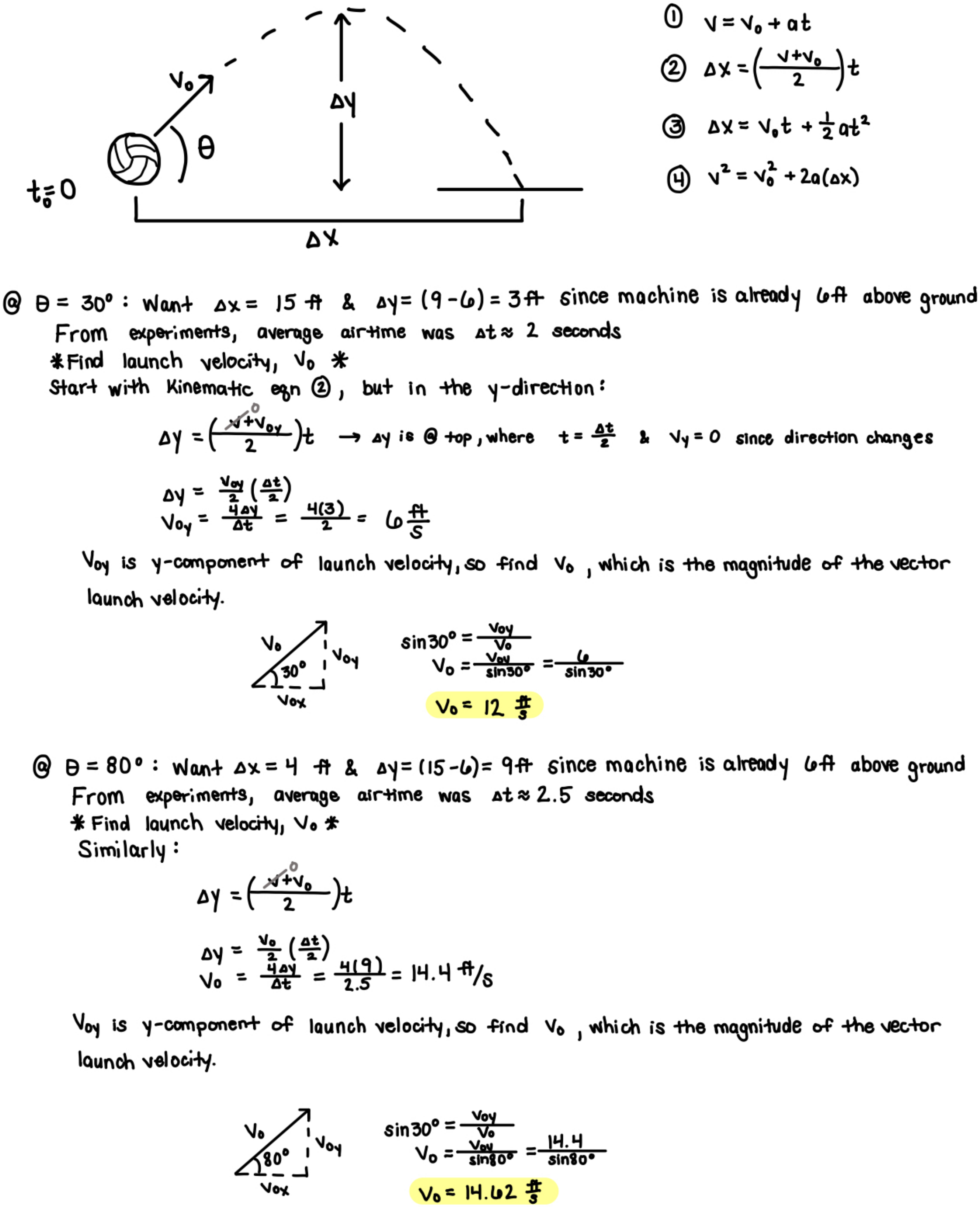



Figure 26: Calculations for the necessary launch velocity when launching at 30° and 80°using kinematic principles [1].

