Abstract

As it stands, there are currently no means to wash clothing aboard the International Space Station (ISS). Astronauts are forced to re-wear their soiled clothes, despite having to exercise over two hours per day. Instead of cleaning their clothing using a formal laundry machine, astronauts simply discard fouled articles after extensive use. This method of wear-and-tear has worked thus far, as the ISS has remained in an orbit reachable by resupply capsules. However, with agencies aiming to travel farther and longer than ever before, this practice seems both wasteful and costly. To address this problem, a terrestrial pedal-powered washing machine has been developed to provide proof-of-concept data for a microgravity iteration. The machine consists of a horizontal drum unit linked to the drivetrain of a bicycle, which has been modified to replicate the ISS CEVIS exercise bike. Using computer simulations, the concept of an axial-running agitator to induce mechanical agitation in space was explored and verified. This project served as the first step towards making clean clothes a reality for astronauts.
# Contents

1 **Introduction** ........................................ 3  
   1.1 Motivation ........................................ 3  
   1.2 System Overview .................................. 5  
   1.3 Impact ........................................... 6  

2 **Prior Work** .......................................... 8  
   2.1 Washing Machines Designed for Microgravity .......... 8  
   2.2 Terrestrial Washing Machines ........................ 9  

3 **Relevant Research** .................................. 12  
   3.1 Washing Machine Basics ................................ 12  
   3.2 Water in Space ..................................... 14  

4 **Design Goals** ....................................... 16  
   4.1 Overview .......................................... 16  
   4.2 Specifications ...................................... 18  

5 **Inner Drum** ........................................ 23  
   5.1 Modeling & Calculations .............................. 24  
   5.2 Fabrication & Assembly ............................... 32  

6 **Mechanical Subsystems** ............................ 35  
   6.1 Drum Mount ........................................ 35  
   6.2 Agitator ........................................... 40  
   6.3 Bicycle ............................................... 42  

7 **Putting it All Together: System Assembly** ......... 46  
   7.1 Power Transmission Challenge ........................ 46  
   7.2 Leaking ............................................. 48  
   7.3 Terrestrial Prototype .................................. 50  

8 **Testing & Analysis** ................................ 51  
   8.1 Process for Terrestrial Prototype Use .................. 51  
   8.2 Terrestrial Prototype: Testing & Results .............. 53  
   8.3 Microgravity Simulation: Testing & Results .......... 58  

9 **Design Evaluation** ................................ 64  

10 **Conclusion** .......................................... 66  

11 **Acknowledgements** ................................ 67  

12 **References** ......................................... 68  

A. **MATLAB Code** ..................................... 72  

B. **LAMMPS & C++ Code** ............................... 74  

C. **Bill of Materials & Budget** ......................... 76
List of Figures

Figure 1: CEVIS exercise bike [45] ................................................................. 4
Figure 2: Fully-integrated terrestrial laundry machine system ........................... 5
Figure 3: Potential users of the pedal-powered laundry machine ........................ 7
Figure 4: UMPQUA’s water-jet washer [19] .................................................... 8
Figure 5: Foot and hand crank washing devices ............................................. 10
Figure 6: MIT’s Bicilavadora [12] ................................................................. 11
Figure 7: Mechanical workings of the inner drum [3] ...................................... 13
Figure 8: Water levels for horizontal and vertical washing machines [36] ....... 14
Figure 9: A water particle in microgravity ..................................................... 15
Figure 10: iRED exercise machine dimensions ............................................. 19
Figure 11: Example cotton load ..................................................................... 20
Figure 12: Front-view of horizontal washer .................................................. 22
Figure 13: SolidWorks model of final inner drum .......................................... 23
Figure 14: Inner drum parameters [10], [42] .................................................. 25
Figure 15: Volume of water needed for high-efficiency compact washers ....... 26
Figure 14: Three stages of clothing’s movement within a horizontal tumbler [42] 27
Figure 17: The parabolic trajectory of an unbalanced load ............................. 28
Figure 18: RPM vs. Impact Velocity plot ....................................................... 32
Figure 19: Laser-cut lid fasteners ................................................................. 33
Figure 20: The inner drum .......................................................................... 34
Figure 21: Compost drum-mount .................................................................. 36
Figure 23: Early sketches of basket mount .................................................... 38
Figure 24: Basket drum mount ...................................................................... 39
Figure 25: Terrestrial baffle system .............................................................. 40
Figure 26: ISS agitating system .................................................................... 41
Figure 27: Bike-to-outter drum rigid attachment .......................................... 42
Figure 28: CEVIS-inspired design ............................................................... 43
Figure 29: Fork fitting between chain stays................................................... 44
Figure 30: Prototype bicycle structure .......................................................... 45
Figure 31: Bicycle cassette-axle system ........................................................ 46
Figure 32: No-slip end caps ......................................................................... 47
Figure 32: O-rings prevent lateral slip............................................................ 48
Figure 33: Rubber trim around door’s perimeter .......................................... 49
Figure 35: Step-by-step process to use terrestrial prototype ............................ 52
Figure 36: Colilert Coliform Testing materials .............................................. 54
Figure 38: Visual effect of mechanical wash on muddy clothing .................... 56
Figure 40: Simulating clothing movement under the influence of gravity ....... 58
Figure 41: Simulation parameters ................................................................. 59
Figure 42: Simulation demonstrating microgravity agitation .......................... 62
1 Introduction

1.1 Motivation

For the average citizen, the ability to wash clothing is oftentimes taken for granted, as the means to do so are available both at home and on extended trips. In this day and age, washing clothing has become as commonplace as brushing teeth—both of which are seemingly simple tasks, as water supplies are readily available. The less-than-average citizen, however, is not allowed this luxury. In its near twenty-year existence, the International Space Station (ISS) has yet to see its inhabitants clean their own clothing with a formal washing machine [26]. As a result, astronauts are forced to re-wear their soiled clothing following their 1.5 – 3 hour daily exercise regimes [11]. In space, clothing is simply discarded after extensive use or once the articles are deemed too dirty to wear. This method of wear-and-tear has worked thus far, as the ISS has remained in Low-Earth-Orbit (LEO)—an orbit level that can be reached by resupply capsules filled with articles of clothing. However, with private and public agencies aiming to travel farther and longer than ever before, this method seems wasteful, unhygienic, and costly, as cargo launched to the ISS costs about $10,000 per pound [26].

To address this problem, a bicycle-powered laundry machine was proposed. In its simplest form, the terrestrial machine consists of an inner drum lined with agitating baffles, which links to the drivetrain of an exercise bike that has been reconfigured to mimic the Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS) bike. The objective of this project was twofold. First, to design and build a working proof-of-concept laundry machine that can be further evolved and tested for parabolic flight-testing. Second,
to simulate an agitator’s effect on clothing in microgravity to prove that minimal geometry is sufficient.

Figure 1: CEVIS exercise bike [45]
1.2 System Overview

Key Features

1. **Structural support**: welded steel
2. **Outer Drum**: Watertight and sealed, hinged to facilitate reentry
3. **Inner Drum**: Perforated with side-running baffles
4. **Basket**: Cups the outer drum for support, removable for storage
5. **Plumbing**: PVC open-loop
6. **Seat**: refurbished bike system

Figure 2: Fully-integrated terrestrial laundry machine system

In order to prepare for parabolic in-flight testing of a laundry unit, the machine shown above was first developed for terrestrial use. The basic idea is that the user would spin the pedal during exercise, drive the chain unit, rotate the inner drum, and agitate a load of laundry. The structural support for the machine was constructed from welded steel so is entirely joined into one unit. This support system was essential for terrestrial testing, as it provided a structurally sound way to spin the laundry machine.

The real crux of the machine is the drum system, as it was used for assessment on Earth and will be further tested in air during parabolic tests. The outer drum is a 15-gallon container that was made watertight via gasket and silicone sealing; this drum stores the water as the user cycles and features a hinged door for clothing to be put in and pulled out. The inner drum is a repurposed 5-gallon paint bucket that was perforated to facilitate water movement. This component was lined with three side-running baffles in order to
incite agitation. The basket of the drum system was built out of PVC piping and is used to both bear the weight of the laundry and orient the axel. The terrestrial machine is composed of an open-loop PVC valve system to quickly dispose of fouled water. Lastly, the frame and handle bar of a bicycle was refurbished to mimic the CEVIS’s functionality and ergonomics.

1.3 Impact

By developing the previously shown machine, it is now possible to prepare for parabolic in-flight testing of a laundry machine unit. The terrestrial washer successfully agitated soiled clothing and brought the colony-forming unit (CFU) count down to the level accepted by ISS physicians: 50 CFUs/mL [43]. Further, the machine was able to destroy bacteria through mechanical agitation alone; that is, without laundry detergent being added to the water solution. Computer simulations proved that the designed inner drum would successfully agitate clothing in a microgravity setting.

