# Design Report: The One Way to Vending Machine Accessibility

Word Count: 2994

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# 1. Introduction

This report recommends a viable design to improve the ease of product retrieval from the Sanford Fleming (SF) vending machine near room 1101. The recommended design was selected after iterations of diverging, converging, and testing. The original vending machine is outdated with a difficult to open flap, making product retrieval strenuous and inconvenient. This affects various stakeholders, particularly engineering students who frequent SF. Replacing the current retrieval flap with a new similar one is a short term solution, as it is bound to wear down again. Candidates for improvement of the current design were created and tested to converge to a final recommendation for long term improvement. Of these designs, the primary recommendation is the implementation of a new chute style opening on the bottom of the vending machine. This document will detail further background to this opportunity, the stakeholders, the requirements framework, 4 candidate solutions, the final recommendation, and the verification, comparison, and testing process to justify this recommendation.

# 2. Background

This section discusses the opportunity, needs of affected stakeholders, and NGO's, requirements, and evaluation criteria governing the design process.

## 2.1 Opportunity: Snack out of reach

After discovering a high degree of difficulty getting a quick snack, the opportunity of improving the ease of product retrieval by modifying or adding to the dispenser bin assembly of the original SF vending machine was developed. Its importance can be found in the original design brief [1, Appendix A]. The scope is limited to this vending machine, and altering **only the retrieval process**, not dispensing features. The framing focuses on improving the ergonomics involved in the process of grabbing the product, thus prioritising force and difficulty of hand motion over the ergonomics in bending down and the retrieval height.

## 2.2 Stakeholders:

This subsection discusses various groups impacted by this opportunity, whose interests must be considered in the design process for a viable solution, as demonstrated in table 1.

*Table 1: Stakeholders, how they are impacted, and their interests in the project - in order of priority.*

| Stakeholder | How Stakeholder is Impacted | Stakeholder Interest |
|---|---|---|
| Primary Stakeholders: Directly use, interact with, or are most affected by the splartz. | | |
| Able Bodied Engineering Students (including design team). | Rely on this vending machine for quick sustenance between classes, especially since it is the only nearby food provider. | Desire a solution that is easy to use, ergonomic, and allows for quick product retrieval. |
| University Staff | Staff also use the machine at various points. | |
| Visitors. | Visitors to Sandford Fleming may attempt to use this machine and be discouraged during the retrieval process. | |
| Secondary Stakeholders: Directly support, regulate, or influence how the design is used/maintained | | |
| Safety Regulators. | Ensure that designs comply with standards and operating protocols. | Desire a solution that meets relevant accessibility standards, codes, protocols, and ensures safe operation. |
| Maintenance and Custodial Staff. | A poorly designed vending machine will complicate tasks such as servicing the machine and expedite wearing. | Desire a solution that is durable, easy to maintain, and simple to repair. |
| Tertiary Stakeholders: Groups who are indirectly impacted by the operations of the design. | | |
| University Facility | Rely on consistent operation to generate revenue. Do not want to replace the machine and efforts to redesign will cost money and time. | Desire a solution that is implementable, long-term, avoids full machine replacement, and maintains revenue. |

*Note: Users with physical disabilities were considered, but not prioritized as a stakeholder due to the inherent inaccessibility of the working environment/machine location and the limitation of scopes in this course.*

## 2.3 NGO's, Requirements, Evaluation Criteria:

This subsection discusses the need, goals, objectives that create the design space based on stakeholder needs. Their corresponding requirements and evaluation criteria that govern the viability of solutions are also stated. The need is **improving the ease of product retrieval by altering the dispenser bin assembly [**2, Appendix A**] of the original SF first floor snack vending machine.**

Tables 2, 3, and 4 describe requirements (R), and evaluation criteria (EC) that support design goals (G), corresponding objectives are in Appendix B. Prioritized requirements are outlined in red. The more a solution meets each EC, the better. Justification and metrics for EC's in Appendix C. Unspecified citations in Source Extracts

*Table 2: Goal 1 - Reduce the effort needed for product retrieval, desired by primary stakeholders.*

| **Requirements** | **Evaluation Criteria** |
|---|---|
| R110: Force exerted throughout the complete retrieval process shall not exceed 22N.<br><br>In compliance with [1], the force exerted to operate self service devices cannot exceed 22N. | EC111: Less force required to retrieve the snack.<br><br>EC112: Shorter duration retrieval process. |
| R120: Wrist movement required during retrieval shall not exceed 10° flexion and 35° extension and reach distance shall not exceed 170mm.<br><br>In compliance with wrist movement needed to complete normal daily tasks [2], necessary operation should be between 10° flexion and 35° extension. In compliance with [3], reach distance should be accessible to average adults [4] with forearm reach distance of 170mm. | EC121: Smaller the reach depth.<br><br>EC122: Less wrist extension and flexion needed to reach the entire depth. |
| R130: Products of size 180x100x94 mm shall fit through the opening of the product retrieval bin with ease and without causing damage to the product packaging or its contents.<br><br>The largest product available measures 180x100x50mm [1, Appendix G], with the inclusion of hand dimensions while holding is accounted for with anthropometric data [5][2, Appendix G], expanding minimum to 180x100x94mm. | EC131: Less compression or tension the product has to undergo. |

*Table 3: Goal 2 - Adjust the product retrieval height of the vending machine, desired by primary stakeholders.*

| Requirements | Evaluation Criteria |
|---|---|
| R210: Purchased products shall be between 211mm and 1200mm above the ground.<br><br>Limits retrieval height of product to maximum from [6] and minimum such that it is improved from measured null height of 211mm. | EC211: Closer retrieval height is to 900mm from ground. |
| R220: Purchased products shall be retrieved with a reach distance not exceeding 255 mm if there is an obstruction.<br><br>In compliance with [7] so there are minimal additional distances beyond height in retrieval. | EC221: Less obstruction. |

*Table 4: Goal 3 - Preserve the integrity of the existing vending machine, desired by secondary and tertiary stakeholders.*

| Requirements | Evaluation Criteria |
|---|---|
| R310: The machine as a whole must continue to effectively operate and remain compliant with the 1 accessibility standards and 2 operating protocols.<br><br>According to the manual [8], the machine complies with US ADA standards [9] and runs a multi-drop-bus protocol [8, Bibliography] and the data exchange protocol [9, Bibliography]. The overall function of the machine must also be retained. | EC311: Allowing the machine to reach additional standards. |
| | EC312: Less major alterations to the machine. |
| | EC313: Less failure cases and easier retrieval during failure. |
| R320: An anti-pilfer system shall be implemented such that no objects with a diameter larger than 12mm and length of 328mm may enter the storage area of the machine to dislodge a product during retrieval.<br>In compliance with the global enclosure standard within the electrical industry [10], it should rank a 2 in the enclosure IP ratings preventing objects of 12mm diameter from "fishing" unpurchased products. The length of 328mm comes from primary research [3, Appendix G]. | EC321: Prevention of foreign objects that are smaller. |
| | EC322: Greater effectiveness against aggressive forces. |

Considering the opportunity and stakeholders, we converged to three top requirements:

1. **R110:** The scope has a primary focus on the excessive force required during product retrieval, which relates to our primary stakeholder needs.

2. **R120:** The scope focuses on improving ergonomics by avoiding discomfort experienced from excessive wrist flexion or extension during product retrieval, tying into primary stakeholders needs.

3. **R320:** The integrity of the vending machine must be preserved to meet secondary and tertiary stakeholder needs. Therefore, preserving the anti-pilfer system is a key aspect to prevent theft or damage. From these requirements, the four most important evaluation criteria were chosen, and are referenced as metrics in Section 4.

We developed our top four priority requirements:

1. **EC111:** The scope of this opportunity is centered around retrieval ease for users, primarily from excessive force exertion.

2. **EC112:** A longer product retrieval process means more effort required from users to retrieve products.

3. **EC122:** Requiring the user to overtly extend or flex their wrists to retrieve products causes discomfort.

4. **EC321:** Effectiveness of the vending machine's anti-pilfer mechanism is dependent upon the possibility of objects bypassing the anti-pilfer system.

# 3. Solutions

With diverging and converging tools [Appendix D] over multiple cycles, we came up with 7 possible solutions [3, Appendix A]. This section discusses our top four candidates with their advantages and disadvantages.

## 3.1 Recommended Design: Snack Chute

A chute-style one way flap system is implemented, and the original flap is replaced by an open retrieval tray. The force of gravity allows the product to push down the flap and fall onto the tray. The spring-hinged flap is able to snap back to its closed position after the product passes through. A protruding ledge above the flap prevents its upwards motion, inspired by [1, Appendix E]. Users then retrieve products from the open retrieval tray. A sketch prototype [Figure 1] and video demonstration of a physical prototype depicts the design [12, Bibliography].

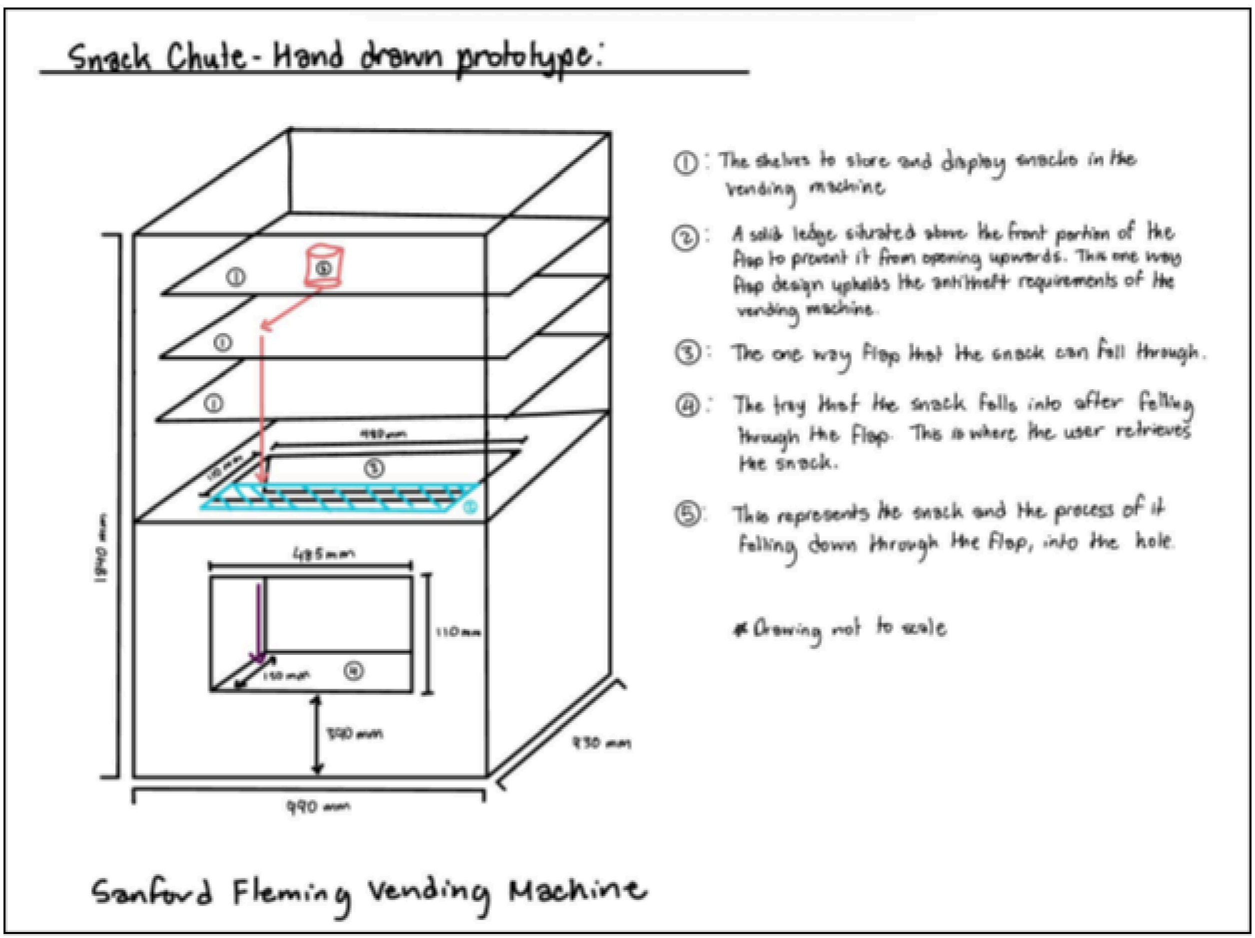



*Figure 1: Sketch prototype of Snack Chute.*

**Advantages:**

- No barrier between user and the product removes the need for excessive force exertion to reach products.
- Preserves the anti-pilfer functionality of the vending machine.
- Raises product retrieval height.

**Disadvantages:**

- Note: Both of the following disadvantages relate to the dispensing process, which falls outside the current scope, however are still worth considering for next steps
  - The process of the snack falling down through a flap may damage the contents of the snack
  - If the snack is not heavy enough, it may not fall through the flap.

**Key Design Decisions:**

*Table 5. Key design decisions of Snack Chute and their justifications.*

| **Decision** | **Justification** |
|---|---|
| Removal of the current flap and addition of a downward facing chute-style flap | - No obstruction between the user and the product:<br>    - Reduces product retrieval force to 0N. [3, Appendix F]<br>    - Shortens the duration of product retrieval [2, Appendix F].<br>    - Minimizes required wrist extension/flexion required for product retrieval [1, Appendix F].<br>- Opening size of the downwards flap is able to accommodate the largest product [Figure 1] |
| Ledge above hinged flap, restricting upwards motion from its parallel, neutral state, making it a one-way-flap | - Maintain anti-pilfer requirements with:<br>    - One-way flap, which prevents users from reaching the unpurchased products, proven through research. [4, Appendix F] |
| Hard carbon, hard-drawn torsion spring for hinged mechanism | - The hinge mechanism ensures the flap closes upon dispensing a snack to uphold anti-pilfer requirements.<br>- Hard carbon, hard-drawn torsion spring were deemed as optimal [2, Appendix E] |

## 3.2 Other Design Considerations

This subsection discusses other effective solutions used to compare with the recommended design.