#### 6.1.2 Launch Forces and Ball Holder

Since the launch velocities at different angles were calculated using kinematic principles, work-energy principles can then be used to calculate the amount of slingshot force required to launch the ball at the calculated velocities. This will be the amount of force that the user has to exert on the slingshot to complete a successful launch. This is also the amount of force that the slingshot must be able to withstand without breaking. The work-energy analysis is shown in Fig. 27. The important variables in the work-energy equations are the work ($W$), the mass ($m$), the initial velocity ($v_i$), the final velocity ($v_f$), the slingshot force ($F$), the distance the slingshot gets pulled back ($d$), and the angle between the applied slingshot force and slingshot distance ($\phi$). Known measurements to aid in these calculations are: the mass of an average volleyball is 9 ounces, or 0.5625 pounds; the mass of our 3D printed ball holder is 0.60 pounds; the distance the slingshot gets pulled back is roughly 2 feet. From Fig. 27, the user must pull back on the slingshot with a force of 42 pounds for a 30 degree angle and 62 pounds for an 80 degree angle.

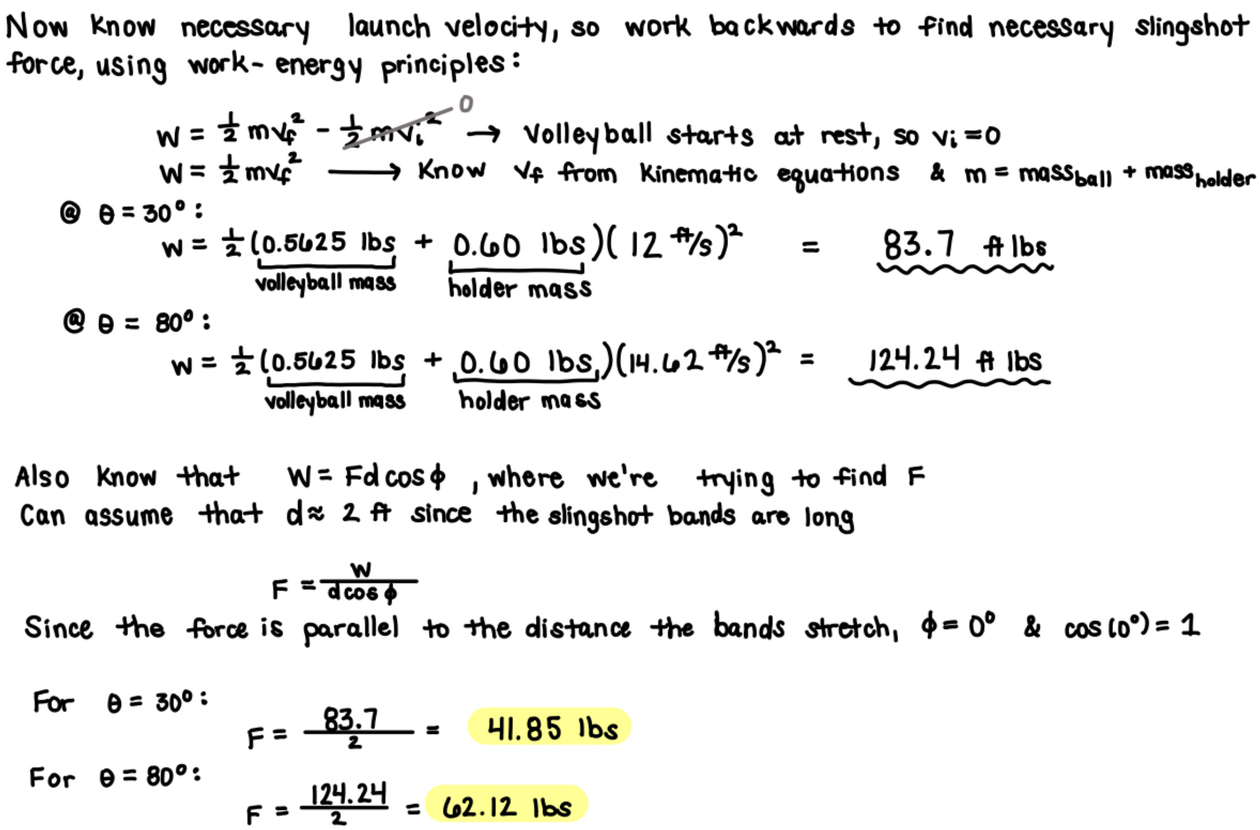



Figure 27: Calculations for the necessary launch force when launching at 30° and 80°using work-energy principles [1].

The engineering principles shown in Fig. 26 and Fig. 27 can be used to make guides for the users indicating how far and how hard they will need to pull back to achieve a certain set. These two engineering principles guided the decision of which exercise band to purchase to use for the slingshot. Using bands that are not strong enough would result in the bands snapping when the user pulls back on them. It was ensured that the purchased bands could withstand at least 120 pounds of force, which would withstand double the highest necessary launch force. Additionally, we