The development of a terrestrial pedal-powered washing machine puts the goal of cleaning clothes aboard the ISS closer into reach. Simulations indicating that clothing can be mechanically agitated in microgravity prove that the goal is attainable. The entire drum system and basket support is flight-ready so may be taken aboard a reduced gravity aircraft for further testing. If the unit performs well in this environment, it could be taken aboard a capsule and delivered to the ISS for installation and use. Thus, astronauts may soon be able to clean their exercise clothing, which would allow for a more hygienic International Space Station. Because the washing machine was designed to work in a microgravity environment, it may also be used to support further human space exploration efforts.
Figure 3: Potential users of the pedal-powered laundry machine

(a) ESA astronauts conducting parabolic flight tests [39]
(b) NASA astronaut with clothing shipment aboard ISS [38]
(c) SpaceX capsule drawn on Mars [1]
2 Prior Work

2.1 Washing Machines Designed for Microgravity

As it stands, there are currently no means to wash clothing aboard the International Space Station. Astronauts can rinse their clothes by squirting drinking water onto individual pieces of clothing, although this practice is discouraged [16]. Further, water is a commodity aboard the ISS, and most astronauts do not see the benefit in wasting their recycled water on clean clothes [46]. Instead, they opt with wearing their soiled clothing until fresh clothing arrives on a resupply mission. Once they are finished with their clothes, astronauts fill up either the Russian Progress or an American expendable cargo capsule, and their clothes simply burn up upon the capsule’s reentry into the atmosphere [26].

Figure 4: UMPQUA’s water-jet washer [19]

Although a laundry machine seems like a fairly straightforward technology on Earth, it is not so simple in space because of microgravity’s effect on fluids. Thus, NASA has invested nearly $125,000 in R&D work in this field; research company UMPQUA was
officially commissioned to develop a washer and dryer system that could work in microgravity given a small water supply [19]. The project manager for the company described the technology as, “a system of water jets inside a plastic bag with clothes and water and no air” [19]. Essentially, the jets would move the clothing in such a way that the liquid soap would penetrate the clothing fibers, thereby washing the piece of clothing. The company received NASA funding in 2011, but there have been no further developments on the technology [19].

2.2 Terrestrial Washing Machines

Because there are currently no solutions to this problem, terrestrial technologies were further studied for inspiration. A number of patented pressure-based systems exist which force detergent and water through clothing fibers—thereby speeding up the washing process and ensuring a thorough job on Earth. These devices require little-to-no water and do not need electricity to operate. Although such machines seem like ideal solutions to the clothes-washing problem, they do not require physical exertion from the astronaut and so do not coincide with the design goals of the project. Further, by forgoing a pressure-based system, the theory that mechanical agitation alone can induce clothing can be further studied.

Foot pedal-powered washing machines have recently sprung up throughout developing countries, as they are inexpensive, require little water, and are oftentimes portable. The GiraDora is one such machine, which was created to expedite the clothes-washing process and alleviate the physical burden of hand washing for poor citizens in electricity-scarce countries [8]. The portable device is entirely mechanical, in that the user lifts the lid, fills the tub with soap and water, sits on the lid, and pumps the extended
spring-loaded pedal. Another human-powered machine—the Laundry Pod—requires the user to physically agitate the clothing by rotating an attached crank [40].

![Pedal-powered GiraDora machine (20)](image1) ![Hand-powered Laundry Pod (40)](image2)

Figure 5: Foot and hand crank washing devices

Although both of these designs were innovative and human-powered, they were not suited for the ISS, as they require multiple refills of clean water to properly wash. Further, the ergonomics of the designs called for entirely new machines to be developed were they to be used on the ISS, as both require the driving unit to be rigidly installed to the agitator. Considering one of the project goals was to have an astronaut simultaneously exercise and wash clothing, these machines would not suffice. There are no exercise machines currently aboard the ISS that allow for the ergonomics of these mechanically driven units.

Because mere pedal-powered machines were not suitable choices for design inspiration, a study on explicitly bike-powered machines was required. MIT's Bicilavadora, or "bike washing machine," was invented to both speed up washing clothes and to create jobs in underdeveloped countries [4]. The Bicilavadora was built from readily available parts, like oil drums and bicycle drivetrains. Like modern washing machines, the device
can operate in multiple cycles, thanks to a multi-geared drive unit. Despite many of its components being too bulky for the space-constrained International Space Station, the Bicilavadora still stood as the key exemplar throughout the design process.

![Figure 6: MIT's Bicilavadora [12]](image)

In studying pedal-powered washing machines, it was realized that most machines are entirely mechanical-based, very ergonomic, and ultimately require little water input—all of which are factors that aligned with the ISS machine design goals. Although some current technologies could clean clothing using bicycles and some are intended for space purposes, no one system has been developed to combine both: to utilize an already-present bike aboard the ISS to power a water-scarce laundry machine. Further, this technology could potentially reduce the current cost needed to achieve in-space laundry action.
3 Relevant Research

3.1 Washing Machine Basics

Laundry Cycles

The three main laundry cycles include washing, rinsing, and spinning. During the washing phase, water and detergent fill the inner drum and the clothing is soaked and properly agitated. Generally, the water used in this cycle is extremely hot so as to remove bacteria. The rinse cycle follows and involves the draining of dirty water. At this time, clean water is sprayed onto the clothing to ensure a thorough wash. Once the rinsing cycle is complete, the machine begins to spin the clothing more rapidly to extract as much water as possible.

Due to the open-loop nature of the proof-of-concept machine, the washing cycle was of the utmost importance in the project. Because the bicycle chosen was single-speed and could be controlled by the user’s physical input, a spinning cycle could also be achieved. This latter cycle allowed for the clothing’s dirty water to collect itself at the bottom of the outer drum.

Mechanical System Breakdown

Terrestrial washing machines generally consist of five main components: a motor and drive mechanism, an agitator, an inner drum and outer drum, and a pump or hose system. The motor provides the power to activate the agitator and clean the clothing. The agitator is the component responsible for moving the clothing throughout the water and ensuring its thorough cleaning. The inner drum stores the clothing and is generally perforated, so as to allow water to flow in and out of the system. The successful rotation of this part is crucial, as the movement disturbs the system and sets both the water and clothing into motion.
The outer drum is essential to any washing machine, as it rigidly supports the system while the inner drum rotates and cleans the clothes; this component must be watertight, as it is responsible for holding the entire fluid system together.

![Diagram of washing machine](image)

**Figure 7**: Mechanical workings of the inner drum [3]

**Type: Horizontal vs. Vertical Washers**

Two main types of laundry machines exist on the Earth today: horizontal-axis and vertical-axis rotators. The latter option is most widely used in America, and it utilizes a finned, vertical agitator to properly stir the clothing [9]. Although this kind of washing machine is known to be very thorough, it operates at a comparatively low RPM, requires more water, and does not extract water efficiently. Horizontal washers, on the other hand, tend to tumble the clothing through the water, thereby eliminating the need for bulky agitators. Impellors and fins are oftentimes used in horizontal-axis rotators to agitate the clothing.
Horizontal washing machines are advantageous, in that they only need to be partially filled—using about 1/3 of the water needed by a vertical washer—to achieve the same level of cleaning [9].

The horizontal washing machine was ultimately selected, as the design requires substantially less water for the same level of clean. Although the notion of less water generally only applies to terrestrial-based horizontal machines, as it is dependent upon both rotation and gravity, using less water was also important for the final space-based prototype. Further, horizontal washers are also operated at high rotational speeds; the faster the drum rotates in space, the more likely it is to simulate gravity through centripetal force.

Figure 8: Water levels for horizontal and vertical washing machines [36]

3.2 Water in Space

Unsurprisingly, water behaves quite differently in space than it does on Earth, due to the reduced effects of gravity. In space, the surface tension of water forces the liquid into one or more spheres [21]. Hydrogen bonding occurs rapidly in space because gravity is not present to override its effect [33]. That being said, water particles are cohesive with neighboring molecules, which essentially makes water cling to itself.
Despite water’s complicated behavior in space, machines have been developed to properly handle and make use of the liquid. On the International Space Station’s predecessor, the Skylab, for instance, astronauts would shower using a foldable device that was mounted to the floor. The system relied on a pressurized water flow and suction device. Like other gravity simulators, this pressurized water flow system depended on continuous airflow to act as a gravity substitute [17].

Although this pressure-based showering system is no longer in use, the technology successfully proved that water could indeed be used in a microgravity environment. That is, if enough force is generated, water may behave as if gravity is acting upon it. Thus, the complicated fluid dynamic effects of water in microgravity were ignored for simplicity’s sake. As long as the rotating axel and agitator system induced enough force, it was assumed that all conditions on Earth would be similar to those on the ISS.
4 Design Goals

4.1 Overview

Upon review of existing pedal-powered terrestrial machines, typical laundry features, and water’s behavior in space, specific design goals were created to help guide the project. These sub-goals were formulated with one ultimate objective in mind: to build a machine that would allow International Space Station astronauts to wash their spare exercise outfits while exercising on the CEVIS bike.

The first underlying goal of the project was to keep the machine compact and water-scarce. Due to tight space constraints, great attention is put into minimizing mass, space, and water when adding new machines or features to the ISS. Because it is so expensive to ship cargo via expendable capsules, designing a compact, lightweight machine package was optimal: thus, the decision to build a removable washing unit was made. Only the drums and its internals would be shipped using a capsule, as the unit can be installed directly to the CEVIS bike already aboard the ISS.