### 3.2.1 Design 1: Snack Sack

The maximum opening angle is increased by reducing hinge friction with UHMW-PE bushings between the flap and the hinge pin. Inside the dispensing bin, an inclined-slope is attached to the inner wall, with a plastic pouch connecting the lower flap edge to the inclined slope; this forms a shallow "sack", so the final product location is closer to the opening, reducing reach distance and pushing flap force. A sketch prototype [Figure 2] depicts the design, reference designs used in development found [3, Appendix E].

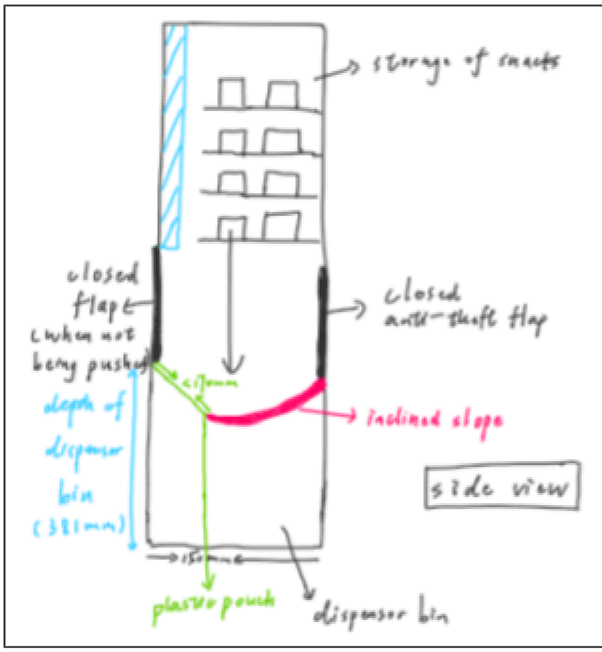



*Figure 2.1: Sketch Prototype of Snack Sack (closed)*

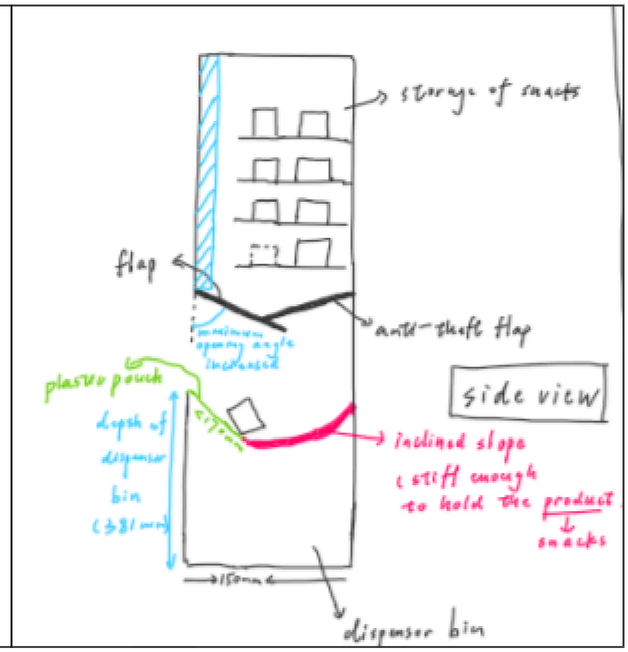



*Figure 2.2: Sketch Prototype of Snack Sack (open)*

**Advantages:**

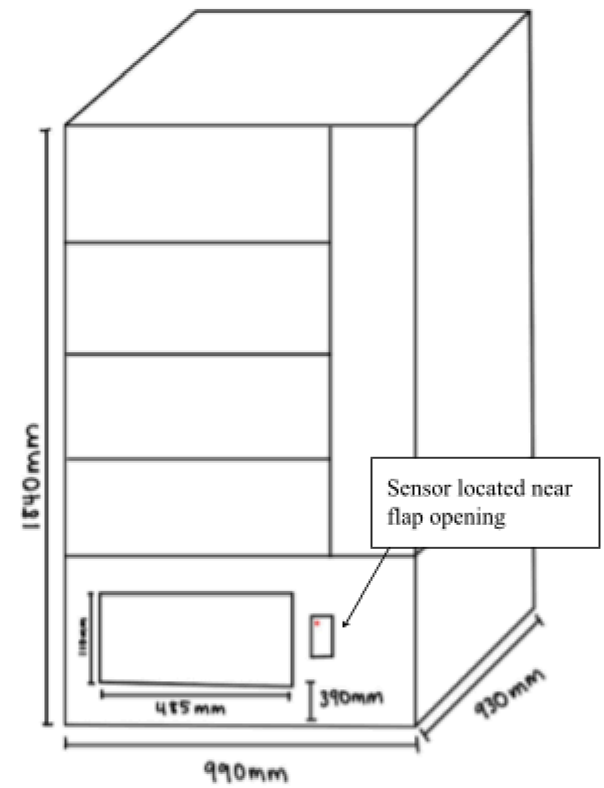
- Simple to implement since Snack Sack keeps the existing flap and cabinet geometry, only adding UHMW-PE bushings and an internal slope and pouch.
- Preserves anti-pilfer functionality of the vending machine.

**Disadvantages:**

- By maintaining the same geometries, there is:
    - Minimal increase in product retrieval height,
    - Minimal reduction in force required, and
    - Minimal reduction in hand ergonomics during retrieval.

### 3.2.2 Design 2: Wave n' Take

An angled-down, motion-operated sensor located adjacent to the flap door triggers after payment. When triggered, the sensor displays a green light for 7 seconds after product is dispensed, then the flap opens. It remains open for 45 seconds post-trigger, and blinks red light for the final 10 seconds for closure warning. The flap door gently closes. Depicted in Figure 3. Inspiring reference designs found [4, Appendix E] and calculations used in development found [4, Appendix G].



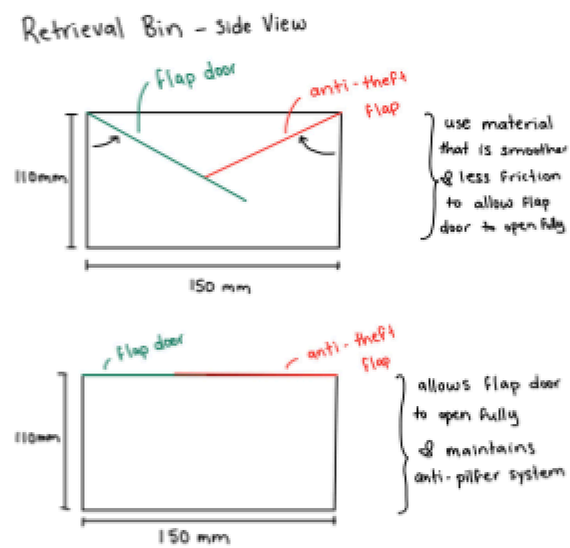




*Figure 3.1: Sketch Prototype of Wave n' Take* *Figure 3.2: Flap Door Mechanism of Wave n' Take*

**Advantages:**

- Significant force reduction in the retrieval process.
- Preverses anti-pilfer functionality of the vending machine.

**Disadvantages:**

- Requires significant alterations to the existing vending machine.
- Complicated installation and servicing process with additional electrical sensor components.
- Introduces several edge cases from automation.
  - May malfunction due to sensor misreads, motors failing, products obstructions, etc.

### 3.2.3 Design 3: Lift n' Pick

A vertical pull-up sliding opening mechanism is activated to reach the dispenser bin with the purchased product. The sliding door bends up to a horizontal position such that it blocks the unpurchased snacks, allowing for anti-pilfer functionality. The sliding feature has a ball-bearing-roller system, where the roller reduces force from friction between the walls and slider depicted in Figure 4. Inspiring reference designs found [5, Appendix E]

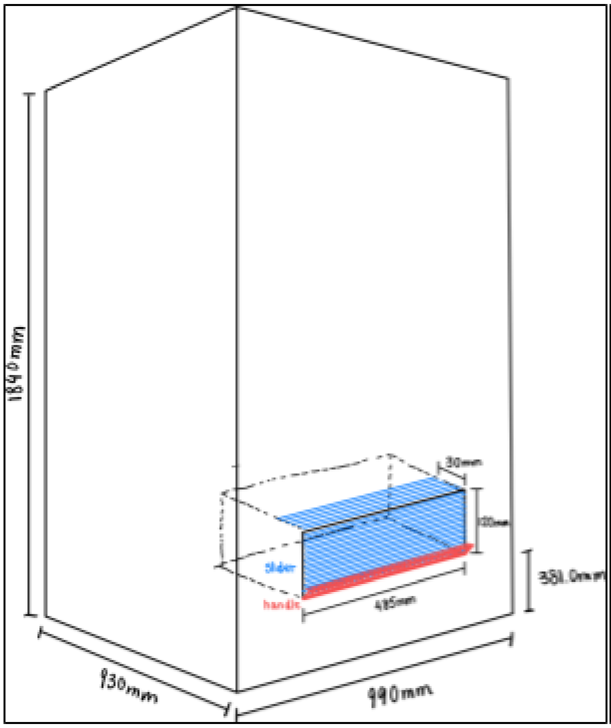



*Figure 4.1: Sketch prototype of Lift and Pick when closed.*

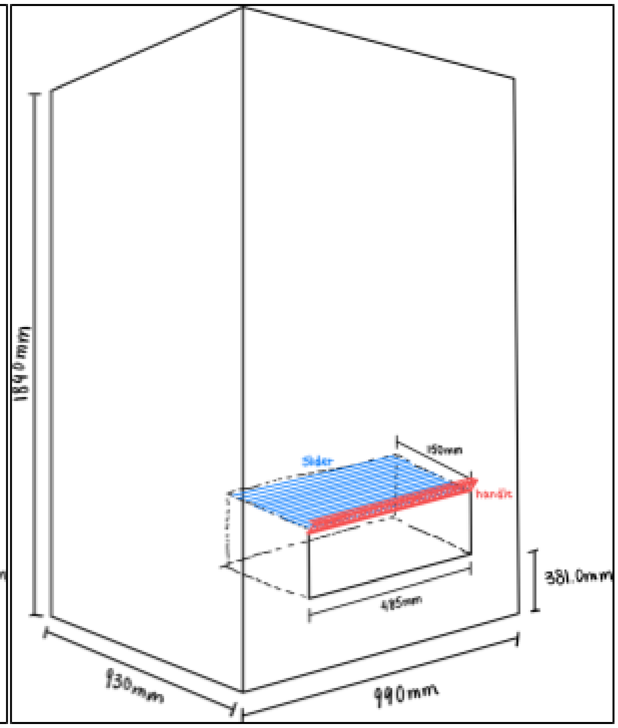



*Figure 4.2: Sketch prototype of Lift and Pick when opened.*

**Advantages:**

- Reduces some force required for opening the dispenser bin than the original vending machine.
- Preverses anti-pilfer functionality of the vending machine.

**Disadvantages:**

- Requires some mechanical alteration to the existing vending machine.
- The user needs to apply some force to retrieve the product.
- The friction between the sliding door and walls may need frequent maintenance to remain low.

# 4. Verification and Comparison

This section discusses the verification and comparison process, allowing us to converge to one final recommended solution.

## 4.1 Verification

We must ensure our recommended design meets requirements.

### 4.1.1 Physical testing of the Snack Chute

**User Diversity:** During the testing process, a diverse population of individuals with varying hand sizes, body heights, and genders was representative of stakeholders. The obtained data points represent a diverse user population and any conclusions drawn are reliable.

*Figure [5.1]: Wrist flexion and extension measuring device setup used throughout all trials.*

*Figure [5.2]: Measuring the wrist flexion by attaching the device to the back of the wrist.*

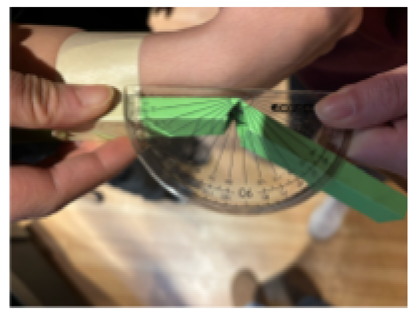


*Figure [5.3]: Measuring the wrist extension by attaching the device to the front of the wrist.*

*Figure [6]: Testing for the wrist bending needed for retrieving products from an opening with no obstruction. The left image depicts measuring wrist extension. The right image depicts measuring wrist flexion.*

**Wrist Flexion and Extension**
The data was collected using the measurement tool from Figures 5 and 6, and a cardboard box opened at one side. Since the motion required to retrieve products from the Snack Chute is similar to retrieving snacks from an open box, this cardboard box was chosen as the prototype for this testing. Testing data found in the appendix [1, Appendix F]

**Duration of Retrieval Process**

The timestamps from the video recordings of retrieving the product are used for the duration. Testing data found in the appendix [2, Appendix F]

Note: Metrics for the other two top requirements, force and anti-pilfer, were determined through both calculations and secondary research, shown in Appendix F. The testing for the other designs are shown in Appendix F.

### 4.1.2 Fulfilled Requirements

Through design dimensions, proxy testing, and secondary research it is verified that Snack Chute meets all requirements.

- ☑ R110: 0N [3, Appendix F] → < 22N.
- ☑ R120: 2.6° flexion [1, Appendix F] → < 10°, 5.2° extension [1, Appendix F] → < 35°, 150mm [Figure 1] → < 170mm.
- ☑ R130: Opening dimensions of 110x480x150mm [Figure 1] accommodates 180x100x50mm products.
- ☑ R210: 390mm [Figure 1] → < 1200mm & > 211mm.
- ☑ R220: 0mm → < 255mm. *0mm seeing as there is no obstruction between the user and the machine
- ☑ R310: Does not affect standards or protocols [7, Bibliography]
- ☑ R320: Objects of 12mm diameter and/or 328mm length cannot “fish” products [4, Appendix F].