minimized the weight of the ball holder according to the work-energy principle calculations. There is no way to change the volleyball mass or the launch velocity, so the only way to decrease the force needed to launch the volleyball is to decrease the mass of the ball holder. The final design of the ball holder was a lightweight design that was still sturdy enough to endure the forces the slingshot places on it.

### 6.1.3 Tipping Force, Height, and Weight

Now that the launch forces are known, a static force analysis can be done on the system to determine whether the launch forces will cause the machine to tip over. In static force analysis, the important variables are the reaction forces ($A_x$, $A_y$, $B_x$, and $B_y$), the slingshot force ($F_S$), the weight of the entire structure ($W$), the width of the structure ($x$), the height of the structure ($y$), and the angle of launch ($\theta$). Figure 28 shows the force analysis using the 30° angle scenario, since that is when the machine is most likely to tip over. During all launch experiments, there have been no tipping issues associated with the 80° launch angle scenario. The force analysis showed that the machine will tip when the user exerts a force of approximately 150 pounds on the slingshot. Since this is greater than the actual force needed to hit the customer's needs, it can be concluded that tipping will not be an issue for the user's typical needs. If the user wants to add more force to achieve higher/longer launch distances, weights can be added to the base of the machine to shift the centroid down and add mass, both scenarios making the tipping force higher. The original triangular design was modified slightly for this reason. The rectangular base was added to make the machine bottom heavy in addition to making it easier for the user to launch the volleyballs. In recent launch experiments, there have been no issues with tipping once the base was added.