Another goal of the project was to facilitate simultaneous exercise for the astronaut and washing for the clothing. The most obvious way to complete this goal was to have the machine work off the already-installed CEVIS exercise bike. To simulate the CEVIS bike on Earth, consideration was paid to the terrestrial prototype’s ergonomic design and mechanical functionality. Further, a bicycle that could provide the RPM and power outputs required by ISS physicians was selected and modified.

The third—and arguably most important—goal of the pedal-powered washing machine was to mechanically agitate clothing and induce bacteria removal. Achieving
mechanical agitation on Earth was straightforward and required the optimization of certain inner drum parameters; this goal was evaluated based on the machine’s ability to destroy CFUs without chemical assistance. For the space-based design, this goal was evaluated through computer simulations. In the simulation, if particles were prevented from riding the wall upon installation of an agitator, it was assumed that clothing could be mechanically agitated in microgravity.

The last goal of the machine was to successfully clean clothing to an acceptable colony-forming unit (CFU) level. Measuring CFUs is a viable method in determining the number of microorganisms and contaminants in a particular sample. Thus, this method was chosen to determine the cleanliness of clothing articles, as certain CFU levels have been designated by the ISS as acceptable.

**Summary of Qualitative Design Goals**

1. Machine should be built with mass, space, and water constraints in mind.
3. Machine must mechanically-agitate clothing, both on Earth and in microgravity environment.
4. Machine must clean clothing to the designated CFU standard set by the ISS.
4.2 Specifications

Numerical Specifications

<table>
<thead>
<tr>
<th>Design Goal</th>
<th>Variable</th>
<th>Target Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Reduce mass, space, and water</td>
<td>Unit size</td>
<td>&lt; 4 ft x 2 ft</td>
</tr>
<tr>
<td></td>
<td>Load Size</td>
<td>2 sets of shorts, T-shirts, socks, underwear</td>
</tr>
<tr>
<td></td>
<td>Total volume of water needed</td>
<td>&lt; 5 L</td>
</tr>
<tr>
<td>(2) Simultaneous washing and exercising</td>
<td>Time</td>
<td>30-90 minutes</td>
</tr>
<tr>
<td></td>
<td>Speed (RPM)</td>
<td>30-120 RPM</td>
</tr>
<tr>
<td></td>
<td>Power Requirements</td>
<td>25-350 W (instantaneous)</td>
</tr>
<tr>
<td>(3) Mechanically-agitate</td>
<td>On Earth: fill level, perforations, inner drum dimensions, etc.</td>
<td>Reduction in CFU without detergent</td>
</tr>
<tr>
<td></td>
<td>On ISS: no riding the wall</td>
<td>Simulation demonstrates particle’s maintain velocity</td>
</tr>
<tr>
<td>(4) Clean clothing</td>
<td>CFU count</td>
<td>50-100 CFU / mL</td>
</tr>
</tbody>
</table>

Technical Justifications

(1a) Unit Size

The size of the drum unit was determined by the space constraints of the International Space Station’s storage and exercise module, Tranquility [37]. Aboard the module sits various exercise machines, including the Interim Resistive Exercise Device, iRED. Because this unit is so large, it was selected as the storage location for the drum unit when the iRED
is not in use. Although official documentation on the machine is scarce, the dimensions of the machine were determined based on imagery and terrestrial squat rack comparisons. iRED’s rack is about 4 feet wide and features an open section sandwiched between two parallel platforms (see gold platforms in image below). Thus, the drum unit was designed to be less than 4 ft. wide and slightly taller than 1 ft., so as to allow a Velcro fastener to fit snugly around it aboard the ISS.

![Figure 10: iRED exercise machine dimensions](image)

(1b) Load Size

The load size specification was largely based upon need. While aboard the ISS, astronauts are allowed one clean pair of shorts and one t-shirt every three days for exercise; they are allowed to change undergarments every other day [38]. Thus, while one astronaut
exercises on the CEVIS bike, he or she would clean their own set of dirty laundry and also help out another astronaut, if they so desire. This way, the astronauts will only need two sets of exercise clothing and two sets of undergarments per trip—thus bringing down the weight requirements of an expendable capsule.

![Example cotton load](image)

Figure 11: Example cotton load

The total mass contained inside the inner drum comes from the clothing load, water, and detergent solution. The clothing size was based upon a 65-inch female, as this is an acceptable height for an average astronaut [30]. Despite significant research dedicated to finding the ideal textile for exercise aboard the ISS, astronauts continue to wear cotton-based clothing during workout regimes [30]. Thus, 100% cotton articles were used during terrestrial prototype testing.

*(1c) Volume of Water Needed*

Considering water is very much a commodity aboard the International Space Station, one
design goal was to use as little water as possible. Astronauts are allotted 4 liters of water for daily bathing and hygiene, and they typically use half of this supply to drench and ring out soiled clothing [33]. Thus, the goal was to use less than 4-5 liters of water per load, as each run on the CEVIS bike was designed to accommodate two astronauts’ exercise outfits.

(2) Time, Speed, and Power Requirements

The specifications pertaining to the design goal of a simultaneous workout and washing were taken directly from the targets prescribed by physicians familiar with the CEVIS bike. Exercises on the bike range between 30-90 minutes, and the astronaut is expected to exert 25-350W pedaling between 30-120 RPM [28].

(3) Mechanical Agitation

In many ways, the goal of mechanical agitation was a bit more qualitative in nature than the others. Essentially, the target for the terrestrial prototype was to see a reduction in CFU levels without the use of detergent, which was facilitated by optimizing fill level, perforations, and inner drum dimensions. Because it was not physically possible to test in a microgravity condition, a simulation was developed to prove that clothing does not simply ride the wall upon installing a mechanical agitator.
(4) CFU Levels

Colony-forming units (CFUs) refer to the number of bacteria or fungi measured off a particular sample area. Because the ISS does not currently have access to laundry machine washers, NASA has not set an explicit standard for acceptable clothing CFU levels. However, NASA does use a standard of 50 CFU/mL to judge whether water is suitable for drinking purposes and personal hygiene following expulsion from the Potable Water Dispenser (PWD)[43]. On Earth, the EPA deems a CFU count between 100-500/mL as reasonably purified for potable water [25]. Thus, the minimum level on Earth was chosen as the upper limit, and the maximum level in space was chosen as the lower limit, considering potable water standards are much more stringent than textile standards.
5 Inner Drum

![SolidWorks model of final inner drum](image)

Of all the components comprising the pedal-powered washing machine, the inner drum stood as the most significant, despite its seeming simplicity. On Earth, the most important part of the mechanical wash is the impact of the clothing into the water, as it falls parabolically. Thus, engineers in this field tend to focus on optimizing the impact velocity of clothing by altering the inner drum's various parameters, such as dimensions, fill level of water, and rotational velocity of clothing.

Although a microgravity environment is quite different than Earth, the same general logic was applied to the space-based case. That is, the assumption that the most significant part of the mechanical wash would occur when the greatest force was applied to the clothing was made.
5.1 Modeling & Calculations

Optimizing Fill Level and Volume

*Fill Level*

Designing the inner drum to maximize agitation required balancing the need to stay within certain fill level bounds while also ensuring that the volume stayed under the target specification. In order to facilitate reasonable agitation, the water level coefficient \((K)\), which refers to the ratio of fill level \((h)\) to drum diameter \((D)\), should be between 0.1 and 0.8—an industry standard [42]. Thus, acceptable fill levels for the inner drum were determined using the following equation:

\[
\text{Fill level} = D \times K
\]  

(1)

To stay within the water level coefficient bounds, various standard inner drum diameters were inputted into the equation to determine which diameters provided fill levels compatible with the specified volume.

*Volume*

The volume needed for each laundry load was determined through a literature review and the cylindrical fill volume equation:

\[
\text{Fill volume} (V) = 0.5 \, r^2 \, L \, (\theta - \sin(\theta))
\]  

(2)
where \( r \) refers to the drum radius, and \( L \) refers to the inner drum length. \( \theta \) refers to the angle that the center point makes upon sweeping to the fill level:

\[
\theta = 2 \arccos \left( \cos^{-1} \frac{m}{r} \right)
\]  

(3)

As shown in Figure 14 above, the distance (m) from the center point to the water is entirely dependent upon the fill level found in Equation 1. Using the MATLAB code delineated in Appendix A, an array of fill volumes were determined by first finding fill levels acceptable by the water level coefficient standard. These fill volumes ranged between 0.26 gallons and 4.33 gallons.