## 4.2 Measurement Matrix

A clear comparison between top potential solutions using prioritized ECs is shown in Table 6.

| | Snack Chute | Snack Sack | Lift n' Pick | Wave n' take |
|---|---|---|---|---|
| Force (N) | 0 N | 15-20 N | 5.60 N | 0 N |
| Anti theft preservation (yes or no) | yes | yes | yes | yes |
| Hand flexion & extension (°) | Extension: 5.2° Flexion: 2.6° | Extension: 16.0° Flexion: 13.2° | Extension: 5.4° Flexion: 5.6° | Extension: 7.2° Flexion: 9.0° |
| Duration of retrieval process (s) | 2.515 s | 4.510 s | 4.118 s | 11.160 s |

*Figure 7: Measurement matrix comparison using values found via proxy testing and secondary research [Appendix F].*

Based on quantitative data, the Snack Chute performs equal to or better than other tested designs for top evacuation criterias.

## 4.3 Pugh Charts

A pugh-chart is a tool used to systematically compare multiple design concepts against a set evaluation criteria. In order to identify whether a design performs better, worse, or the same as the baseline design, we used the quantitative values obtained from our physical prototype testing as well as values obtained from secondary sources as the basis for each comparison.

### 4.3.1 First Iteration

For the first iteration, Wave n' Take is baseline.

| | Snack Chute | Snack Sack | Lift n' Pick | Wave n' take |
|---|---|---|---|---|
| Force (N) | Same | Worse | Worse | |
| Anti theft preservation (mm) | Same | Same | Worse | |
| Hand flexion & extension (°) | Same | Worse | Worse | |
| Duration of retrieval process (s) | Better | Better | Better | |

*Figure 8: The first iteration Pugh Chart, helping us to compare potential solutions and converge.*

When each design was evaluated, it became clear that only the Snack Chute offered a compelling improvement over the baseline design. Its respective strengths are comparable to the Wave n' Take design, either being on par or better. One additional factor to consider outside of the factors already within the pugh chart is the implementation complexity of each design. While the Wave n' Take requires significant mechanical and electrical changes to be implemented, the other designs only require mechanical changes. Taking this into account, although the Snack Sack and Lift n' Pick perform worse in comparison to the Wave n' Take, they are easier to implement. As a result, all of the designs will be kept for the second round of iteration.

### 4.3.2 Second Iteration

For the second iteration, Lift n' Pick is baseline.

| | Snack Chute | Snack Sack | Lift n' pick | Wave n' take |
|---|---|---|---|---|
| Force (N) | Better | Worse | | Better |
| Anti theft preservation (mm) | Better | Better | | Better |
| Hand flexion & extension (°) | Better | Worse | | Worse |
| Duration of retrieval process (s) | Better | Worse | | Worse |

*Figure 9: The second iteration Pugh Chart, helping us to compare potential solutions and converge.*

Based on the results, it is clear that Snack Chute offers a significant improvement over the baseline design. Both the Wave n' Take and Snack Sack offer similar improvements to the baseline design Lift n' Pick, with the Snack Sack being significantly easier to implement than the Wave n' Take. As a result, we decided that for the third round of iteration, we would not include the Wave n' Take design.

### 4.3.3 Third Iteration

For the third iteration,  Snack Sack is baseline.

| | Snack Chute | Snack Sack | Lift n' pick |
|---|---|---|---|
| Force (N) | Better | | Better |
| Anti theft preservation (mm) | Same | | worse |
| Hand flexion & extension (°) | Better | | Better |
| Duration of retrieval process (s) | Better | | Better |

*Figure 10: The third iteration Pugh Chart, helping us to compare potential solutions and converge.*

Based on the results, it is clear that both the Snack Chute and Lift n' Pick offer a significant improvement over the baseline design. The only requirement in which they differ is the anti-pilfer preservation. Based on quantitative values [4, 8, Appendix F], the Snack Chute provides significantly better anti-pilfer than the Snack Sack, allowing us to conclude that the Snack Chute was the optimal solution.

## 4.4 Anti-Pairwise Comparison

*Score of each solution represented by values in vertical columns

| | Snack Chute | Snack Sack | Lift n' pick |
|---|---|---|---|
| Snack Chute | – | 1 | 1 |
| Snack sack | 0 | – | 0 |
| Lift n' pick | 0 | 1 | – |

1 - Was determined to be worse

0 - Was determined to be better

*Figure 11: Final anti-pairwise comparison between top three solutions.*

An anti-pairwise comparison further compares our final three solutions through debates within the design team. Ultimately, the Snack Chute was once again determined to be the optimal solution, further justifying our recommendation, as it was deemed best both through quantitative measures, and through a qualitative debate.

# 5. Conclusion and Next Steps

Overall, the Snack Chute is determined to be the best current design concept for fulfilling the requirements and evaluation criteria better than other designs, verified by testing and secondary research. Moving forwards, the next steps are to consider aspects such as optimal materials used for the flap, hinge and more. However, seeing as determining optimal materials pertains to cost, they are not considered within the scope of this design report.

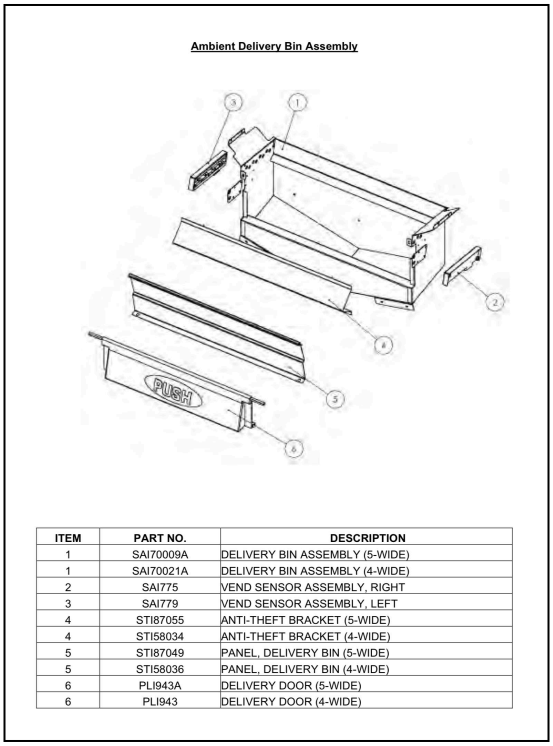
# Appendices:

Supplementary information referenced throughout the main text.

## Appendix A: Background Information

[1] Design Brief: Limited Accessibility in SF Vending Machine

[2] The Dispenser Bin Assembly is shown in Figure 12 and highlighted on the machine in Figure 13:




| ITEM | PART NO. | DESCRIPTION |
| --- | --- | --- |
| 1 | SAI70009A | DELIVERY BIN ASSEMBLY (5-WIDE) |
| 1 | SAI70021A | DELIVERY BIN ASSEMBLY (4-WIDE) |
| 2 | SAI775 | VEND SENSOR ASSEMBLY, RIGHT |
| 3 | SAI779 | VEND SENSOR ASSEMBLY, LEFT |
| 4 | STI87055 | ANTI-THEFT BRACKET (5-WIDE) |
| 4 | STI58034 | ANTI-THEFT BRACKET (4-WIDE) |
| 5 | STI87049 | PANEL, DELIVERY BIN (5-WIDE) |
| 5 | STI58036 | PANEL, DELIVERY BIN (4-WIDE) |
| 6 | PLI943A | DELIVERY DOOR (5-WIDE) |
| 6 | PLI943 | DELIVERY DOOR (4-WIDE) |

*Figure 12: view of delivery bin assemble from [1, Bibliography]*

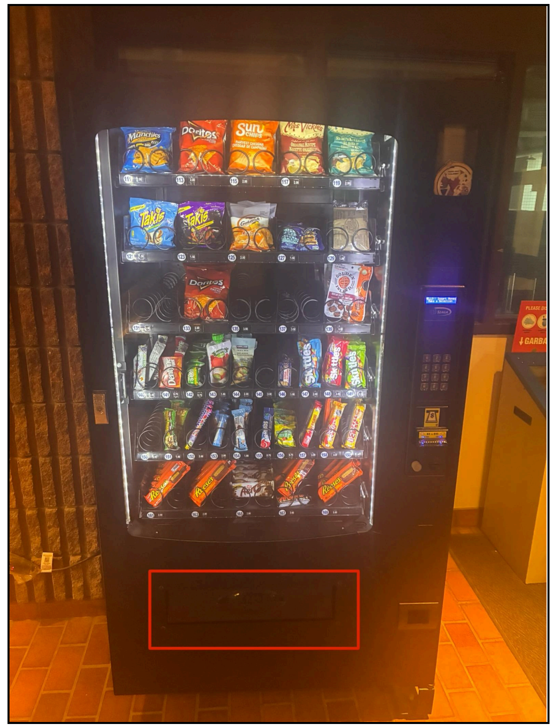


*Figure 13: Delivery bin assembly highlighted on machine*

**[3]** Possible solutions in detail: 7 Solutions

# Appendix B: Objectives

**[1]** *Table 6: Objectives of G100 that led to requirements in Table 2*

| **G100: Reduce the effort needed for product retrieval.** |
|---|
| O110: Force required from the user when retrieving the product should be reasonable.<br>Over-exertion of force to access products may result in hand discomfort for users. |
| O120: Hand flexibility required to reach the entire depth of the retrieval bin should be reasonable.<br>Users should be able to reach and grasp product easily at any location in the retrieval bin. |
| O130: All products, of varying shape and size, should be easily retrievable.<br>No matter the product selected, users should have the same degree of accessibility available. |

**[2]** *Table 7. Objectives of G200 that led to requirements in Table 3*

| **G200: Adjust the product retrieval height of the vending machine.** |
|---|
| O210: The height of the product during retrieval should be optimized.<br>Users should easily be able to reach the height of the product while retrieving. |
| O220: The distance between the opening and the of the user should be reduced.<br>Users should easily be able to reach the vending machine opening even if there is an obstruction. |

***[3]*** *Table 8. Objectives of G300 that led to requirements in Table 4*

| **G300: Preserve the integrity of the existing vending machine.** |
|---|
| O310: Design should preserve 100% compliance with the accessibility standards and operating protocols currently satisfied.<br><br>Secondary stakeholder interests prioritize the safety of the machine and tertiary desires require that the machine remain operational. |
| O320: The unsold products should not be accessible to users so that theft is mitigated.<br>Tertiary stakeholders do not want the possibility of theft of products. |

# Appendix C: Evaluation Criteria Justification

**EC111:** Less force required to retrieve the snack.

This evaluation criterion is directly related to R110 which states that the force exerted during the entire retrieval process must not exceed 22N. The scope of this opportunity is centered around the ease of product retrieval, with the exertion of force being the main factor causing difficulty to users. Lower required retrieval force aligns with the needs of our primary stakeholders, who require a design that is easy to use, ergonomic, and allows for quick product retrieval. Therefore, the required force to retrieve the snack should be minimized.

**EC112:** Shorter duration retrieval process.

This evaluation criterion is directly related to R110 which states that the force exerted during the entire retrieval process must not exceed 22N. Reducing the time spent retrieving the product directly reduces the overall physical effort that a user must exert throughout the retrieval process. An overall faster process of retrieval limits how long force is sustained, helping satisfy our primary stakeholders' needs, who require a design that is easy to use, ergonomic, and allows for quick product retrieval.

**EC121:** Smaller the reach depth.

This evaluation criterion is directly related to R120 which states that wrist movement must remain within 10° flexion and 35° extension and that reach distance shall not exceed 170mm. By minimizing the depth of how far a user must reach, the design reduces the need for excessive wrist movement, ensuring that the retrieval process stays within the required ergonomic limits. Lower reach depths align with the needs of our primary stakeholders, who require a design that is easy to use, ergonomic, and allows for quick product retrieval.

**EC122:** Less wrist extension and flexion needed to reach the entire depth.

This evaluation criterion is directly related to R120 which states that wrist movement must remain within 10° flexion and 35° extension and that reach distance shall not exceed 170mm. By minimizing the required wrist motion (flexion and extension), we are able to lower the risk of discomfort or strain and ensure that users are able to retrieve their products whilst staying within the required ergonomic limits. Reduced wrist extension and flexion align with the needs of our primary stakeholders, who require a design that is easy to use, ergonomic, and allows for quick product retrieval.

**EC131:** Less compression or tension the product has to undergo.

This evaluation criterion is directly related to R130 which states that products of size 180x100x94 mm shall fit through the opening of the product retrieval bin with ease and without causing damage to the product packaging or its contents. By minimizing the amount of compression or tension that a product experiences throughout the retrieval process, we are able to lower the risk of any harm that may occur to the user's hand. Reducing the amount of compression or tension the product has to undergo during the retrieval process aligns with the needs of our primary and secondary stakeholders, who require a solution that is easy to use, ergonomic, allows for quick product retrieval, meets relevant accessibility standards, codes, protocols, and ensures safe operation. When a product does not overly undergo compression or tension, users do not need to exert excessive force and are able to freely move around within the retrieval bin (no scraping, pinching, or strain experienced by the user's hand).

**EC211:** Closer retrieval height is to 900mm from ground.

This evaluation criterion is directly related to R210 which states that purchased products shall be less than 1200 mm and greater than 211mm above the ground. By making the retrieval height as close to 900mm above the ground as possible, we are able to ensure that users are retrieving products from the most optimal height [5, Appendix G] . At this height, bending and reaching are both at a minimum. This aligns with the needs of our primary stakeholders who require a solution that is easy to use, ergonomic, and allows for quick product retrieval.

**EC221:** Less obstruction.

This evaluation criterion is directly related to R220 which states that purchased products shall be retrieved with a reach distance not exceeding 255 mm if there is an obstruction. Obstruction refers to any possible barriers that may exist in front of the vending machine, thereby limiting how far into the vending machine a user can reach. By minimizing the barriers in front of the ending machine, we are able to ensure that users are able to stand as close to the vending machine as necessary and reach the appropriate required height without needing to navigate around external obstacles or adopt awkward body postures. This aligns with the needs of our primary stakeholders, who require a design that is easy to use, ergonomic, and allows for quick product retrieval.