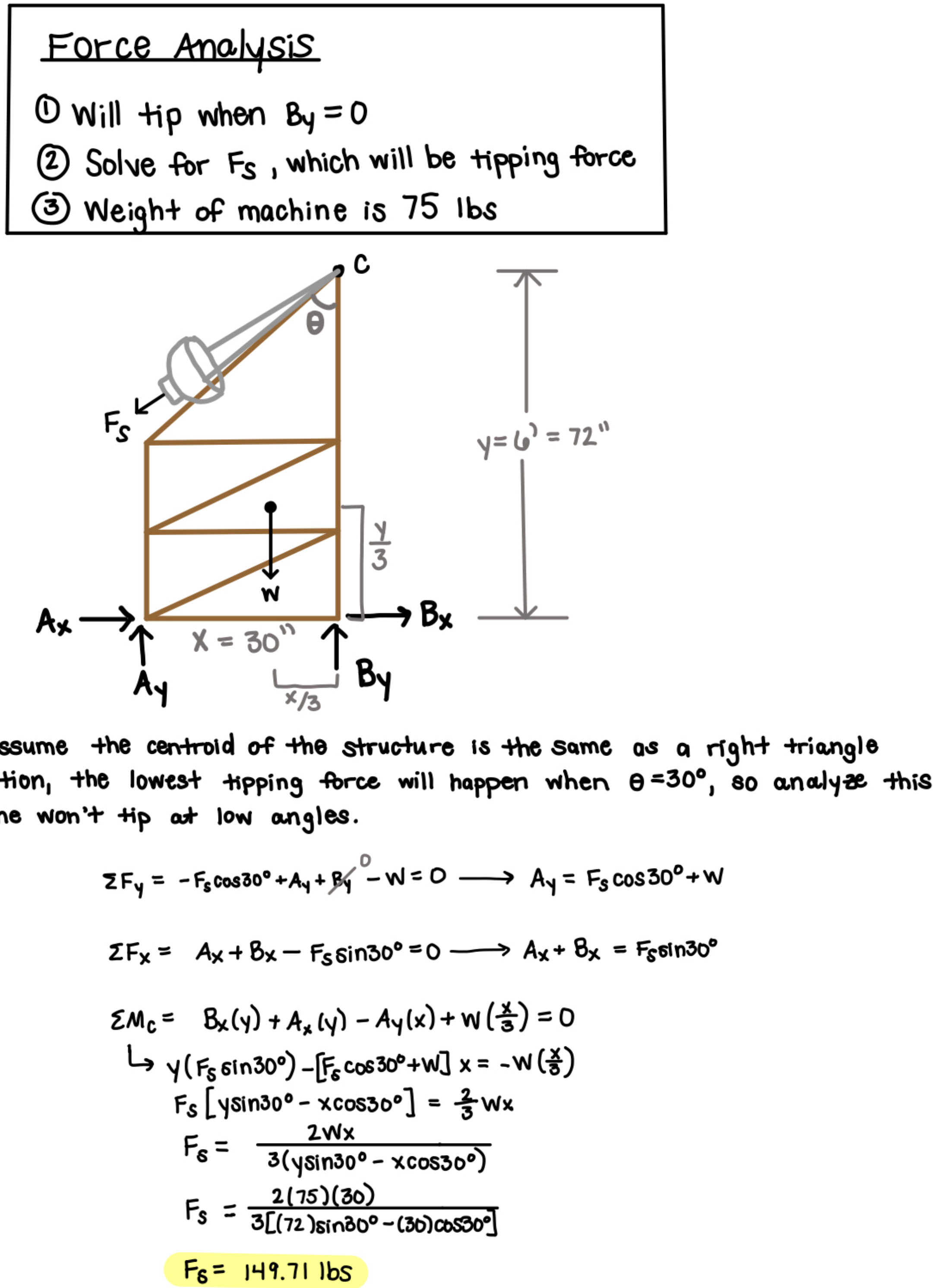



Figure 28: Calculations for the tipping force of the machine [2].

## 6.2 Design for Safety

### 6.2.1 Risk #1: Collision with the machine

**Description:** When the machine is in use, it is possible to collide into the machine. Collisions may occur when surrounding players and users run, jump, or dive near the machine. Collisions are most probable with the the tall supports of the machine, but diving may result in injury due to collision of the sturdy base. Players may also trip over the machine, especially the wheels that protrude from the machine.

**Severity:** The severity of injury can be critical. It is possible to hit your head on parts of the machine, resulting in a concussion, and The risk of breaking a bone is also quite possible in a collision. These are serious injuries that would require immediate medical attention. With that being said, those are the most drastic outcomes when running into the machine, and the individual would most likely walk away unharmed.

**Probability:** The likelihood of realizing a collision may occur is seldom. The players are more often than not going to be worried about hitting the ball and not very worried about their surroundings. Therefore, they will most likely dismiss the thought of colliding with the machine.

**Mitigating Steps:** Users and players should always be weary of their surroundings and not attempt any hits when close to the machine. There will be a safety note on the device that reminds the user to keep a safe distance from the machine when it is being used. The machine will also be surrounded by padding, but there is still a high risk of injury when coming in close proximity to the machine to hit a ball.

### 6.2.2 Risk #2: Recoil from bands

**Description:** Bands were selected with greater tension such that the user is able pull the ball holder back a shorter amount and launch it with a greater force. However, the recoil from the bands following release has the potential to hit the user in the face or hands.