To crosscheck the cylindrical fill volume calculation, an industry-wide study was conducted on high-efficiency compact horizontal washers. To gather information, laundry machine data sheets were collected and company representatives were consulted for validation. Both load capacity (lbs.) and volume of water (gallons) needed per load were
readily-available information (see Figure 15 below). Thus, the amount of water being used (gallons) per load capacity (lbs.) was determined using the following equation:

\[
\frac{\text{Water usage}}{\text{Load capacity}} = \frac{\text{Volume of water/load}}{\text{Load capacity}} = \frac{[\text{gallons}]}{[\text{lbs.}]} \tag{4}
\]

The water usage per load capacity was averaged amongst the four washers and turned out to be 0.90 gallons / lbs. of laundry. Thus, the volume of water (gallons) needed for the cotton load was found using the following:

\[
\frac{\text{Volume of water}}{\text{Load}} = \left( \frac{\text{water usage}}{\text{load capacity}} \right)_{\text{average}} \times \text{load capacity}
\]

\[
\frac{\text{Volume of water}}{\text{Load}} = 0.9 \frac{\text{gallons}}{\text{lb}} \times 1.32 \text{ lbs} = 1.19 \text{ gallons} \tag{5}
\]

| Bosch Clothes Washer Axxis, [2] | 13.20 | 13.00 | 1.02 |
| Bosch Ascenta Compact Washer, [7] | 10.00 | 15.40 | 0.65 |
| LG Compact Washer, [22] | 10.10 | 10.10 | 1.00 |
| Miele Little Giant PW, [24] | 14.00 | 15.00 | 0.93 |
| Terrestrial prototype | 1.19 | 1.32 | 0.90 |

Figure 15: Volume of water needed for high-efficiency compact washers
The industry-approved volume of 1.19 gallons per load was validated by the MATLAB code’s cylindrical fill volume. The 1.19 gallons fell between a chosen cylindrical fill volume range of 1.02 and 1.47 gallons, which corresponded to fill levels between 7 and 9 cm. Thus, the fill levels and water volumes were calculated in such a way that the agitation of the clothing was optimized.

**Maximizing Impact Velocity of the Clothing**

Clothing’s impact velocity into the water has been, “concluded to be the most significant physical action of the wash process, in terms of inducing a deformation and hence flow through the textile structure” [23]. Thus, to maximize the impact velocity, it was crucial to optimize the rotational velocity of both the clothing and the drum. This would result in an increased tangential velocity of the clothing upon its slip from the wall, which would maximize the impact velocity.

![Figure 14: Three stages of clothing’s movement within a horizontal tumbler](image)

(a): Pulled through water   (b): Riding the wall, out of water   (c): Slipping, parabolic trajectory

**Impact Velocity: Equation Derivation**

In order to explore the dynamics of the clothing and the resultant impact velocity, it was necessary to work through a basic physics problem on parabolic trajectories. The impact
velocity of any terrestrial article is most directly governed by the tangential velocity \( v_t \) of the article, as well as the angle at which it slips. The tangential velocity of the clothing was found to depend entirely on the rotational velocity, \( \omega \), of the drum:

\[
v_t = \omega \times r_c
\]

\[
v_t = \omega \times 0.05
\]

where 0.05 m refers to the average radius of the unbalanced load. For domestic and industrial-grade machines, this tends to be 0.23 m; however, the inner drum of the prototype is substantially smaller than such machines so was scaled down [42].

![Diagram of an unbalanced load](image)

**Figure 17:** The parabolic trajectory of an unbalanced load

An unbalanced load of laundry of mass \( m_{cl} \) is able to ride the wall until the critical slip angle, \( \phi \), is reached. The angle of the clothing was determined by first equating the centripetal force in the y-direction and the downward force due to gravity:
\[ m_{cl} \omega^2 r_c = m_{cl} g \sin \phi \quad (7) \]

and rearranging to find:

\[ \phi = \sin^{-1} \frac{v_t^2}{r_c g} \quad (8) \]

Once the slip angle was determined, a study on parabolic motion was undertaken to further characterize the clothing’s movement. The clothing’s tangential velocity was first broken down into y and x-components:

\[ v_{ty} = v_t \sin \phi \quad (9) \]

\[ v_{tx} = v_t \cos \phi \quad (10) \]

Using these tangential velocity components, the time \( t_1 \) it would take the article to reach peak height before falling downward was found by rearranging the formula typically used to compute velocity at peak altitude \( (v_y = 0) \).

\[ v_y = v_{ty} - gt_1 \quad (11) \]

\[ t_1 = \frac{v_{ty}}{g} \]
To make use of this time calculation, the distance between the fill level and the point at which slip occurs \((h_s)\) was found by incorporating the tangential velocity, the radius of the drum \((r_d)\), and the fill level \((h_f)\):

\[
h_s = \frac{v_t^2}{g} + (r_d - h_f)
\]  

(12)

It was now possible to determine the distance \((d)\) between the point of slip and maximum height using the following:

\[
d = h_s + v_{t_y}t_1 - 0.5gt_1^2
\]  

(13)

Knowing the distance between the slip and maximum height, the time \((t_2)\) it took for the unbalanced load to fall from the maximum height was found to be:

\[
t_2 = \sqrt{\frac{d}{g}}
\]  

(14)

The total time \((t_{tot})\) of travel was then derived by adding the two travel times:

\[
t_{tot} = t_1 + t_2
\]  

(15)

The \(y\)-component of the impact velocity \((v_{y,imp})\) was then found via:
\[ v_{y,imp} = gt_2 \]  \hspace{1cm} (16)

which ultimately allowed the magnitude of the impact velocity to be analyzed by combining the y- and x-components:

\[ \nu_{imp} = \sqrt{v_{y,imp}^2 + v_{t_x}^2} \]  \hspace{1cm} (17)

**Modeling Impact Velocity with Derived Parameters**

Deriving the impact velocity equation made it possible to determine probable impact velocities the clothing would experience within the terrestrial prototype’s inner drum. Because the user can change the speed at which he pedals, the RPM and, therefore, the impact velocity of the garment can be changed. Using the lower bound of the previously-mentioned fill level, 7 cm, the following plot of RPM vs. impact velocity was plotted in Figure 18. The plot depicts a linear trend, with higher rotation speeds leading to higher impact velocities for the unbalanced loads. It is important to note that this model ignores the fact that exceedingly fast rotation speeds will cause the clothing to ride the wall.
Once the component’s parameters were better understood and numerically defined, focus shifted to fabrication of the inner drum. The inner drum was constructed out of a simple, 5-gallon paint bucket made of polyethylene—a plastic commonly found aboard the ISS for shielding and experiment purposes [31]. This bucket was selected because of its lightweight but durable quality; further, the drum was inexpensive which would have allowed for multiple iterations, were they necessary. Using a basic perforation calculation as a guide, a number of holes were punched out of the drum to facilitate water movement within the tub (see Appendix A).

Figure 18: RPM vs. Impact Velocity plot
Inside the drum, three square polycarbonate baffles were affixed to agitate the clothing as it spun within the terrestrial prototype. In order to put clothing into the drum while making for easy removal, a 6” x 6” square door was cut out via a Dremel tool. The door was attached back to the inner drum using two plastic hinges and plastic screw sets; plastic was chosen over metal-based hardware, as the latter would rust upon reuse. Towards the bottom of the door, two 1-inch thick strips of female Velcro were attached using laser-cut acrylic fasteners. These fasteners were necessary, as the female Velcro alone could not attach to its male counterpart on the inner drum, as they both had adhesive backings.

The final iteration of the inner drum featured the PVC axel running axially, a three-baffle system lining the walls, and a door to allow loading and unloading. The inner drum was not designed to be watertight, as the perforations make this unfeasible. The size, placement, and number of perforations facilitate water’s sloshing in and out of the inner drum. Although the unit is not entirely watertight, the door was precision-cut so that
minimal leaking would occur at the opening. Ideally, enough water remains in the drum during tumbling to soak the clothing; if there were a large gap in the system, water would almost certainly dump out into the outer holding drum.

Figure 20: The inner drum

(a): Lid open, revealing PVC axel

(b): Lid closed, revealing plastic hinges and Velcro
6 Mechanical Subsystems

Aside from the inner drum itself, other components were important in ensuring both a mechanically-stable and mechanically-agitating device. Although the subsystems were ultimately designed for the terrestrial proof-of-concept prototype, they were constructed with the space-based machine in mind. Thus, the goals of building a compact, lightweight, and mechanically-effective machine guided the design. If the terrestrial prototype’s drum unit proved its mechanical cleaning abilities, it could be removed and its materials swapped for space-grade equivalents. Eventually, the unit could be taken aboard a resupply capsule for installation onto the CEVIS bike. At that point, the proof-of-concept build would be deemed a success.

6.1 Drum Mount

One component of particular interest and focus was the drum mount. That is, the connection point between the 15-gallon polyethylene outer drum and the support structure, be it the terrestrial steel base or the CEVIS bike. This component went through a series of iterations, as its design was critical in assessing the feasibility of a drum unit being sent to the ISS via a resupply capsule. For capsule transport to be a reality, the drum mount had to be lightweight, compact, and entirely removable.

Iteration 1: Compost-Inspired Mount

Horizontally oriented compost tumblers evidently inspired the first drum mount. These drum mounts feature two rods or planks crossing at the ends of the drum to form an ‘X’-shaped gap for the axel. This design very much relies on gravity, as the axel of the machine simply sits within the ‘X’ of the crossing plates; because the axel is not held rigidly in place
by a bearing, vibration and noise caused by spinning is common. Upon prototyping this mount, the bulky nature of the design was revealed. Although it was prototyped using just the X-shaped rods, it was obvious that an axis-running connection would need to be installed between the ends so as to mediate the vibrational and stability issues. Thus, the compost design would be rather bulky, requiring a stand-alone mount system that would be extremely difficult to transport. Because of its reliance on gravity and its sizable structure requirements, this design was eliminated following prototyping.