**EC311:** Allowing the machine to reach additional standards.

This evaluation criterion is directly related to R310 which states that the machine as a whole must continue to effectively operate and remain compliant with the 1 accessibility standards and 2 operating protocols. By ensuring that designs are able to meet all required standards/protocols and possibly even exceed them, this criterion ensures that design solutions do not violate any required safety regulations. This aligns with the needs of our secondary stakeholders who require a design that meets relevant accessibility standards, codes, protocols, and ensures safe operation.

**EC312:** Less major alterations to the machine.

This evaluation criterion is directly related to R310 which states that the machine as a whole must continue to effectively operate and remain compliant with the 1 accessibility standards and 2 operating protocols. By minimizing any major modifications that must be applied to the original vending machine, the design is more likely to remain in compliance with all required standards and protocols as defined by R310. This aligns with the needs of our secondary and tertiary stakeholders who require a design that meets relevant accessibility standards, codes, protocols, ensures safe operation, is implementable, cost-effective, long-term, avoids full machine replacement, and maintains revenue.

**EC313:** Less failure cases and easier retrieval during failure.

This evaluation criterion is directly related to R310 which states that the machine as a whole must continue to effectively operate and remain compliant with 1 accessibility standards and 2 operating protocols. By reducing the number of possible failure cases associated with every design, such as jams and automated flap door closes before snack is retrieved, this helps make sure that the design remains reliable and functional with minimal failure occurrences during operation. Additionally, by making retrieval easier in the case of a machine failure, this ensures that users can still access their paid products without compromising safe operation. This aligns with the needs of our primary and secondary stakeholders who require a solution that is easy to use, ergonomic, allows for quick product retrieval, meets relevant accessibility standards, codes, protocols, and ensures safe operation.

**EC321:** Prevention of foreign objects that are smaller the better

This evaluation criterion is directly related to R320 which states that an anti-pilfer system shall be implemented such that no objects with a diameter larger than 12mm and length of 328mm may enter the storage area of the machine to dislodge a product during retrieval. By evaluating how effectively each design prevents objects of increasingly smaller diameter and length from reaching the storage area to dislodge a product, this ensures that the design not only meets the base requirement, but is also able to potentially exceed this minimum threshold. This reduces the risk of tampering, theft, and damage to products within the storage area of the machine. This aligns with the needs of our tertiary stakeholders who require a solution that is implementable, cost-effective, long-term, avoids full machine replacement, and maintains revenue.

**EC322:** Greater effectiveness against aggressive forces.

This evaluation criterion is directly related to R320 which states that an anti-pilfer system shall be implemented such that no objects with a diameters larger than 12mm and length of 328mm may enter the storage area of the machine to dislodge a product during retrieval. A design that withstands stronger, more forceful tampering attempts will ensure a more effective anti-pilfer mechanism. This enhances the reliability of the anti-pilfer system beyond simply meeting the dimensional threshold. This aligns with the needs of our tertiary stakeholders who require a solution that is implementable, cost-effective, long-term, avoids full machine replacement, and maintains revenue.

# Appendix D: Diverging and Converging

## Diverging 1


*Figure 14: Lotus Blossom diverging tool for the first iteration of diverging*

Using the Lotus Blossom diverging tool identifies the many variables affecting accessibility of the vending machine, which helped us branch out. However, we are still mostly focused on our constraints from our design brief, so this technique did not lead to much creativity. So, for our next diverging tool, we used the wishing diverging tool to inspire more creativity.

## Wishing

- no glass
- lazer
- teleport
- sliding door
- better schedule → more time to eat
- no crime world → no anti-theft → change of law needed
- pre-made hot food
- free food!
- no need for food
- personal chef
- looks cooler
- no process needed → mind reading
- get money back if you didn't get snacks
- the vending machine is out of the way
- smaller vending machine
- snacks didn't have to fall
- doesn't have to touch anything

- self-cleaning vending machine
- robot
- portable
- no payment → sensor
  ↳ Amazon store

- not cash only
  ↳ more payment options
  ↳ trade

*Figure 15: Wishing diverging tool for the first iteration of diverging.*

Wishing inspired more creativity and it helped us to think beyond what was possible. This expanded our mindset, helped us to view things from a different perspective. For example, we were no longer fixated on the scooper design from the design brief and considered modifying the machine, leading to a wider design space. To continue widening the design space, which was proven to be useful, we decided to continue with the Reverse Brainstorming diverging tool.

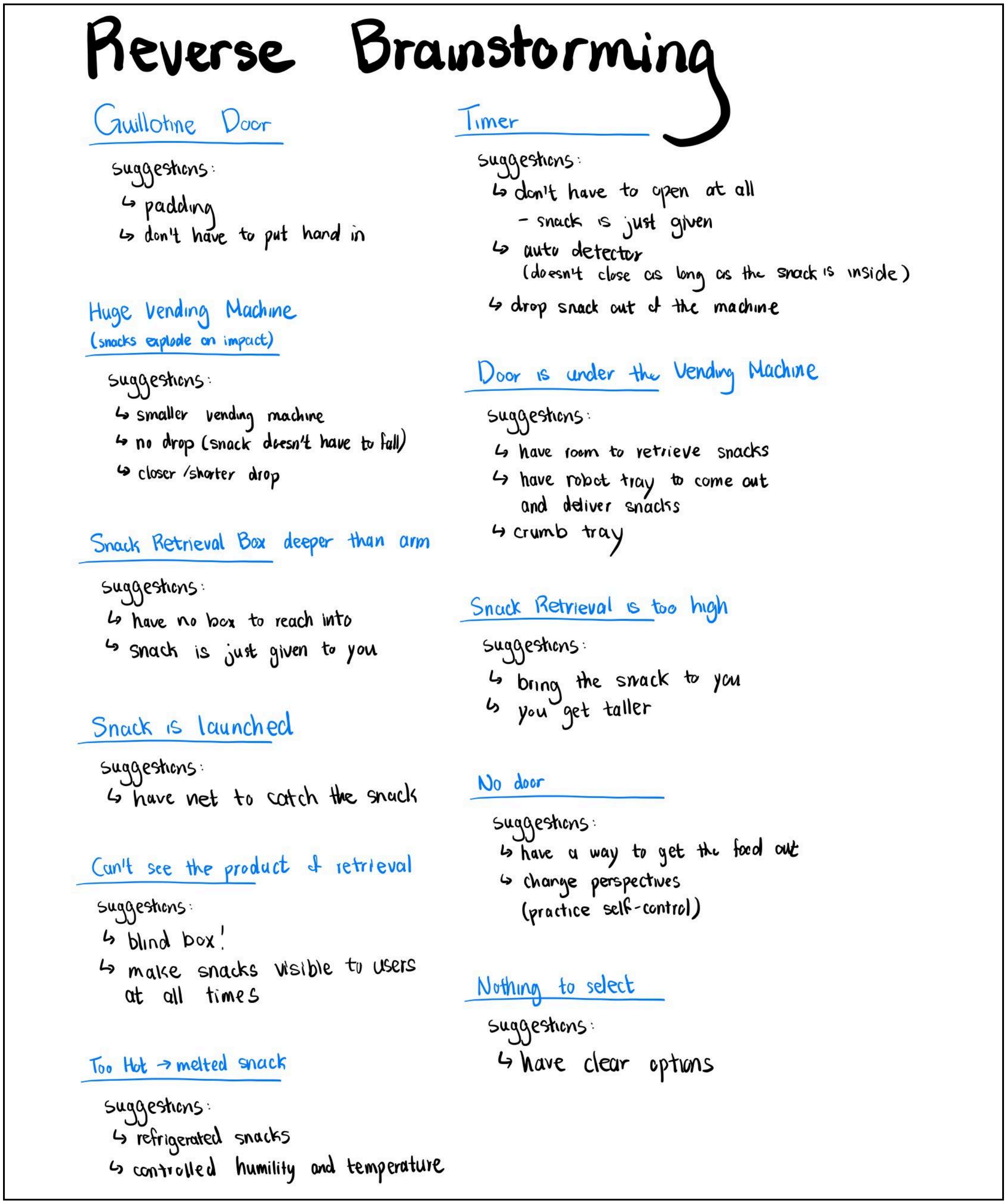



*Figure 16: Reverse Brainstorming diverging tool for the first iteration of diverging.*

Reverse brainstorming helped us better recognize and define the basic requirements of the vending machine, that we would have looked past before. This deeper understanding inspired us to remove some part of the existing vending machine design instead of adding parts to the existing vending machine. This tool led to a simpler, yet effective design. Because of this, this is the diverging technique that left us with the most usable concepts that led to our final design choice. More diverging was done with Random Input and Challenging Assumptions diverging tools for more insights that can improve on this design.

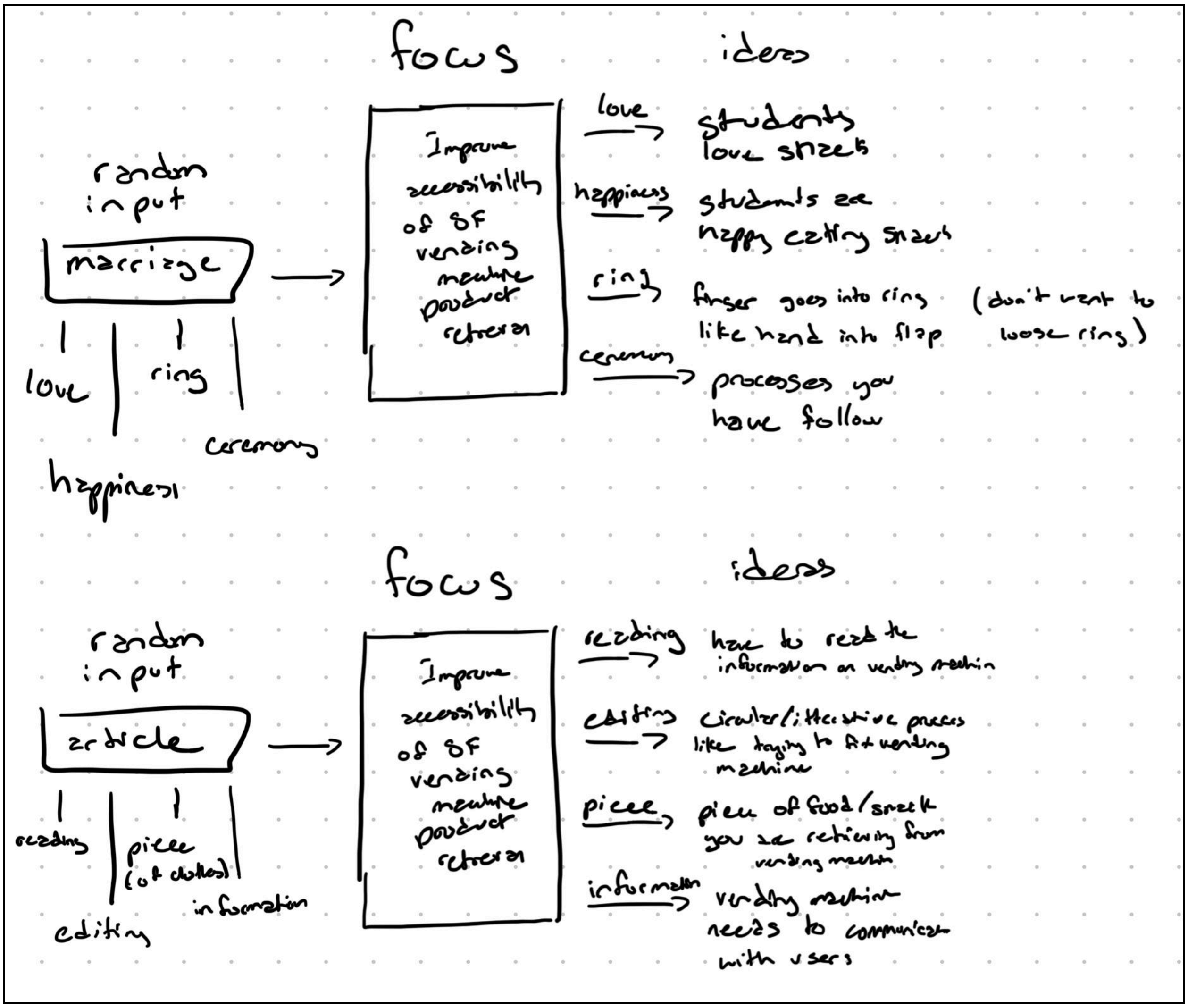



*Figure 17: Random Input diverging tool for the first iteration of diverging.*

The goal of the Random Input diverging tool was to help us make connections between our current concepts for the vending machine and the random word generated. However, after the first three diverging tools, this diverging tool did not lead to any new ideas due to the words “marriage” and “article” generated. It was a struggle relating the vending machine to these words, leading to far connections that are not beneficial for the new concept generations.