**Severity:** The ball holder is a solid, hard, plastic material, so recoil collision from the bands may result in marginal personal injury. Depending on the force and location of contact injuries can range anywhere from minor scratches to major contusions, and in the most extreme circumstances could break a nose or teeth.

**Probability:** The high tension of the bands and the positioning of the user should typically prevent recoil contact from happening. Under typical operations the bands do not recoil far enough to make contact where the user is standing, but negligence or complacency still make it a possibility.

**Mitigating Steps:** Users should remain alert when using the machine and stay aware of their proximity to the ball holder and bands. They should stand at least half an arm's length away from the machine such that they are still able to easily operate the machine at a safe distance from recoil effects.

### 6.2.3 Risk #3: Ball holder breaks

**Description:** If enough force is applied into the ball holder or if there is a sudden and drastic increase in the force, the ball holder handle might break. This could also occur if the handle is twisted in any way that it was not intended to.

**Severity:** The ball holder breaking is a marginal risk as the ball holder would simply sling forward as intended. At worst, the user would fall back from the ball holder breaking, and may be injured from this fall.

**Probability:** The ball holder was created and simulated to withstand forces much higher than it would be experiencing with its use. The probability is unlikely of the holder breaking early on, but with continued use and degradation, the probability of it breaking increases.

**Mitigating Steps:** Users should examine the ball holder before and after every use of the machine. They should also be listening for any creaks from the ball holder while using it, as this may indicate that the holder material is beginning to crack and break. A user note will be attached to the machine indicating this cautionary step.

#### 6.2.4 Risk #4: Machine tips over

**Description:** If enough force is applied by the user when pulling back on the ball holder and bands, the machine might tip over. This could occur either as an unbalanced wobble that interrupts practice operations or as a complete collapse of the machine.

**Severity:** The setting machine fully tipping over may be catastrophic, especially if it were to fall on top of the user or another player. The machine is heavy enough that it could cause serious personal injury were it to land on top of someone. If the machine were simply to tip over and land on the ground, the impact could potentially damage the machine and render it unusable.

**Probability:** A moment analysis on the machine found that the minimum applied force that would disrupt static equilibrium is approximately 150 lbs. The probability of the machine tipping over will depend on the angle at which the ball is to be launched, with a higher probability at smaller angles than larger ones. The machine tipping over is unlikely to happen if the user simply puts a foot down on the bottom of the device.

**Mitigating Steps:** The machine is built such that the user's body weight will help minimize the likelihood that the machine will tip over, but this is not the only mitigating step. To account for variability in user weight and applied force, sandbags will be added the bottom of the machine in order to provide more structural stability.

#### 6.2.5 Risk #5: Wheels break during transportation

**Description:** Two wheels are positioned on the machine such that tilting it backwards enables the wheels to make contact with the ground and for the machine to be moved. These two wheels carry the entire weight of the machine, and so it is possible that the wheels break off during transportation as a result of the weight or by rolling over some obstacle.

**Severity:** The wheels breaking off is a negligible risk. In extreme circumstances this might damage the structural integrity of the machine, but more likely it will just make the machine more difficult to move. The wheels are intended to simplify transportation, but the machine can also be manually lifted and moved by two or more players.

**Probability:** The probability of the wheels breaking off during transportation is unlikely. Gym floors are typically smooth so there are not many obstacles that would cause significant damage. The size of the wheels, too, will determine their ability to support the entire weight of the machine.

**Mitigating Steps:** The most important mitigating step to take is selecting large and strong enough wheels that can support the weight of the machine and withstand that wear over time. The size of the wheels is directly related to the first risk, collision with the machine, so the wheels should be big enough to perform their function but not so large that they increase unnecessary risk to the user and players.