Figure 21: Compost drum-mount
**Iteration 2: Traditional Horizontal-Machine Mount**

The second design for the drum mount was similar to a traditional horizontal-load washing machine's suspension system. Because of its proven excellence in stability and minimization of noise, the four-leg bottom mount suspension system was seriously considered for prototyping [13]. The design is extremely well-defined both within industry and research arenas, so calculations to assist with dimensioning the machine could be undertaken. However, the design was ultimately waived once logistical realizations were made. For one thing, the four legs would have to be directly bolted to the outer drum, which would certainly cause leaking from the system. Further, this option was ultimately overkill for the drum mount in question, as this design is intended for washing loads vulnerable to walking, or excessive movement. Considering the terrestrial prototype was to be subjected to less than 2 lbs. of laundry and the space-based machine would be bolted down, this design was overly sophisticated.

![Figure 22: Four-leg horizontal washer drum mount](image)

(a): Preliminary sketch  (b): SolidWorks model  (c): Inspiration [13]
Iteration 3: Basket Mount

With two inspired designs dismissed, focus shifted to the development of a novel drum mount system. Because the previous designs were either too bulky or required a fixed connection, the new mount system was designed to be compact, lightweight, and entirely detachable from the outer drum itself. This would allow astronauts to remove the drum unit from the CEVIS and place the device in the previously mentioned iRED storage area.

![Figure 23: Early sketches of basket mount](image)

As is illustrated in the sketch above, the initial basket drum holder design was merely a three-branch system; two pipes (A, B) would sit orthogonal to the long, body-running connector (C) and another (D) would branch downward and then parallel to A and B. Although this design would minimize the piping used, it would not make for a stable outer drum. Further, it would have likely required bolting between the outer drum’s bottom surface and pipe D. To resolve this issue, the unit was converted into a symmetrical drum-
encasing PVC basket. PVC was ultimately selected as the basket material, as it is extremely lightweight and durable, and it is often the choice material when zero-G testing add-ons for the ISS underwater [41]. The PVC piping was held in place by 8 elbows and 3-way joints that were PVC-cemented to inhibit movement.

Figure 24: Basket drum mount

(a): SolidWorks model

(b): Final machine basket
6.2 Agitator

As for the mechanical agitator system, two designs were considered—one for the terrestrial proof-of-concept prototype and another for the ISS-based machine. The two must be differentiated, as an agitator that works on Earth may not be sufficient for clothing agitation in microgravity. Further, an unorthodox agitator designed for space could very well overcomplicate a terrestrial system and render it ineffective.

**Terrestrial Agitator**

For the terrestrial machine, a simple three-baffle system was chosen. 1-inch square polycarbonate baffles, also known as fins, were placed symmetrically along the walls of the inner drum. Because a horizontal drum’s rotation alone elicits a parabolic trajectory from an unbalanced load, the spinning itself can adequately induce cleaning. Thus, the baffles are not a necessity to the machine, but they do aid in the agitation of clothing articles, as they tend to pull on the clothing and allow water to penetrate the fibers.

![Terrestrial baffle system](image)

**Figure 25:** Terrestrial baffle system
Microgravity Agitating System

Because the ISS only experiences 1e-6 Earth g’s, the parabolic trajectory that terrestrial horizontal machines depend on to mechanically agitate clothing cannot be relied on in space [34]. With minimal gravity, clothing can simply ride the wall of a spinning drum. Thus, the 3-baffle agitating unit of the terrestrial machine—a conventional option in horizontal washing machines—would not be enough to agitate the clothing. The space-based machine requires an active agitating unit, like those found in vertical-load washing machines.

The machine’s agitating system, sketched in the image below, will feature two key components: a system of wall-running baffles and an axial-running agitator. The baffles will be added solely to provide additional agitation and disruption within the system. The propeller-inspired agitator will include a hole to insert the axel. That way, as the shaft rotates, so too does the inner drum and attached agitator.

The necessity of an active agitator unit in a space-based machine was further explored and will be discussed in the Testing & Analysis section.

Figure 26: ISS agitating system
6.3 Bicycle

Designing the bicycle for the terrestrial machine was an iterative process involving two different designs. Ultimately, both designs had their advantages, as one called for minimal modification to the purchased bicycle, and the other closely emulated the CEVIS bike.

**Iteration 1: Bike-to-Outer Drum Attachment**

One rather simple design called for rigidly attaching the bicycle’s handlebar unit to the outer drum, as shown in Figure 27. The front of the bike would connect to the drum using bolted sheet metal, molded into the shape of the drum. This design was very much inspired by MIT’s Bicilavadora, depicted in Figure 6. Although this would make for an extremely sturdy device, the design is better suited for larger loads, as the steel connecting piece would limit any walking. Further, the design instructs the user to balance by holding in-front, as opposed to the recumbent-style, which prompts users to hold to the side or backwards.

![Figure 27: Bike-to-outer drum rigid attachment](image)
**Iteration 2: CEVIS-inspired Ergonomics**

Considering one of the goals of the project was to mimic exercise conditions aboard the ISS, the bicycle design that most closely resembled the CEVIS was selected. Although the exact dimensions of the CEVIS bike were not taken into consideration upon designing the final bicycle structure, the general ergonomic quality was considered. That is, the bicycle was designed for an astronaut standing between 62-75 inches tall, holding backwards as he pedals [30]. The seat was situated such that the user’s leg would be fully elongated during a downward stride—similar to the illustration in *Figure 28.*

![CEVIS schematic](image)

(a): CEVIS schematic [30]

![Sketch of CEVIS bike](image)

(b): Sketch of CEVIS bike

*Figure 28: CEVIS-inspired design*
To construct this bicycle configuration, the fork and handlebars were removed from the head tube and taken to the back. The fork was physically widened so that its bottom could fit snugly within the chain stays and align with its drop outs. To hold the fork in place, a square rod of 1-inch cross-section was welded to the chain stay. In order to balance the bicycle in the back, a 16” steel rod was welded to the back fork piece at an angle of 40° with the ground.

Welding was ultimately the machining style of choice for the bicycle system because of the tricky angling and forces at play. As shown in Figure 29a, a threaded aluminum rod was first considered for the connection point between the fork and chain stays’ drop outs. Lock-nuts were placed on the rod, both inside the inner fork drop outs and outside of the chain stays’ drop outs. Although this made for an extremely lightweight connection mechanism, it also made for a risky attachment method as the drop outs were slotted which made slipping a potential risk. Further, bolting the bike to the ground support was not an option, as both aluminum and steel support rods must be hollowed out should the...
goal of a lightweight machine be achieved. Thus, bolts and screws were replaced with more accommodating welding beads.

Figure 30: Prototype bicycle structure
7 Putting it All Together: System Assembly

With the subsystems designed and constructed, it was possible to put all of the components together to test the machine. Although much time and consideration went into the individual subassemblies, an equal amount was needed to piece everything together in a way that would facilitate a sturdy, effective prototype on Earth and a detachable, easy-to-use drum unit and holder in space.

7.1 Power Transmission Challenge

One of the trickiest parts of the assembly was ensuring power was transmitted to the PVC axel, as this component was responsible for spinning the inner drum. Even converting the PVC tubing into an axel posed a challenge, as the bicycle’s axel was customized to fit within the cassette. Thus, the PVC tubing had to be lathed to size in order to facilitate a snug, reliable press-fit between the metal axel and the tube.

![Figure 31: Bicycle cassette-axel system](a): Before: cassette to hub system  
(b): After: cassette to PVC system

The PVC axel was designed to run from the cassette, through the outer drum and
into the inner drum, its rotation ensured by bearings on either side of the drum. However, guaranteeing rotation of the PVC axel did not necessarily mean rotation of the inner drum. Because both PVC and polyethylene are fairly un-textured materials with smooth finishes, press-fitting the axel into the inner drum and relying on friction would not be enough to facilitate rotation. Thus, a connecting plate was needed to prevent the PVC from slipping upon contact with the inner drum. As shown in Figure 32, the laser-cut Delrin endplate featured through-holes to accommodate four screws, which were tapped into the inner drum below. A slot—allowing room for the PVC axel and just enough room for a screw and nut—was centrally placed to ensure proper inner drum spinning; the basic idea being that as the PVC spins, the screw would catch the side of the slot and rotate the inner drum along with it.

Figure 32: No-slip end caps
Just as it was crucial to prevent rotational slipping between the PVC axel and the inner drum, so too was it necessary to prevent lateral slipping between the PVC and the outer drum. Because the inner drum was designed to rotate while the outer drum remains stationary, the PVC, and thereby inner drum, were vulnerable to lateral displacement. To inhibit this movement, tight, under-sized O-rings were placed on either side of the two bearings. Because O-rings rely only on compression to hold position, they could be easily removed as repairs were made and axel alignment perfected.