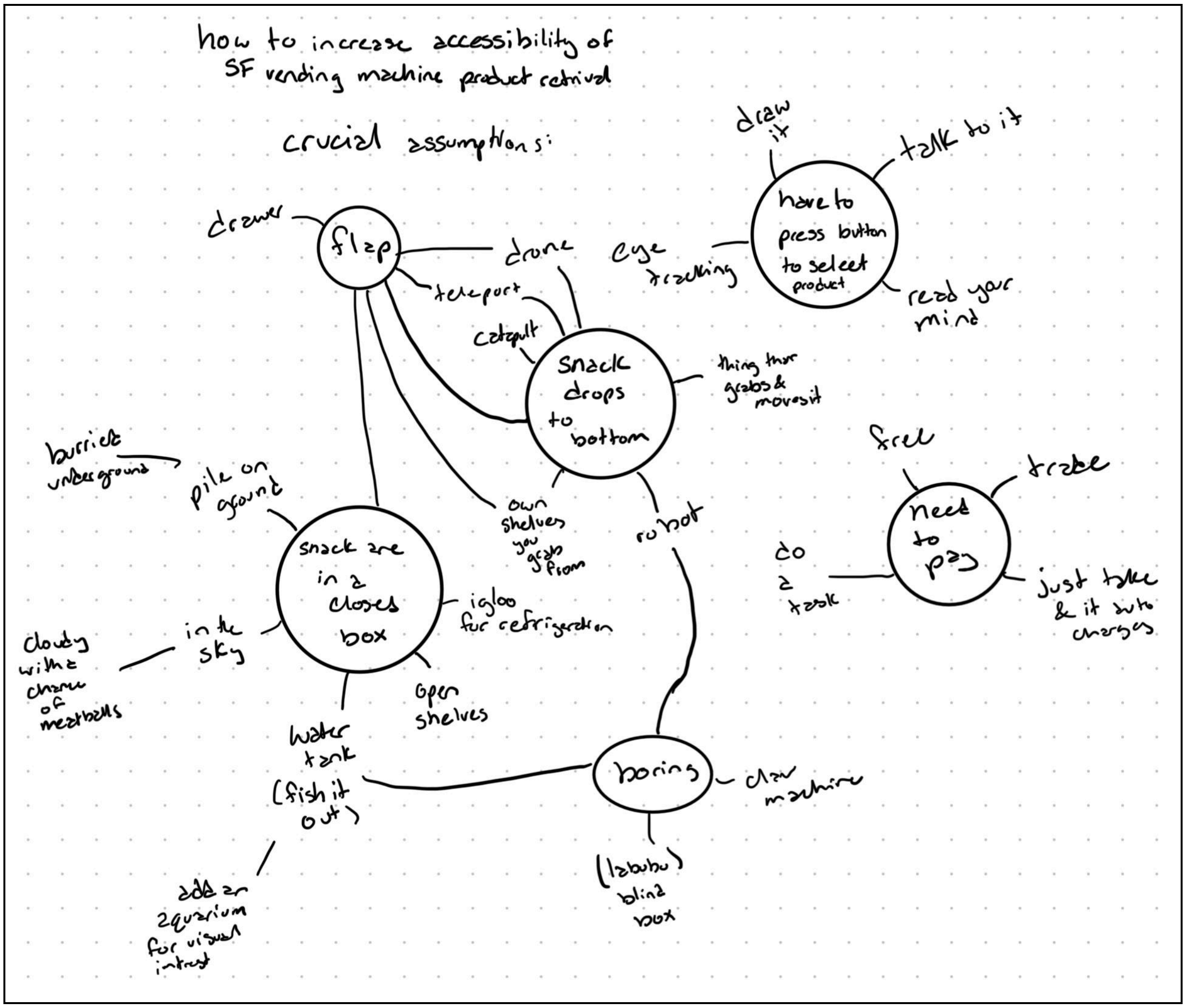



*Figure 18: Challenging Assumptions diverging tool for the first iteration of diverging.*

The goal of challenging assumptions was to break apart any assumptions that were limiting our creativity and options. However, after the first three diverging tools, where Wishing caused us to ignore many assumptions and Reverse Brainstorming helped us recognize only the basic requirements of the vending machine, our use of this diverging tool led to mostly unrealistic ideas that were not beneficial for the next diverging iteration.

## Converging 1

The unrealistic, infeasible concepts and any concepts that were outside of our scope.

Examples of removed concepts include:

- Having teleporting snacks
- Having drones to deliver snacks
- Using an igloo to place snacks
- Any consideration for the payment methods of the vending machine

## Diverging 2

| | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|
| Method of Accessing Opening | Flap | Drawer | Sliding door | no door |
| Force Reduction Method | auto-opening (with sensor) | spring-assisted<br>pop! | magnetic levitation | wheels to reduce friction |
| Snack elevation method | User bending (up to 60°)<br>60° | Snack tray with lift table | long handle scooper for reaching | pulley |
| User movement required | hand/arm push | hand/arm pull | hand movement/ presence for sensors<br>wave | pinch / grip onto an object |

*Figure 19: Morph Chart diverging tool for the second iteration of diverging.*

From the first iteration of diverging and converging, we determined and chose the practical concepts we had. The four key sub-functions of the vending machine retrieval process were determined. With the morph chart, these remaining concepts were combined, leading to functional n+1 concepts for the vending machine retrieval process that meets our needs, goals, and objectives.

These n+1 concepts included:

- The Snack Chute: An one-way-flap with no door in the snack retrieval area to eliminate the need for the user to apply force to get to the product.
- The Snack Sack: a similar design to the existing vending machine with an inclined slope to get the snack closer to the opening for easier retrieval.
  It features a roller-bushing for less friction between the flaps.
- The Drawer: change the flap with a drawer. It features wheels in the drawer sliding system to reduce friction, therefore, reducing force.
- The Scooper: An external tool used to be inserted into the existing vending machine product retrieval bin. It features a scoop to pull the product out so the user can easily grab it.
- The Sensor: A motion sensor is used to replace the user force needed to apply force to the flap.

- The Slider: A sliding-elevation mechanism that raises the snack up as the sliding door is opened. It features a pulley system to elevate products and a magnetic levitation system to reduce friction and force while sliding.

## Converging 2

After reframing to only altering the dispenser bin assembly of the vending machine, the Scooper no longer fits within the scope, so only the other five remaining concepts were considered in this converging process.

**Anti-pairwise**

1 - Was determined to be worse

0 - Was determined to be better

Score of each solution represented by values in the vertical columns

*Table 9: Anti-Pairwise Comparison results*

| | Snack Chute | Snack Sack | Drawer | Slider | Sensor |
|---|---|---|---|---|---|
| Snack Chute | - | 1 | 1 | 1 | 1 |
| Snack Sack | 0 | - | 1 | 1 | 1 |
| Drawer | 0 | 0 | - | 1 | 0 |
| Slider | 0 | 0 | 0 | - | 0 |
| Sensor | 0 | 0 | 1 | 1 | - |

An anti-pairwise allows the design team members to argue about the downsides of each solution rather than the advantages. This process allows us to reflect and compare the various solutions methodologically, and the results reflect that the Snack Chute was argued to be better than the other 4 by the design team. Along with this, the Snack Sack, Sensor and drawer were all deemed to be better than at least one other design, whereas the slider was deemed worse in each comparison. Therefore, moving into further convergence, the slider was removed from consideration.

## Diverging 3

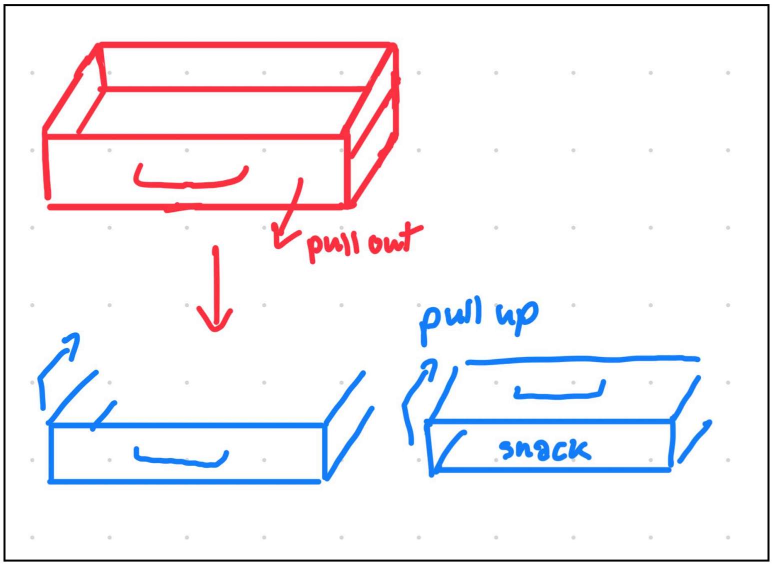



*Figure 20: A section of the Brainwriting 6-3-5 diverging tool for the third iteration of diverging.*

In this image, the suggestion is made to slide the drawer handle up instead of pulling it out.

Brainwriting 6-3-5 aims to have all members participate in generating one concept. Through this diverging tool, the Lift n' Pick solution was generated from the drawer when a design team member suggested a change in the movement of the drawer. Sliding the drawer out can be difficult, as the user is crouching down, and would have to back up to slide the drawer out. Therefore, a suggestion was made to instead be able to lift the drawer handle up, making it slide up as a Lift n'Pick would. This solution reimagines the drawer in a way that preserves the anti-pilfer of the vending machine, reduces the required force, and also allows the user to operate in a more ergonomic position compared to the original drawer. Thus, this potential solution was then considered in further testing and comparison and the drawer was removed.

# Appendix E: Solutions’ Reference Designs, & Research

**[1]** Reference design inspiring the one-way flap: One way pet doors [11, Bibliography]

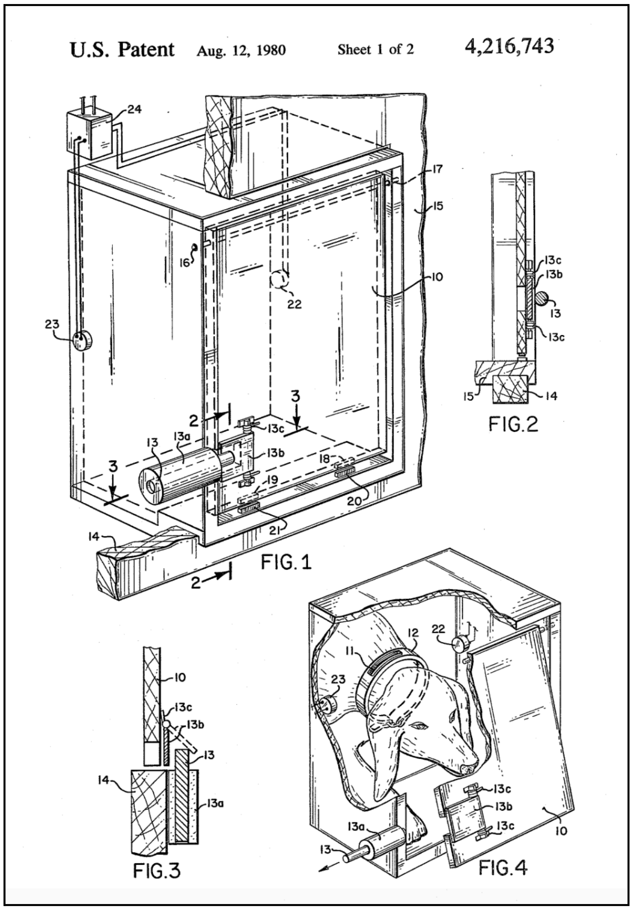



*Figure 21: Patent drawing of a one-way pet door, hinged at the top to open in both directions for ingress and egress, but is prevented from opening in the ingress direction by a one-way latch*

This reference design helped to inspire the one-way flap design of the Snack Chute. The Snack Chute utilizes a similar flap which is hinged and is able to open in both directions, however is prevented from opening in one direction to achieve the anti-pilfer goal.

**[2]** Research for the spring choice of the Snack Chute in the Three Key Decisions [13, Bibliography]

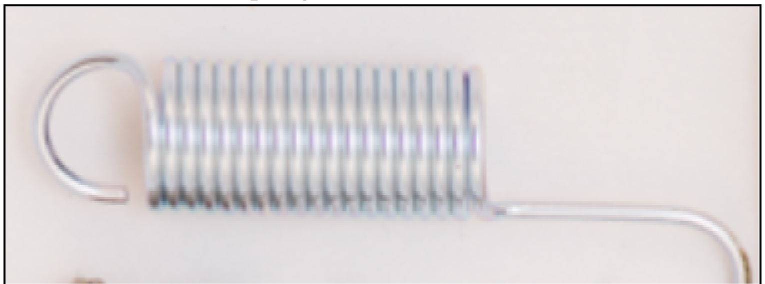


*Figure 27: A hard carbon hard-drawn torsion spring*

Torsion springs are used for bending purposes with common materials including:
- Alloy Steel: for high strength and durability
- Plastics: for extremely light-duty needs
- Hard-drawn steel: for general-use where high strength and durability are not required

Since the spring must handle repetitive movement, so plastic cannot be chosen, and the mass of the one-way-flap and snacks, which are lightweight and alloy steel cannot be chosen, therefore hard-drawn steel is chosen.