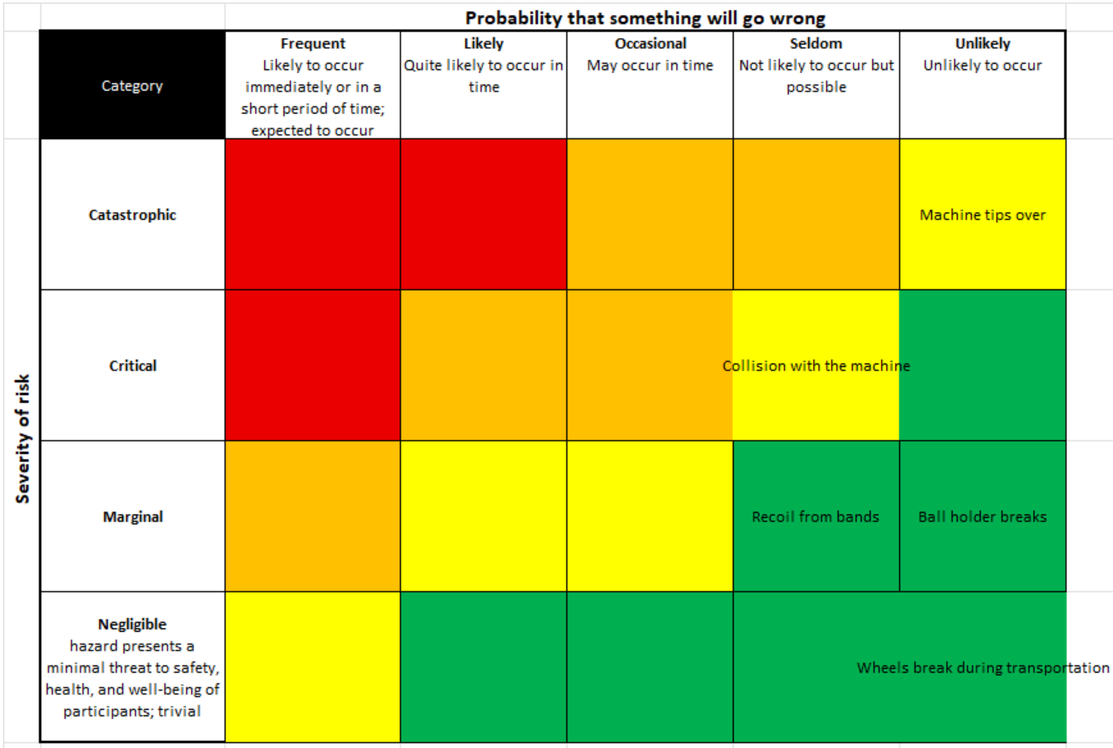



Figure 29: Risk Assessment map.

In Fig. 29, we can see the risk assessment of the various risks identified in our design. The highest priority risks are the machine tipping over and a person colliding with the machine. The machine tipping over could have catastrophic consequences as the injury could be severe to anyone that gets caught under it. A person running into the machine would not have catastrophic injuries, but could receive critical injuries depending on how hard and where they run into it. These are two risks that we have been working continuously on to ensure they are mitigated throughout the design process. The next priority risks are the recoil from the bands, the ball holder breaking, and the wheels breaking during transportation. As these are all low severity and low probability risks, they are not the highest priority for us to be mitigating.

## 6.3 Design for Manufacturing

There are 31 parts and around 100 threaded fasteners in the current design.

### 6.3.1 Theoretically Necessary Components

- **Ball holder:** The ball holder is a necessary part as it is what houses the ball for launch. The ball holder is the main part of the machine that the user interacts with.
- **Elastic bands:** The elastic bands are a necessary part as they store the force input from the user, and deliver that force into the launching of the ball.
- **Wheels:** The wheels are a necessary part as they are the main means of transporting the machine around the gym floor.
- **Net:** The net is a necessary part as it is what holds and stores the volleyballs for use.