![Figure 32: O-rings prevent lateral slip](image)

### 7.2 Leaking

Preventing leaking was an essential aspect of the project, as no water should go to waste aboard the International Space Station, considering it runs on a closed-loop water system. The two areas most vulnerable to leaking were the outer drum’s clothing door and its detachable lid. To prevent leakage around the terrestrial prototype’s clothing door, the opening was cut with a precision Dremel to ensure a tight fit upon closing. A rubber trim
and wiper set—traditionally used to weatherproof doors—was applied to the perimeter of the opening to prevent further spillage. The clothing door was also placed at the top of the terrestrial prototype’s outer drum to make use of gravity.

Because the outer casing was originally a 15-gallon open-lid plastic drum, leakage from the side of the drum was a concern. Although the drum did come with a foam O-ring to maintain a seal, the drumhead was not precision cut so featured gaps upon resealing. Because of this manufacturing flaw (it was found in 3 of the drums ordered), the outer lid had to be permanently sealed using a Silicone-sealant. Although this was not the cleanest means to prevent leaking, it was discovered that this is also the way astronauts seal air and water aboard the ISS [29].

Figure 33: Rubber trim around door’s perimeter
7.3 Terrestrial Prototype

Upon correction of the slipping, alignment, and leaking, the terrestrial prototype was assembled.

<table>
<thead>
<tr>
<th>Key Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <em>Structural support</em>: welded steel</td>
</tr>
<tr>
<td>2. <em>Outer Drum</em>: Watertight and sealed, hinged to facilitate reentry</td>
</tr>
<tr>
<td>3. <em>Inner Drum</em>: Perforated with side-running baffles</td>
</tr>
<tr>
<td>4. <em>Basket</em>: Cups the outer drum for support, removable for storage</td>
</tr>
<tr>
<td>5. <em>Drivetrain</em>: pedaling rotates PVC axel, spins inner drum</td>
</tr>
<tr>
<td>6. <em>Plumbing</em>: PVC open-loop</td>
</tr>
<tr>
<td>7. <em>Seat</em>: refurbished bike system</td>
</tr>
</tbody>
</table>

Figure 34: Final terrestrial prototype
8 Testing & Analysis

Testing the prototype involved physically riding the bicycle to drive the inner drum, collecting water samples for CFU levels, comparing bacterial levels with and without detergent, and ensuring that the mechanical quality of the machine was intact. Thus, the hard data coming from the tests were very dependent on procedures typically conducted in environmental and biological settings. Even so, a clean water sample, albeit a biological result, would very much imply a successful mechanical result, as mechanical agitation was needed to reduce bacterial levels. As for the microgravity aspect of the project, computer simulations that imitated an inner drum in space were undertaken; the latter tests were necessary, as they proved that mechanical agitation could occur in space, just as it does on Earth.

8.1 Process for Terrestrial Prototype Use

In order to properly run the tests, familiarity with the machine was essential. Thus, a step-by-step protocol for use was developed:

1) Unlatch the lock of the outer drum and Velcro hatch of the inner drum to place two sets of laundry within the inner drum. If laundry mass exceeds design specification and limited water use is desired, use Equation 5 to calculate volume needed for proper cleaning.

2) Pour in the pre-determined set of water and detergent for the desired load.

3) Close both doors of the drum unit: for the inner drum, fasten the Velcro strips together. For the outer drum, secure the hatch in place.

4) Climb onto the exercise bike, grip the handlebars from behind for stability, and spin
the pedals. To properly clean clothing, pedal for at least 30 minutes. To achieve both exercise and wash, pedal between 30 and 120 minutes.

5) At end of regime, climb down from the bike and turn the valve counterclockwise to evacuate dirtied water.

6) Remove clothing from the drum, rinse in clean water, and air-dry.

Figure 35: Step-by-step process to use terrestrial prototype
8.2 Terrestrial Prototype: Testing & Results

To determine whether clothing was being washed according to ISS standards, CFU levels on clothing samples were tested in two different ways. The first test involved running the machine with water, detergent, and baffle agitators, while the second test forwent the detergent to characterize the mechanical agitating abilities of the clothing.

In both tests, three different clothing samples were used: clean clothing, muddy clothing, and exercise clothing. The clean clothing was used as a control to insure the water was relatively decontaminated; that is, that the water was not introducing bacteria or colony-forming units (CFUs), as this would have invalidated the results. Muddy clothing was selected for the tests, as such samples could show that visible cleaning does not necessarily imply cleaning on a microbiological level. Considering washing exercise clothing was the objective of the CEVIS-laundry machine, such articles were included in all tests conducted by the terrestrial prototype.

Procedure

The basic procedure to quantify the prototype’s cleaning abilities is as follows:

1. Place two loads of laundry in cold tap water within a disinfected tub. Allow the clothing to soak by gently moving the articles throughout.
2. Take a 100 mL sample of the fouled water to provide a pre-wash bacterial baseline.
3. If running a chemically assisted test, pour detergent into the tub and close the machine’s doors. If running a mechanical agitation-only test, ignore.
4. Ride the bicycle for 30-120 minutes to properly agitate the clothing.
5. Evacuate the dirty water from the tub by opening the valve.
6. Remove the clothing from the tub, and transfer it into another disinfected tub.
7. Rinse the clothing by filling the tub with clean water and ringing out the articles.

8. Transfer the clothing to a third disinfected tub, and fill with water.

9. Take a 100 mL sample to provide a post-wash bacterial sample.

10. Run the Colilert Coliform Bacterial Test:
    a. Add provided dye packet to both the pre- and post-wash 100 mL sample, and mix thoroughly.
    b. Pour each water-dye mixture into the provided packages.
    c. Place package in the QuantiTray Sealer to seal the package.
    d. Incubate the package at 35°C—temperature needed for bacterial growth.

11. Allow the packages to sit for 24 hours until removing.

12. Count the number of small and large wells stained a bright yellow color—these pertain to the CFU-positive areas.

13. Use the Test’s provided data sheet and equation to determine the Most Probable Number (MPN) of colony-forming units within the sample.

14. Repeat the process for the three different samples, using the two previously mentioned testing conditions.

Figure 36: Colilert Coliform Testing materials

(a): Testing dye [44]  
(b): QuantiTray Sealer [5]
Results

Chemical-Assisted Test

The side-by-side images in Figure 37 illustrate the workout and muddy clothing, respectively, pre- and post-wash. As previously mentioned, the highlighter yellow wells indicated high bacterial levels, where the most probable number of CFUs (colony-forming units) could be found according to a pre-determined equation. As is apparent in both the table and images, the post-wash samples of both the workout and muddy samples contain virtually no colony-forming units. This could be due to either the detergent’s chemicals or the baffles’ agitation; it could also be the result of a combined effort of both.

<table>
<thead>
<tr>
<th></th>
<th>Pre-sample count (CFU) / mL</th>
<th>Post-sample count (CFU) / mL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Workout clothing</strong></td>
<td>360.9</td>
<td>0</td>
</tr>
<tr>
<td><strong>Muddy clothing</strong></td>
<td>8.5</td>
<td>0</td>
</tr>
</tbody>
</table>

(a): CFU count

(b): Workout sample, pre and post

(c): Muddy sample, pre and post

Figure 37: Chemical-assisted CFU data
**Mechanical-Only Test**

Although the positive result of the chemical-assisted test proved that the clothing was in fact being agitated, it did not convey any information on the baffles’ role in the cleaning. Thus, a purely mechanical test—one making use of the baffles and the water’s sloshing—was run on the aforementioned clothing samples.

It was expected that the mechanical agitation of the clothing by the baffles would at least clean the laundry on a superficial level. That is, the mechanical action would eliminate a number of the stains, particularly on the muddy articles. This hypothesis did prove correct, as multiple muddy samples were free of stains by the end of the test.

![Figure 38: Visual effect of mechanical wash on muddy clothing](image)

Besides cleaning the clothes on a material level, the mechanical agitation incited by the baffles also aided in bacterial removal, as shown in the samples of Figure 39. Although CFU levels decreased quite substantially in both the muddy and exercise clothing tests, a disparity did exist between the two sample types. The exercise wash saw a CFU count
A reduction of 40%, whereas the muddy wash experienced a reduction of 99.9%. This was a curious result that could imply that anthropogenic bacterial counts are more likely to subside under the influence of chemical reagents. Either way, a sizable reduction in CFU levels was induced by mechanical agitation alone. This was an extremely powerful result of the tests, as it indicated that mechanical agitation—if further optimized—may be sufficient in killing off bacteria both on Earth and in space.

<table>
<thead>
<tr>
<th></th>
<th>Pre-sample count (CFU) / mL</th>
<th>Post-sample count (CFU) / mL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Workout clothing</strong></td>
<td>45.7</td>
<td>27.9</td>
</tr>
<tr>
<td><strong>Muddy clothing</strong></td>
<td>2420</td>
<td>3</td>
</tr>
</tbody>
</table>

(a): CFU count

(b): Workout sample, pre and post

(c): Muddy sample, pre and post

Figure 39: Mechanical-assisted CFU data
8.3 Microgravity Simulation: Testing & Results

Background

One essential component of the project was to prove that an added agitator, regardless of its geometrical complexity, would add energy to the drum, agitate the clothing, and prevent articles from riding the wall in microgravity. Using the program LAMMPS—a molecular dynamics simulator—a simulation was developed to study objects’ movement in a drum under a microgravity condition.