**[3.1]** Reference design inspiring the pouch: Skateboard ramp [14, Bibliography]

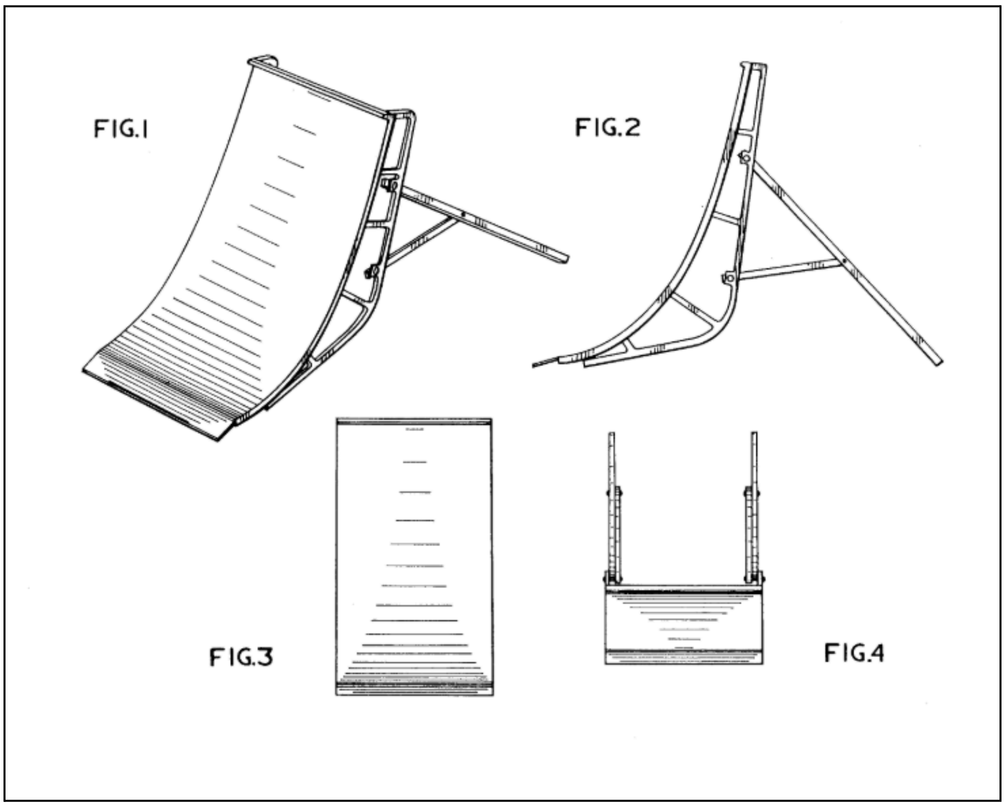



*Figure 22: Patent drawing of a compact skateboard ramp, whose smooth curved profile inspired the inclined slope in Snack Sack, guiding snacks along a continuous surface toward the user.*

The skateboard ramp patent provides a compact, smoothly curved ramp geometry that allows a skateboard to roll from a higher platform down to ground level without sharp corners or sudden drops. We used this as a reference design for the Snack Sack slope: the same gradual curved transition is applied inside the vending bin so that snacks slide along a continuous surface, rather than bouncing or sticking on a flat ledge, and are guided to a predictable, higher resting point near the user within the 170 mm reach range.

**[3.2]** Reference design mentioned in Snack Sack: Ultrahigh molecular weight polyethylene (UHMWPE) [15, Bibliography]

*Figure 23: Example of a UHMWPE bushing, used in Snack Sack at the flap's pivot to provide a low-friction, wear-resistant bearing surface that increases the flap's opening angle.*

We chose ultrahigh molecular weight polyethylene (UHMW-PE) for the bushings because it is explicitly designed for low-friction sliding contacts such as bearings and bushings: it has a very low coefficient of friction, excellent abrasion resistance, and is widely used in conveyor and material-handling bushings for exactly this reason. Together, these properties make UHMW-PE a good candidate for reducing hinge friction while keeping the retrofit simple and durable.

**[4]** Reference design inspiring the sensor: Sensor operated trash can [16, Bibliography]

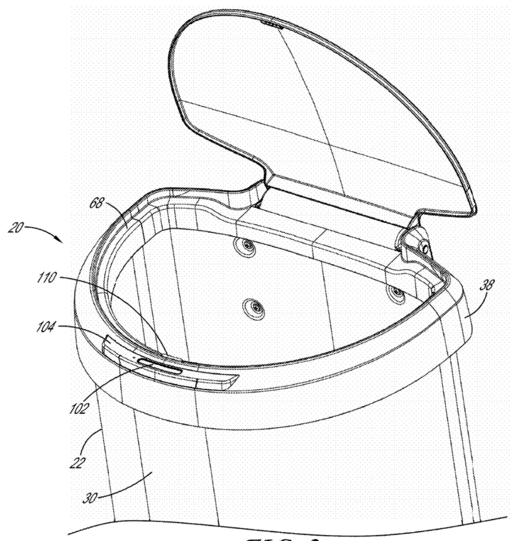



FIG. 2

*Figure 24: Patent drawing of a sensor-operated trash can illustrating its automated lid operation mechanism.*

This diagram shows the functionality of a sensor-activated trash can, including its automatic lid opening mechanism and visual indicator system. The trash can's use of a blinking green light to signal sensor activation and a blinking red light to warn for the closure of the lid directly influenced the design of our sensor operated vending machine flap door. While both systems (garbage can and vending machine) rely on visual cues and automated movement to improve the ease of user interaction, the two systems are not exactly the same. The garbage can is automated such that the sensor is placed directly underneath the user's field of view and the flap opens outwards rather than inwards like the vending machine does.

**[5]** Reference design inspiring the Lift n' Pick: Garage door [17, Bibliography]

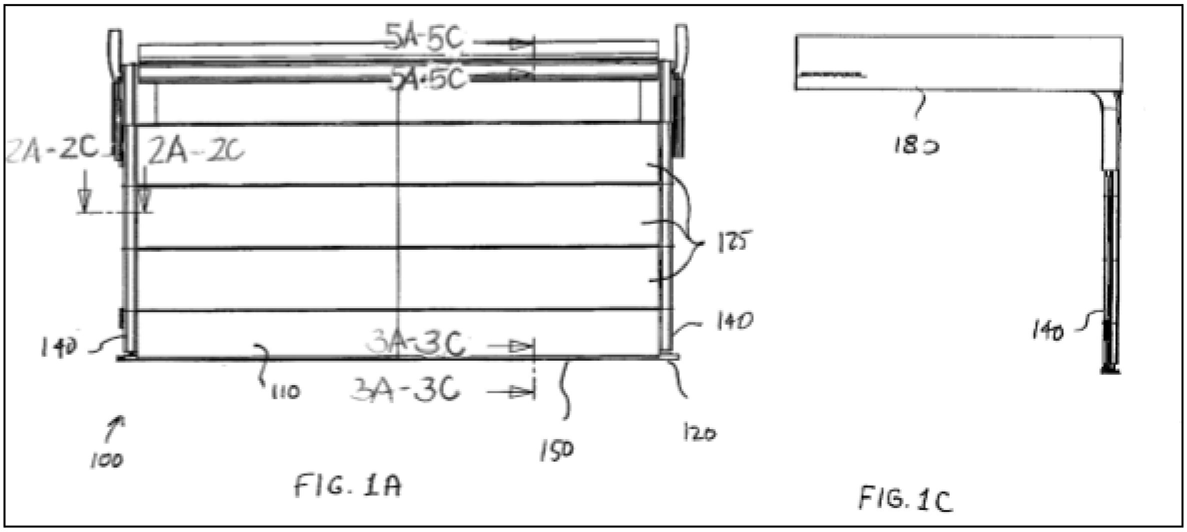



*Figure 25. A garage door sealing system illustrating a closed garage door on the left and the path the garage door would follow when opened.*

This diagram displays the opening and sealing mechanism of a garage door from the front and side view. The moving mechanism for opening a garage door is similar to the mechanism inspired by the vertical sliding door for Design 4. As the garage opens, the metal from the door is shifted to the top, blocking the horizontal ceiling, which in the case of the vending machine, blocks access to the stored snacks above. Although the purpose of the garage door and vending machine sliding door are both for opening and enclosing a space, the garage door is significantly heavier and larger, so it is difficult to be opened by human wrists. Therefore, the garage door fails to address the force requirement of the vending machine opening system.

**[6]** Reference design for proxy testing of Lift n' Pick: Suitcase handle [23, Bibliography]

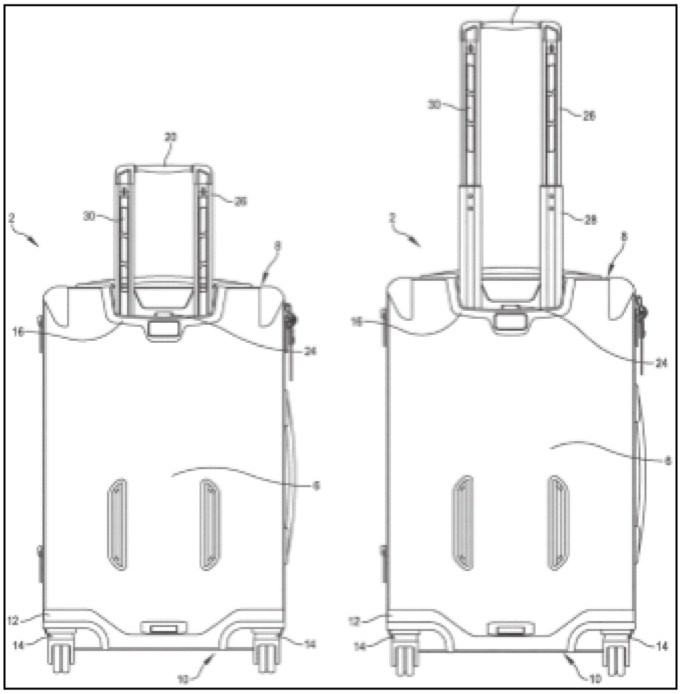


*Figure 26. A patent of extendable handles of a suitcase showing varying heights of the handle.*

This diagram shows the extendable handle features of the suitcase. The vertical wrist movement necessary for extending this suitcase handle is similar to the motion of vertically pulling on a sliding door. Therefore, a suitcase is used to model and measure this motion during our testing. However, the suitcase handle is designed for elevating height to make luggage easier to pull, while the sliding door is designed for opening and enclosing a space. Therefore, the suitcase handle fails to address the open and closing purpose of the vending machine slider.

# Appendix F: Proxy Testing and Research

## Snack Chute

**[1] Snack Chute: Wrist Flexion and Extension**
A demo of this proxy test is available [18, Bibliography]
*Table 10: Data collected for Snack Chute - Wrist Flexion and Extension*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Wrist Extension | 5° | 1° | 6° | 6° | 8° | **5.2°** |
| Wrist Flexion | 2° | 3° | 4° | 0° | 4° | **2.6°** |

**[2] Snack Chute: Duration of Retrieval Process**
A demo of this proxy test is available [18, Bibliography]
*Table 11: Data collected for Snack Chute - Duration of Retrieval Process*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Trial 1 Duration | 1.89s | 2.35s | 1.23s | 1.77s | 3.25s | 2.098s |
| Trial 2 Duration | 3.15s | 1.65s | 2.57s | 2.05s | 5.24s | 2.932s |
| **Overall Average** | | | | | | **2.515s** |

**[3] Snack Chute: Force**
Since no physical contact with the vending machine is necessary during the retrieval process, the force required is 0N.

**[4] Snack Chute: Anti-Pilfer**
By Virginia Laws, the gap between the vending machine covering between the exterior and product storage space must be no greater than 1.5mm [11, Source Extracts].
The same laws apply in Pennsylvania [12, Source Extracts]. Due to Canada's close proximity to these US states, the assumption is made that Canada follows the same laws. Therefore, the gap of the one-way flap is assumed to be 1.5mm, which is not enough for a test object 12mm in diameter to fit through. Therefore, the anti-pilfer performance is maintained from the original vending machine.

*Figure 28: Testing for the wrist bending needed for retrieving products from an existing, normal functioning vending machine on Chestnut 27th floor. The left image depicts measuring wrist extension. The right image depicts measuring wrist flexion.*

**[5] Snack Sack: Wrist Flexion and Extension**

The data was collected using the measurement tool from Figures 5 and 6, and the existing vending machine on the 27th floor of Chestnut residence. Since the motion required to retrieve products from the Snack Sack is similar to that of a normally functioning vending machine, this vending machine was chosen as the prototype for this testing.

A demo of this proxy test is available [21, Bibliography]

*Table 12: Data collected for Snack Sack - Wrist Flexion and Extension*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Wrist Extension | 32° | 15° | 6° | 21° | 6° | **16°** |
| Wrist Flexion | 10° | 3° | 15° | 17° | 21° | **13.2°** |

**[6] Snack Sack: Duration of Retrieval Process**

The timestamps from the video recordings of retrieving the product are used for the duration.

A demo of this proxy test is available [21, Bibliography]

*Table 13: Data collected for Snack Sack - Duration of Retrieval Process*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Trial 1 Duration | 4.44s | 3.13s | 4.61s | 6.15s | 4.22s | 4.510s |
| Trial 2 Duration | 6.28s | 5.36s | 3.40s | 4.32s | 4.08s | 4.688s |
| Trial 3 Duration | | 4.55s | | | 3.56s | 4.055s |
| **Overall Average** | | | | | | **4.508s** |

**[7] Snack Sack: Force**
We assume Snack Sack uses the same basic flap as a properly maintained INF5S delivery door, so the relevant force is simply the normal hand force required to push a vending-machine flap. Because no manufacturer or peer-review source reports a specific “vending flap force,” we instead used general accessibility guidelines for hand-operated hardware (≈20–22 N maximum) to set a realistic target range of 15–20 N; this is an estimate rather than a directly measured value.

**[8] Snack Sack: Anti-Pilfer**
Snack Sack keeps the original delivery door and hinge geometry; only low-friction bushings and an internal slope/pouch are added inside the bin. The outer flap still closes against the cabinet with the same 1.5 mm gap, so a 12 mm test object 12mm in diameter cannot pass through, meaning the anti-pilfer performance is unchanged relative to the original vending machine.

*Figure 29: Testing wrist bending required to trigger a sensor near the Myhal first-floor entrance. Testers stood on a chair to replicate the intended user activation height. The left image depicts measuring wrist flexion. The right image depicts measuring wrist extension.*

**[9] Wave n’ Take: Wrist Flexion and Extension**

The data was collected using the measurement tool from Figures 5 and 6, and a sensor on the first floor of Myhal. Since the motion required to activate the door sensor is similar to operating the vending machine sensor on the Sensor Design, this door sensor was chosen as the prototype for this testing.

A demo of this proxy test is available [22, Bibliography]

*Table 14: Data collected for Wave n’ Take - Wrist Flexion and Extension*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Wrist Extension | 9° | 8° | 10° | 6° | 12° | **9°** |
| Wrist Flexion | 7° | 3° | 8° | 7° | 6° | **7.2°** |

**[10.1] Wave n' Take: Duration of Activating Sensor and Total Duration**

The timestamps from the video recordings of activating the sensor are measured. After sensor activation, the vending machine opening would be like that of the Snack Chute, so the duration from the Snack Chute and the sensor activation time (taking the 7 seconds buffer time into account) are added to get the total duration.

A demo of this proxy test is available [18, Bibliography]

Duration of activating the sensor is determined with the door sensor near the front entrance of Myhal as shown in the table below.