- **Wooden 2x4s**

The design already has minimal components as the machine itself is very simple. The main number of parts is coming from the many wooden 2x4s that make up the frame of the machine. The design could be improved to minimize the number of wooden supports needed by changing the layout of the supports to optimize stress distribution. Another option is to use a material that is heavier and stronger than wood to use as supports, i.e. steel or iron, as we could achieve the same structural stability with much less supports. The elastic bands could be simplified to one band if we had a way to attach the band to the ball holder and to the supporting structure without losing functionality. The net is one component that could be decoupled into multiple components. The net functions as storage for the volleyballs, but could be replaced if the lower half of the structure was instead surrounded by plexiglass. The plexiglass would optimize the space for storage, protect the outside of the machine from any damage, and shield the balls from any outside contaminants. Figure 32 displays the final prototype of the Bueffer 3000 with all the necessary components.

## 6.4 Design for Usability

### 6.4.1 Vision Impairment

A person with a visual disability should not have any issue using our device as there are no visual components necessary for its use. One thing that can be noted, is if there are markers indicating where to pull back the ball holder to, then those markers should be a color that any person with a visual disability could read clearly.

### 6.4.2 Hearing Impairment

A person with a hearing disability should not have any issue using our device. There are no sounds that are necessary for the machines use. One hazard that can noted is that if the ball holder were to begin to break/crack, a person with a hearing disability would not be able to hear that breaking.

### 6.4.3 Physical Impairment

A person with a physical disability would have a lot of issues with using our current design. Since our design is based off of a person being able to pull back the ball holder and exert a considerable force in doing so, a person who cannot do that would not be able to use the machine at all. We could implement a way for the bands to be automatically pulled back to a certain location using a winch or some sort of torque driven system. A person could then push a button or some sort of input device to tell the machine what sort of launch angle and height the user wants.

### 6.4.4 Control Impairment

A person with some sort of control impairment would still be able to use our device, but they may have some difficulty in doing so. A person experiencing some sort of control impairment may not be able to exert the necessary force to launch the ball. The person could move the device closer to where they want the ball to go, or we could implement the automatic launch system as discussed in the Physical Impairment section.

# 7 Final Prototype

## 7.1 Overview

The objective of the project was to design and build a machine that would simulate a volleyball set for hitters to practice spiking the ball. The project was specifically designed to fit the customer needs of the WashU Men's Club Volleyball team. After a discussion with our client regarding the wants and needs of the machine, a few iterations were designed and graded on functionality, portability, ease of use, and safety. An initial prototype was designed which served as a proof-of-concept. The initial prototype was tested to see if it would achieve the three performance goals listed below:

(1) The device can launch $\geq$10 balls in 1 minute.
(2) The device can launch balls at elevation angles of 30 degrees, 80 degrees, and at least two intermediate angles.
(3) The device can launch balls that reach $\geq$14 ft above the top of the device, and (in a different launch) land $\geq$20 ft away from the base of the device.

After successfully meeting the three performance goals, the initial prototype was used as an inspiration for the construction of the final prototype. The initial prototype did not include some of the needs of our customer, so the objective for the final prototype was to integrate the needs of our customer with the fundamental components that allowed our initial prototype to achieve the performance goals. With this in mind, we can confidently say that the final iteration of the Bueffer 3000 meets all three performance goals while also meeting the needs of our customer.

## 7.2 Documentation

See the images below for the final iteration of the Bueffer 3000. The Bueffer 3000 stands at 6' tall, with a wooden base and surrounding structure. The wooden base allows for storage of volleyballs while simultaneously increasing usability of the machine by allowing the user to stand straight up to launch volleyballs instead of kneeling or bending over. The elastic bands were reused from exercise equipment and the ball holder was designed and 3D printed.

Figure 30: Final prototype of the Bueffer 3000.

Figure 31: The Bueffer 3000 in action just before a launch.

Figure 32: The Bueffer 3000 launching a volleyball at a great height and distance.

# Bibliography

[1] R. D. Knight. *Physics for Scientists and Engineers: A Strategic Approach with Modern Physics*. Pearson Publishing, 2017.

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