The simulation relied heavily on Dr. Chris Rycroft’s previous work, which he developed to study molecular interaction both on Earth and in space. As shown in Figure 40’s frames, eight articles of clothing, shown here as blue balls, fall into the bucket in a gravity-governed environment. The clock-wise progression from the left-most frame illustrates the balls falling into the drum, bouncing off the bottom, and finally settling towards the ground.

Figure 40: Simulating clothing movement under the influence of gravity
Parameters and Code Adjustments

Dimensionless parameters characterized the script, input file, and simulation of the microgravity drum. Thus, converting from dimensionless parameters into parameters of physical value was a priority. The results of this conversion are summarized in Figure 41.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Simulation Value</th>
<th>Physical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (d)</td>
<td>Length</td>
<td>1</td>
<td>2 inches</td>
</tr>
<tr>
<td>Mass (m)</td>
<td>Mass of wet clothing</td>
<td>1</td>
<td>1 lb.</td>
</tr>
<tr>
<td>Time (T)</td>
<td>Time of movement</td>
<td>1</td>
<td>0.07 seconds</td>
</tr>
<tr>
<td>Omega (ω)</td>
<td>Rotation of agitator</td>
<td>0.22</td>
<td>30 RPM</td>
</tr>
</tbody>
</table>

Figure 41: Simulation parameters

The length and mass parameters were assigned hard values prior to the simulation, whereas time and omega were determined numerically. Time was found through a relation between length (d) and gravity (g):

\[
T = \sqrt{\frac{d}{g}}
\]

(18)

\[
T = 0.07 \text{ s} = \sqrt{\frac{2}{386.1 \ \frac{\text{inches}}{\text{inches/s}^2}}}
\]
Thus, 1 unit of simulation time corresponded to a physical time of 0.07 seconds. As for the agitator’s rotation rate, omega’s physical value was known, as it was the machine’s lower RPM specification, but the simulation value was unknown and had to be derived. First, a conversion from RPM to radians per seconds was necessary, followed by a conversion from a physical, dimensioned value to a dimensionless simulation parameter.

\[
\omega = RPM \times \frac{2\pi \text{ rad}}{\text{rev}}
\]

\[
\omega = 3.14 \frac{\text{rad}}{s} = \frac{30 \text{ [rev]}}{1 \text{ [min]}} \times \frac{2\pi \text{ [rad]}}{1 \text{ [rev]}} \times \frac{1 \text{ [min]}}{60 \text{ [s]}}
\]

\[
\omega \times T = 0.22 = 3.14 \frac{\text{rad}}{s} \times 0.07 \text{ s}
\]

Once the parameters were set in both dimensionless, simulation terms and physical terms, modifications to the code were made. Essentially, the agitator was included in the model by adding code that was interpreted as a spinning central boundary wall (see Appendix B). The agitator simulated was extremely simple, as the goal was to see whether complicated geometry made the difference in rotating clothing in microgravity.

**Results**

The results of the code could be analyzed visually by observing the agitator’s effect in a Perl-based frame, or they could be interpreted analytically through a study of the code’s kinetic energy outputs. Essentially, if the kinetic energy of the system continued to increase, it was assumed that the particles themselves were indeed moving, thereby being agitated. Because the kinetic energy output was unitless, it first had to be dimensioned by
using the previously defined parameters. *Note: the units were converted to metric standard for simplicity's sake:* 

\[ KE [J] = (KE\text{ unitless}) \cdot mgd = [kg]\left[m\right]\left[m\right] \]  

(20)

For instance, for a kinetic energy output of 0.14, the associated dimensioned kinetic energy of the system would be:

\[ KE = 0.03 J = (0.14)(0.45 \text{ kg})\left(\frac{9.8 \text{ m}}{1 \text{ s}^2}\right)(0.05 \text{ m}) \]

To determine the average particle velocity associated with this energy, the kinetic energy equation was employed, with the magnitude of the energy multiplied by a factor of 1/8 to account for the 8 different particles:

\[ v = \sqrt{\frac{2KE}{8m}} \]  

(21)

\[ v = 0.13 \frac{m}{s} = \sqrt{\frac{2(0.03 J)}{(8)(0.45 \text{ kg})}} \]

Velocities, both above and below this discrete point, were found throughout the output file. Further, the velocities were constantly changing. That is, there was no linear increase or decrease, as expected due to the chaotic nature of the agitated system. Thus, it could be
conclusively said that the articles of the clothing were indeed agitated upon installing a simple rectangular agitator.

In addition to the quantitative outcome, the qualitative results proved useful in visualizing the agitator’s effectiveness and determining particular locations of the articles as the agitator rotated about its axis. In Figure 42, the progression of the agitation moves left-to-right starting at the left-most top drum. It is evident that the articles begin at the bottom of the drum and do not begin to move until the agitator begins its rotation.

Figure 42: Simulation demonstrating microgravity agitation
The agitator’s setup—both the physical built and the rotational attributes—are described in Appendix B.
9 Design Evaluation

<table>
<thead>
<tr>
<th>Design Goal</th>
<th>Variable</th>
<th>Target</th>
<th>Realized Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Reduce mass, space, and water</td>
<td>Unit size</td>
<td>&lt; 4 ft x 2 ft</td>
<td>2.3 ft x 1.2 ft</td>
</tr>
<tr>
<td></td>
<td>Load Size</td>
<td>2 sets of shorts, T-shirts, socks, underwear</td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td>Total volume of water needed</td>
<td>&lt; 5 L</td>
<td>4.5 L</td>
</tr>
<tr>
<td>(2) Simultaneous washing and exercising</td>
<td>Time</td>
<td>30-90 minutes</td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td>Speed (RPM)</td>
<td>30-120 RPM</td>
<td>40-100 RPM</td>
</tr>
<tr>
<td></td>
<td>Power Requirements</td>
<td>25-350 W (instantaneous)</td>
<td>~ 250 W</td>
</tr>
<tr>
<td>(3) Mechanically-agitate</td>
<td>On Earth: fill level, perforations, inner drum dimensions, etc.</td>
<td>Reduction in CFU without detergent</td>
<td>Met</td>
</tr>
<tr>
<td></td>
<td>On ISS: no riding the wall</td>
<td>Simulation demonstrates particle moves</td>
<td>Met</td>
</tr>
<tr>
<td>(4) Clean clothing</td>
<td>CFU count</td>
<td>50-100 CFU / mL</td>
<td>0 - 30 CFU / mL</td>
</tr>
</tbody>
</table>

Once the terrestrial prototype was constructed and tested and the microgravity simulation complete, the realized specifications were compared with the intended target specifications. Despite some improvements that could be made moving into the parabolic-flight testing stage, the proof-of-concept machine did succeed in meeting the original design specifications.

The washing unit itself turned out to be quite compact due largely to the removable PVC basket support. Despite its relatively small capacity, the inner drum successfully cleaned two loads of laundry using only 4.5 L of water. To determine the cap on the washing unit's load capacity, several runs were taken while incrementally increasing the loads. The drum
could physically handle four sets of active wear, although the CFU tests were not conducted during this time so its ability to clean larger loads is still in question.

The goal of washing clothing while exercising was met, as an iPhone cadence sensor tracked the machine’s RPM as the user pedaled at varying speeds. The output power \( P \) was determined by multiplying the bicycle’s torque \( \tau \) and RPM:

\[
P = 247 \, W = \tau \times \omega
\]

where the torque was found to be:

\[
\tau = F_g \times \text{pedal crank}
\]

\[
\tau = 82.32 \, N \cdot m = \left( 60 \, kg \times 9.8 \, \frac{m}{s^2} \right) \times 0.14 \, m
\]

The calculated power output was quite high, as it assumed that the user was standing up and bearing his entire weight on the pedal crank. In reality, this power output will be lower but still within the target range.

The clothing was successfully agitated in the terrestrial machine, as well as in microgravity via the computer simulation. Mechanical agitation alone induced reductions in CFU levels during terrestrial tests, which was a promising result.

As for the CFU levels of the different clothing samples, a range existed between 0-30 CFU/mL—a level well below the ISS CFU specification.
10 Conclusion

The ultimate goal of the project was to design and construct a bike-powered laundry machine that could be tested on Earth for validity and simulated in a microgravity environment to facilitate future use. The underlying objective—rooted both in the terrestrial prototype and the microgravity simulation—was to prove that mechanical agitation alone may be sufficient in inducing proper cleaning of clothing. By the end of the project, the final product did just that.

Mechanical agitation alone removed fiber stains and also reduced colony-forming units on articles of clothing; in fact, the force applied to the clothes was so powerful that CFU levels fell below the specified target. By simulating eight pieces of clothing in a microgravity environment, the notion that complex, expensive machinery was needed to agitate clothing in space was invalidated. The outcome of the simulation proved that nearly any agitation would suffice in cleaning clothing, as any agitator geometry would introduce additional energy and disturbance into the drum.

Moving forward, additional fluid dynamics models should be examined in order to explore water’s behavior in space. Before transitioning to the parabolic flight stage, two design modifications are necessary: first, an entirely closed-loop water system should be installed, and second, a more compact, lightweight structural foundation should be created. An undergraduate team from MIT’s AeroAstro department has expressed interest in taking on this task.