A demo of this proxy test is available [22, Bibliography]

*Table 15: Data collected for Wave n' Take - Duration of Product Retrieval*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Trial 1 Duration | 1.82s | 1.77s | 1.43s | 1.13s | 1.73s | 1.576s |
| Trial 2 Duration | 1.62s | 1.91s | 1.44s | 1.96s | 1.64s | 1.714s |
| **Overall Average** | | | | | | **1.645s** |

**[10.2] Wave n' Take: Overall duration of Retrieval process** = duration of activating sensor + duration of retrieving object + 7 seconds buffer time

= 1.645s + 2.515s + 7s

= **11.160s**

The duration of retrieving the object was found from [2, Appendix F].

**[11] Wave n' Take: Force**

Since no physical contact with the vending machine is necessary during the retrieval process, the force required is 0N.

**[12] Wave n' Take: Anti-Pilfer**

The opening of the sensor keeps the original design of the vending machine, which has the same 1.5mm gap as the Snack Chute. So a test object 12 mm in diameter cannot pass through, meaning the anti-pilfer performance is unchanged relative to the original vending machine.

*Figure 30: Testing for the wrist bending needed for a vertically pull-up motion by pulling on an extendable suitcase handle. The left image depicts measuring wrist extension. The right image depicts measuring wrist flexion.*

**[13] Lift n' Pick: Wrist Flexion and Extension**

The data was collected from the using the measurement tool from Figures 5 and 6, and extendable handle of a suitcase. Since the motion required for sliding the handle of a suitcase vertically up is similar to the motion of opening a sliding door on the vending machine, this extendable suitcase handle was chosen as the prototype for this testing [6, Appendix E].

A demo of this proxy test is available [24, Bibliography]

*Table 15: Data collected for Lift n' Pick - Wrist Flexion and Extension*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Wrist Extension | 4° | 9° | 8° | 4° | 2° | **5.4°** |
| Wrist Flexion | 7° | 5° | 4° | 3° | 7° | **5.6°** |

**[14.1] Lift n' Pick: Duration of Opening Sliding Door**

The timestamps from the video recordings of sliding the suitcase handle are measured, which is similar to sliding open the vending machine door. After sensor activation, the vending machine opening would be like that of the Snack Chute, so the duration from the Snack Chute is added to get the total duration.

A demo of this proxy test is available [18, Bibliography]

The duration of sliding the luggage handle was added to the duration of retrieval of the Snack Chute, as this duration reflects the time taken to pull up the door, then reach into an unobstructed retrieval tray to retrieve the snack. The duration data for the time duration is shown in the table below.

A demo of this proxy test is available [24, Bibliography]

*Table 16: Data collected for Lift n' Pick - Duration of Door Opening*

| Person | Addison | Vaisnavi | Alina | Helen | Caleb | **Average** |
|---|---|---|---|---|---|---|
| Trial 1 Duration | 1.21s | 2.17s | 1.88s | 1.33s | 1.35s | 1.588s |
| Trial 2 Duration | 1.54s | 1.87s | 1.3s | 1.52s | 1.86s | 1.618s |
| **Overall Average** | | | | | | **1.603s** |

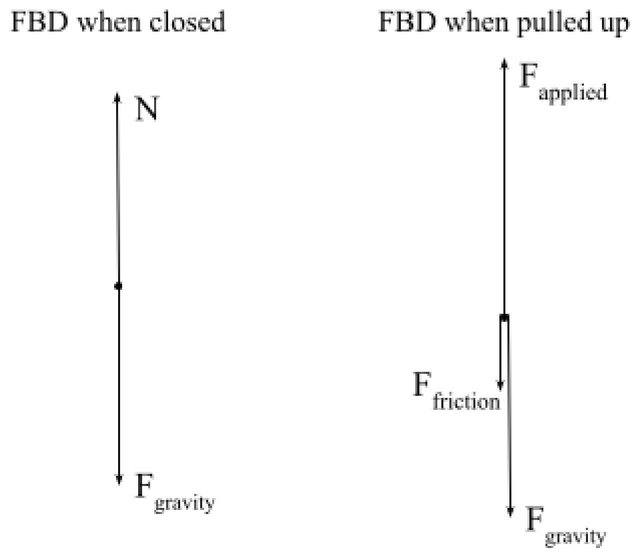
**[14.2] Lift n' Pick: Overall duration of Retrieval process** = duration of opening sliding door + duration of retrieving object

= 1.603s + 2.515s
= **4.118s**

The duration of retrieving the object was found from [2, Appendix F].

**[15] Lift n' Pick: Force**

$$F = F_{gravity} + F_{friction}$$
$$F = mg + \mu N$$
$$F = mg + \mu mg$$
$$F = (1 + \mu)\, mg$$




$F_{gravity} = N$

From research, $\mu = 0.001$ for ball bearings made with hard steel. [14, Source Extracts]
The vending machine flap from the original design is made from galvanized steel for its high security and resistance to heavy abuse. From research, the weight of galvanized steel is approximately 7.85 g/cm^3 [15, Source Extracts]). For primary research, the measurement of the flap base is 48.5cm and the length the flap must cover for the antitheft to work is 15cm, the thickness of the flap is 0.1cm. Therefore, $M_{flap} = 48.5 \times 15 \times 0.1 * 7.85 = 5710.875g = 0.5710875\, kg$

Therefore, from physics modelling with research,
$F = (1 + 0.001) \times 0.5710875 \times 9.8 = 5.6022541575N$

Since 5.60N is less than 22N required by the standard, therefore this meets the force requirement.

**[16] Lift n' Pick: Anti-Pilfer**
Given the height of the opening of the original vending machine is 12cm, the maximum opening that will allow objects to go through is 12/2 = 6cm. However, due to the angle of the at which the two openings are located, no objects can be stuck into the location of the vending machine with snacks as illustrated in figure 31 and 32.

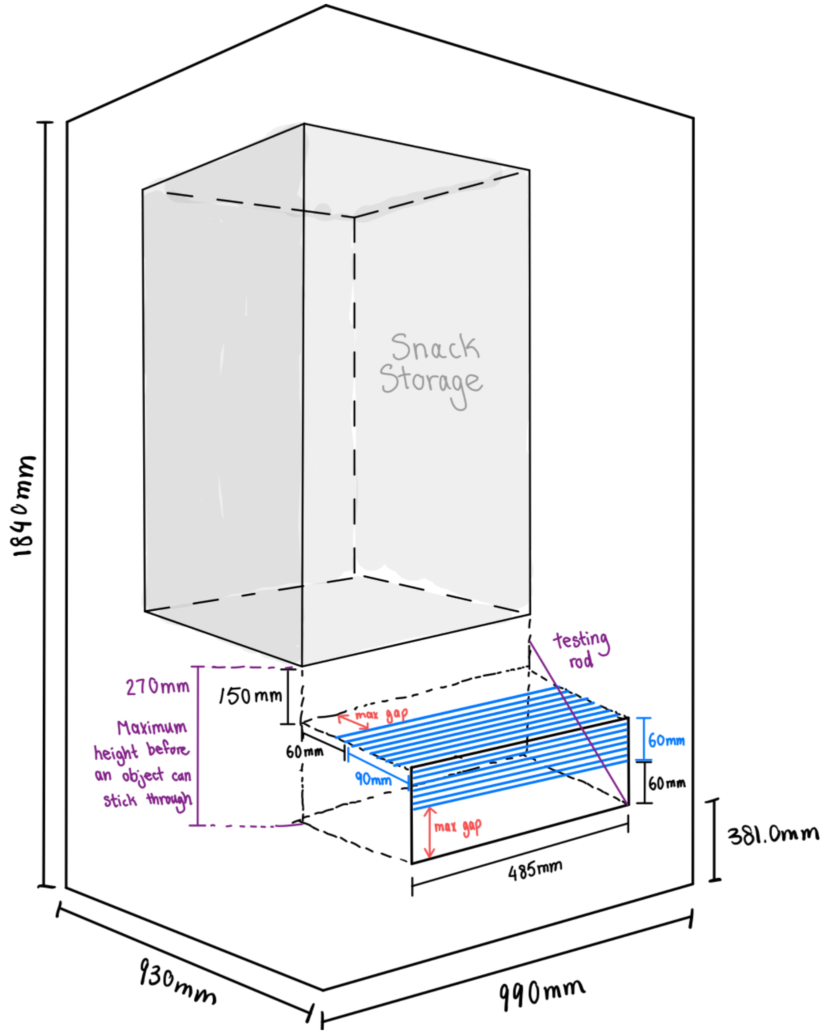



*Figure 31: A diagram of the maximum length the testing rod can reach at the maximum opening width compared to the maximum height the rod can be inserted before the rod can enter the snack area.*

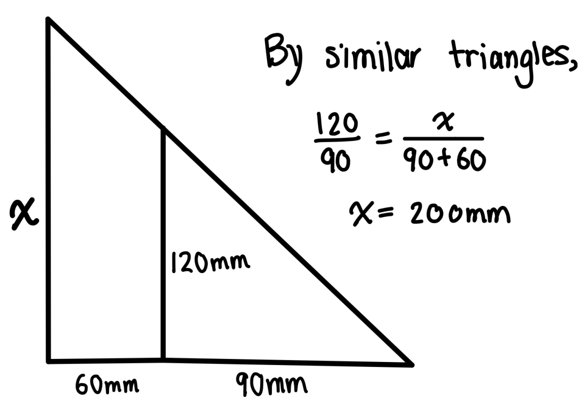



*Figure 32: A model of the calculation for the maximum height reached by the testing rod.*

Since the object can reach a maximum height of 200mm, which is less than 270mm. It cannot enter the snack area. Therefore this design fulfills the anti-pilfer criteria.

# Appendix G: Calculations

**[1]** For the largest product needing to be accounted for. The largest product sold in the vending machine is Miss Vickies Salt and Vinegar chips. We measure the size of these bags to be 180x100x50mm

**[2.1]** For the hand thickness based on largest product on the vending machine
Since the 95th percentile male hand dimensions are greater than those of the 95th percentile female hand dimensions, they were chosen to guide the measurements in objective 1.3

To measure the hand thickness, assume the hand to have a rectangular cross-section, with the hand breadth representing the length of the rectangle and the hand circumference representing the perimeter of the rectangle :

$$Hand\ thickness = \frac{23.03cm - (2 \cdot 9.76cm)}{2}$$

$$= 1.76\ cm$$

Designing to accommodate the largest product whilst also considering 95th percentile male hand dimensions, ensures that all subsequent smaller products and hand sizes will also be accounted for.

**[2.2]** For the minimum product opening retrieval size

Required depth = (depth of bag of chips) + (thumb breadth) + (hand thickness)
= (50 mm) + (26.5 mm) + (17.6 mm)
= 94.1 mm

**[3]** For the minimum distance covered to dislodge a product.
The distance between the external opening and bottom row of products depends on each machine and their setup, therefore primary evidence must be used. The horizontal distance measured from the opening to the depth of the lowest row of products was 200 mm. The vertical distance from the bottom of the flap - opened to its extreme - to the bottom of this product row was 26 cm. Using the pythagorean theorem, the overall minimum distance that must be covered in order to dislodge a product is 328mm. These measurements were taken using a standard metric stationary ruler.

**[4]** For calculating the buffer time required between sensor activation and the flap opening

$$t = \sqrt{\frac{2h}{g}}, \quad h = 1.9m$$

$$t = \sqrt{\frac{2\times1.9}{9.81}}$$

$$t = 0.62\ s$$

So, it takes approximately 0.62 seconds for an object to fall from the highest point/shelf in the vending machine into the bottom of the retrieval bin once the object is free from the coils holding the snack in place.

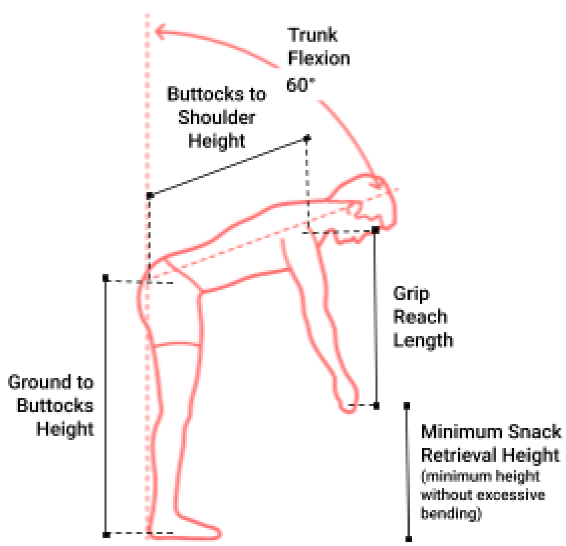
Using primary evidence (averaging the time taken for an item to go into free fall by purchasing several items from the highest shelf of the vending machine), we can conclude that it takes approximately 3.9 seconds for a product to go into free fall once a purchase has been made.

Therefore, the time taken for an object to fall from the highest shelf can be approximated to 4.52 seconds.

Taking into account this is the exact calculated value, in real life this time could be higher/lower, so to account for that we can round 4.52 to 7 seconds.

**[5.1]** For calculating the minimum product retrieval height based on body metrics [16, Source Extracts]

The maximum trunk flexion of 60° is determined from the extract about lower back pain from bending. With the Anthropometric data from the extract, the 900mm is calculated as shown below.




*Relationship between body metrics and the minimum snack retrieval height.*

*(95th percentile ground to buttock height) + (cos 60°)( 95th percentile buttock to shoulder height) - (5th percentile functional grip reach length)*

This equation is chosen because an above-average height should be offset by a below-average arm reach to get a conservative minimum height.

**[5.2]** For the overall minimum product retrieval height.
The minimum height for **males** is *968.9 mm + (cos 60°)(646.3 mm) - 692.8 mm =* ***599.25 mm***.
The minimum height for **females** is *915.0 mm + (cos 60°)(603.6 mm) - 631.9 mm =* ***584.9 mm***.
The maximum of the minimum female and male heights is taken and rounded to a minimum height of 600mm.