The successful implementation of a terrestrial bike-powered laundry machine, coupled with an illuminating microgravity simulation, indicated that astronauts might soon be able to clean their clothing aboard the International Space Station.
11 Acknowledgements

First and foremost, I would like to thank Sydney Do for allowing me to take on this proposed project. It has always been a dream of mine to engineer for the International Space Station, and this project really gave me a taste of that. His patience and insight were absolutely crucial in this project and are both deeply appreciated.

I would like to thank the Harvard SEAS Undergraduate Teaching Lab, namely Jordan Stephens, Elaine Kristant, Sara Hamel, Joe Huggard, and Andreas Haggerty. I can honestly say I would not have been able to complete this project without them. From Jordan’s unwavering, sage advice to Sara’s dedication and patience, the attributes of this team are truly innumerable. Aside from aiding on a technical and intellectual level, the team also helped on a personal level by encouraging me every step of the way.

I would like to thank Chris Rycroft and Katia Bertoldi for their insights into an exceedingly difficult component of the project: microgravity. Without Prof. Bertoldi’s vision and recommendations, the solution to simulate microgravity with Chris would never have been realized. Chris Rycroft exhibited so much patience, genuine interest, and technical expertise throughout the simulation process. His willingness to sit through countless meetings explaining both code and theory proved his ability and dedication.

I would like to thank Chris Lombardo for his steadfast patience and insight. I cannot count the number of emails or impromptu meetings that occurred with Chris throughout this past year. He has truly been an enduring mentor and friend throughout my time as a Mechanical Engineering major, and I could not appreciate him more.

Lastly, I would like to thank my friends and family who supported me along this journey. I truly would not be where I am today without all of your love and support. Your faith means the world to me. In particular, I want to thank my late grandfather, NASA engineer Jack Peddicord, for inspiring me to pursue my dreams and shoot for the stars.
12 References


   <https://www.nasa.gov/vision/space/travelinginspace/radiation_shielding.html>.


   <http://spaceflight.nasa.gov/living/spacewear/>.


   <http://viking.coe.uh.edu/~gkitmacher/_content/humans/humanfactors.pdf>.


Appendices

A. MATLAB Code

Fill Level and Volume

% Geometric dimensions of drum, for fill level
R_d = 0.13081; % radius of drum (m)
K_h = linspace(0.1,0.8,10); % water level coefficient (standard)
h_w = 2*R_d*K_h; % acceptable fill levels (m)
I = 0.3556; % length of drum (m)
m = R_d - h_w; % distance between center to fill (m)
theta = 2*acos(m/R_d); % angle of fill to radius (rad)
V_fill = 0.5*R_d.^2*(theta-sin(theta))*I; % volume of fill, as per calc. (m3)
V_fill_gal = V_fill*264.17; % volume of fill (gal)

Inner Drum Perforations

% Number of perforations
K_p = theta./(2*pi) + 1/pi*sin(theta/2) - (2*sqrt((2*R_d*h_w)-h_w.^2))/(pi*R_d) % ratio of drum perforations
p = R_d.*theta % arclength of fill
syms N_p N
[solN_p,solN] = solve(N_p == N./(pi*2*R_d*I), N_p == (N*K_p)/(p*I))
Impact Velocity of Unbalanced Load

% General constants
RPM = [30 40 50 60 70 80 90 100 110 120]; % acceptable RPM speeds

% RPM
R_d = 0.13081; % radius of drum (m)

% g = 9.8; % (m/s)

% h_w = 0.0669; % acceptable fill levels (m)

% R_p = 0.05; % radius of clothing (m)

% Initial dynamic parameters

% Initial rotational velocity of the drum (rad/s)
w_d = (pi.*RPM)./30;

% Initial tangential velocity of clothing (m/s)

% Initial slip angle of clothing from F_c (radians)
theta = (asin((v_t.^2)/(R_p*g)));

% Initial heights at which slip occurs

% Initial tan. velocity in y-direction

% Initial tan. velocity in the x-direction

% Parabolic movement

% % from slip point to max height

% % from slip to max

t2 = sqrt(d./g); % time to fall from top (s)

% Total travel time

v_yimp = g.*t2 % y-component of impact v

v_imp = sqrt(v_yimp.^2 + v_0x.^2)

scatter(RPM, V_imp)
B. LAMMPS & C++ Code

The following snippet was the main section modified in Chris Rycroft's granular particle code directory, *gran*. This simulation relied on a number of his scripts, input files, etc., so only the code that was substantially adapted for the drum simulation is included.

**Within fix_wall_gran.cpp**

*Adding agitator to wallstyle argument*

```cpp
} else if (strcmp(arg[iarg],"agit") == 0) {
  if (narg < iarg+7) error->all(FLERR,"Illegal fix wall/gran command");
  wallstyle = AGIT;
  lo = force->numeric(FLERR,arg[iarg+1]); // Lower z coordinate of agitator
  hi = force->numeric(FLERR,arg[iarg+2]); // Higher z coordinate of agitator
  wc0 = force->numeric(FLERR,arg[iarg+3]); // Width of agitator
  wc1 = force->numeric(FLERR,arg[iarg+4]); // Depth of agitator
  wc2 = force->numeric(FLERR,arg[iarg+5]); // Angular velocity of agitator
  wc3 = force->numeric(FLERR,arg[iarg+6]); // Initial displacement angle of agitator
  iarg += 7;
}

*Adding rotation to the agitator via minimal vectors*

else if (wallstyle == AGIT) {
  // Rotate coordinates into the frame of the agitator
  double theta=wc2*(update->ntimestep - time_origin) * dt+wc3;
  double cth=cos(theta),sth=sin(theta);
  double rotx=x[i][0]*cth+x[i][1]*sth,
         roty=-x[i][0]*sth+x[i][1]*cth,rdx,rdy;
  // Compute minimal vector in the frame of the agitator
  if (lo > x[i][2]) {dz = x[i][2]-lo;}
```
else if (hi < x[i][2]) {dz = x[i][2] - hi;}
else dz = 0;
if(rotx>wc0) {rdx=rotx-wc0;}
else if(rotx<-wc0) {rdx=0;}
else rdx=rotx+wc0;
if(roty>wc1) {rdy=roty-wc1;}
else if(roty<-wc1) {rdy = 0;}
else {rdy=roty+wc1;}
// Rotate minimal vector back into regular coordinates
dx=rdx*cth-rdy*sth;
dy=rdx*sth+rdy*cth;
// Compute velocity of wall at point of contact
vwall[0]=wc2*(x[i][1]-dy);
vwall[1]=-wc2*(x[i][0]-dx);
// printf("%g %g %g %g\n",lo,hi,wc0,wc1);
// printf("%g %g %g / %g %g %g\n",x[i][0],x[i][1],x[i][2],dx,dy,dz);
}

**Within Input File**

*Dimensioning the agitator for simulation*

Zlo = 3
Zhi = 6
|x| < 1.25
|y| < 0.05
omega = 0.3
## C. Bill of Materials & Budget

<table>
<thead>
<tr>
<th>Component (quantity)</th>
<th>Supplier</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 5-gallon plastic buckets</td>
<td>Home Depot</td>
<td>$2.97</td>
</tr>
<tr>
<td>(1) Leak-proof bucket lid</td>
<td>Home Depot</td>
<td>$1.68</td>
</tr>
<tr>
<td>(2) 1&quot; x 2ft PVC pipes</td>
<td>Home Depot</td>
<td>$3.94</td>
</tr>
<tr>
<td>(1) 0.5&quot; x 5 ft PVC pipes</td>
<td>Home Depot</td>
<td>$2.12</td>
</tr>
<tr>
<td>(3) 0.5&quot; PVC endcap</td>
<td>Home Depot</td>
<td>$1.00</td>
</tr>
<tr>
<td>(1) 5-gallon Inner drum</td>
<td>Home Depot</td>
<td>$4.47</td>
</tr>
<tr>
<td>(1) 5-gallon bucket lid</td>
<td>Home Depot</td>
<td>$7.25</td>
</tr>
<tr>
<td>(3) 15-gallon Outer drum</td>
<td>McMaster</td>
<td>$123.00</td>
</tr>
<tr>
<td>(3) Agitating baffles</td>
<td>McMaster</td>
<td>$17.88</td>
</tr>
<tr>
<td>Sanitation test supplies/instrumentation</td>
<td>Harvard Teaching Labs</td>
<td>$0</td>
</tr>
<tr>
<td>Sample clothing</td>
<td>Self</td>
<td>$0</td>
</tr>
<tr>
<td>Valve</td>
<td>Dickson Bros.</td>
<td>$10.00</td>
</tr>
<tr>
<td>(1) Bicycle</td>
<td>Craigslist</td>
<td>$40</td>
</tr>
<tr>
<td>(2) Bearings</td>
<td>McMaster</td>
<td>$64</td>
</tr>
<tr>
<td>Structural support, hardware, hinges, etc.</td>
<td>Harvard Teaching Labs</td>
<td>$0</td>
</tr>
<tr>
<td>Custom linkages, end-caps, etc.</td>
<td>Harvard Teaching Labs</td>
<td>$0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$278</strong></td>
<td></td>
</tr>
</tbody>
</table>