**[5.3]** For the optimal product retrieval height
With the minimum height of 600mm from 5.1 and the maximum height of 1200mm from 5.2, the optimal height of product retrieval is determined to be the average of the two extremes.

$$Optimal\ Product\ Retrieval\ Height\ =\ \frac{600\ mm + 1200\ mm}{2} =\ 900\ mm$$

# Source Extracts:

**4.2.7 Physical operation of controls**

Where hand controls are used, the complete operation and



information retrieval process shall have at least one mode where controls are operable

a) with one hand;

b) without tight grasping, pinching, or twisting of the wrist;

c) with a force not to exceed 22 N; and

d) from a seated and standing position.

**Notes:**

1) The requirement of Item a) does not preclude several operations one after the other.

2) The operation and information retrieval process of an interactive device may be executed by means of a user's own device which could contribute to a more inclusive experience, e.g., a user configuring a bank transaction through their smartphone and so does not have to interact with the interface of a bank machine.

[1] *CSA /ASC B651.2:25 section 4.2.7: Physical operation of controls [2, Bibliography]*

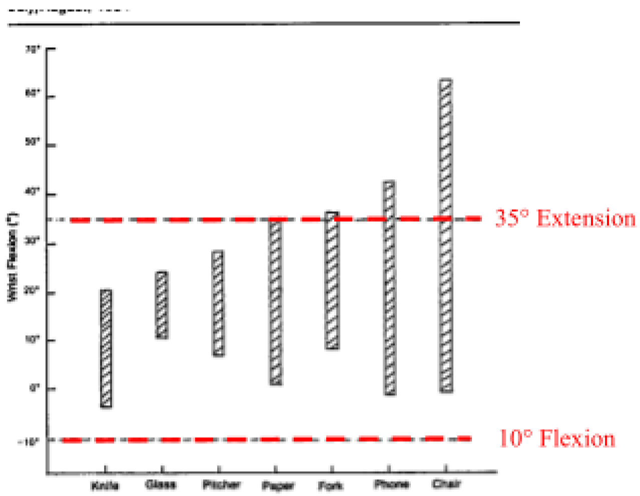



FIG. 3. Activity requiring arc of wrist motion.

requirements of the wrist for daily activities. The main thrust of previous wrist-motion research has been kinematics. Techniques such as plain[5] and stereoscopic[10] roentgenograms, cadaveric dissections,[12] and cineradiography[1] have been used. With the development of the electrogoniometer, it now seems that an arc of wrist motion of 45° (10° of flexion to 35° of extension) is sufficient to perform most of the activities included in this study.

***[2]** The results of the wrist motion required to perform most daily activities from "A Biomechanical Study of Normal Functional Wrist Motion" by Clinical Orthopaedics and Related Research [3, Bibliography]*

CSA/ASC B651.2:25 — Accessible design for self-service interactive devices including automated banking machines

### 9.1.3 Reach distances

Reach distances to all interface functions shall be

a) located within the grasp and touch ranges as specified in Annex A of CSA/ASC B651; and

b) measured from the leading edge of the interactive device or the outer edge of the shelf to the device components.

***[3]** CSA /ASC B651.2:25 section 9.1.3: Reach distances [2, Bibliography]*

**ISO 14738:2002(E)**

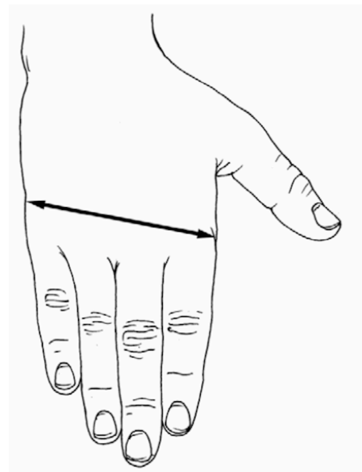
**Table A.1 (concluded)**

| Notation | Explanation | Value P5 mm | Value P95 mm | Definition see | Use see |
|---|---|---|---|---|---|
| $h_6$ | Crotch height | 665 | 900 | ISO 7250 : 1996 4.1.7 | table 7 |
| $h_8$ | Ankle height, fixed value | 96 | 96 | ISO 15534-3 | table 8 |
| $h_{11}$ | Sitting height (erect) | 790 | 1000 | ISO 7250 : 1996 4.2.1 | fig. 6 |
| $h_{12}$ | Eye height, sitting | 680 | 870 | ISO 7250 : 1996 4.2.2 | table 4 |
| $h_{13}$ | Shoulder height, sitting | 505 | | ISO 7250 : 1996 4.2.4 | table 4 |
| $h_{16}$ | Lower leg length (popliteal height) | 340 | 505 | ISO 7250 : 1996 4.2.12 | tables 5 and 6 |
| $h_{17}$ | Fist height below seating surface, sitting - fixed value | 50 | 50 | - | table 4 |
| $t_2$ | Forearm reach, elbow-grip length minus upper arm dia-meter | 170 | | ISO 7250 : 1996 4.4.3 ISO 15534-3 | table 4 |
| $t_3$ | Arm reach to side | 495 | | ISO 15534-3 | table 4 |

*[4] ISO 14738: Forearm reach 5th percentile measurement value [4, Bibliography]*

## Hand Breadth

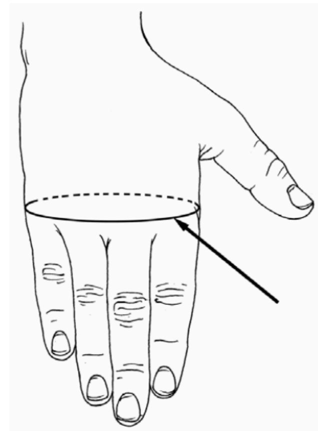
| | FEMALE N = 2208 | | | MALE N = 1774 | |
|---|---|---|---|---|---|
| **Centimeters** | | **Inches** | **Centimeters** | | **Inches** |
| 7.94 | **Mean** | 3.13 | 9.04 | **Mean** | 3.56 |
| .38 | **Std Dev** | .15 | .42 | **Std Dev** | .17 |
| 9.80 | **Maximum** | 3.86 | 10.60 | **Maximum** | 4.17 |
| 6.60 | **Minimum** | 2.60 | 7.70 | **Minimum** | 3.03 |
| | **Percentiles** | | | **Percentiles** | |
| 7.09 | 1st | 2.79 | 8.07 | 1st | 3.18 |
| 7.19 | 2nd | 2.83 | 8.19 | 2nd | 3.22 |
| 7.25 | 3rd | 2.86 | 8.27 | 3rd | 3.25 |
| 7.34 | 5th | 2.89 | 8.36 | 5th | 3.29 |
| 7.47 | 10th | 2.94 | 8.51 | 10th | 3.35 |
| 7.56 | 15th | 2.98 | 8.61 | 15th | 3.39 |
| 8.63 | 20th | 3.00 | 8.69 | 20th | 3.42 |
| 7.69 | 25th | 3.03 | 8.75 | 25th | 3.45 |
| 7.74 | 30th | 3.05 | 8.82 | 30th | 3.47 |
| 7.79 | 35th | 3.07 | 8.87 | 35th | 3.49 |
| 7.84 | 40th | 3.09 | 8.93 | 40th | 3.51 |
| 7.89 | 45th | 3.11 | 8.98 | 45th | 3.54 |
| 7.93 | 50th | 3.12 | 9.03 | 50th | 3.56 |
| 7.98 | 55th | 3.14 | 9.09 | 55th | 3.58 |
| 8.03 | 60th | 3.16 | 9.14 | 60th | 3.60 |
| 8.08 | 65th | 3.18 | 9.20 | 65th | 3.62 |
| 8.13 | 70th | 3.20 | 9.26 | 70th | 3.64 |
| 8.18 | 75th | 3.22 | 9.32 | 75th | 3.67 |
| 8.25 | 80th | 3.25 | 9.40 | 80th | 6.70 |
| 8.32 | 85th | 3.28 | 9.48 | 85th | 3.73 |
| 8.42 | 90th | 3.31 | 9.59 | 90th | 3.78 |
| 8.56 | 95th | 3.37 | 9.76 | 95th | 3.84 |
| 8.66 | 97th | 3.41 | 9.86 | 97th | 3.88 |
| 8.74 | 98th | 3.44 | 9.93 | 98th | 3.91 |
| 8.86 | 99th | 3.49 | 10.04 | 99th | 3.95 |



***[5.1]*** *Anthropometric data: Hand Breadth [6, Bibliography]*

## Hand Circumference

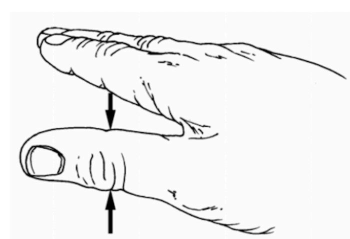
| FEMALE N = 2208 Centimeters | | Inches | MALE N = 1774 Centimeters | | Inches |
|---|---|---|---|---|---|
| **18.62** | **Mean** | 7.33 | 21.38 | **Mean** | 8.42 |
| .85 | **Std Dev** | .33 | .97 | **Std Dev** | .38 |
| 23.00 | **Maximum** | 9.06 | 24.70 | **Maximum** | 9.72 |
| 15.80 | **Minimum** | 6.22 | 18.20 | **Minimum** | 7.17 |
| | **Percentiles** | | | **Percentiles** | |
| 16.73 | 1st | 6.59 | 19.16 | 1st | 7.54 |
| 16.93 | 2nd | 6.67 | 19.45 | 2nd | 7.66 |
| 17.07 | 3rd | 6.72 | 19.62 | 3rd | 7.72 |
| 17.25 | 5th | 6.79 | 19.85 | 5th | 7.81 |
| 17.55 | 10th | 6.91 | 20.18 | 10th | 7.94 |
| 17.75 | 15th | 6.99 | 20.40 | 15th | 8.03 |
| 17.91 | 20th | 7.05 | 20.57 | 20th | 8.10 |
| 18.04 | 25th | 7.10 | 20.72 | 25th | 8.16 |
| 18.17 | 30th | 7.15 | 20.86 | 30th | 8.21 |
| 18.28 | 35th | 7.20 | 20.98 | 35th | 8.26 |
| 18.39 | 40th | 7.24 | 21.11 | 40th | 8.31 |
| 18.50 | 45th | 7.28 | 21.22 | 45th | 8.36 |
| 18.60 | 50th | 7.32 | 21.34 | 50th | 8.40 |
| 18.70 | 55th | 7.36 | 21.46 | 55th | 8.45 |
| 18.81 | 60th | 7.41 | 21.59 | 60th | 8.50 |
| 18.92 | 65th | 7.45 | 21.72 | 65th | 8.55 |
| 19.04 | 70th | 7.49 | 21.86 | 70th | 8.61 |
| 19.16 | 75th | 7.54 | 22.01 | 75th | 8.67 |
| 19.30 | 80th | 7.60 | 22.18 | 80th | 8.73 |
| 19.47 | 85th | 7.67 | 22.38 | 85th | 8.81 |
| 19.69 | 90th | 7.75 | 22.64 | 90th | 8.92 |
| 20.03 | 95th | 7.88 | 23.03 | 95th | 9.07 |
| 20.25 | 97th | 7.97 | 23.28 | 97th | 9.17 |
| 20.43 | 98th | 8.04 | 23.46 | 98th | 9.24 |
| 20.72 | 99th | 8.16 | 23.74 | 99th | 9.35 |



***[5.2]** Anthropometric data: Hand Circumference [6, Bibliography]*

## Thumb Breadth

| FEMALE N = 2208 Centimeters | | Inches | MALE N = 1774 Centimeters | | Inches |
|---|---|---|---|---|---|
| **20.7** | **Mean** | .81 | 2.41 | **Mean** | 0.95 |
| .13 | **Std Dev** | .05 | 0.14 | **Std Dev** | 0.05 |
| 2.50 | **Maximum** | .98 | 2.90 | **Maximum** | 1.14 |
| 1.70 | **Minimum** | .67 | 1.90 | **Minimum** | 0.75 |
| | **Percentiles** | | | **Percentiles** | |
| 1.78 | 1st | .70 | 2.09 | 1st | .82 |
| 1.81 | 2nd | .71 | 2.13 | 2nd | .84 |
| 1.84 | 3rd | .71 | 2.16 | 3rd | .85 |
| 1.86 | 5th | .73 | 2.19 | 5th | .86 |
| 1.91 | 10th | .75 | 2.24 | 10th | .88 |
| 1.93 | 15th | .76 | 2.27 | 15th | .90 |
| 1.96 | 20th | .77 | 2.30 | 20th | .91 |
| 1.97 | 25th | .78 | 2.32 | 25th | .91 |
| 1.99 | 30th | .78 | 2.34 | 30th | .92 |
| 2.01 | 35th | .79 | 2.36 | 35th | .93 |
| 2.03 | 40th | .80 | 2.38 | 40th | .94 |
| 2.04 | 45th | .80 | 2.39 | 45th | .94 |
| 2.06 | 50th | .81 | 2.41 | 50th | .95 |
| 2.08 | 55th | .82 | 2.43 | 55th | .96 |
| 2.09 | 60th | .82 | 2.45 | 60th | .96 |
| 2.11 | 65th | .83 | 2.46 | 65th | .97 |
| 2.13 | 70th | .84 | 2.48 | 70th | .98 |
| 2.15 | 75th | .85 | 2.51 | 75th | .99 |
| 2.18 | 80th | .86 | 2.53 | 80th | 1.00 |
| 2.20 | 85th | .87 | 2.56 | 85th | 1.01 |
| 2.24 | 90th | .88 | 2.60 | 90th | 1.02 |
| 2.29 | 95th | .90 | 2.65 | 95th | 1.04 |
| 2.31 | 97th | .91 | 2.68 | 97th | 1.06 |
| 2.33 | 98th | .92 | 2.71 | 98th | 1.07 |
| 2.35 | 99th | .93 | 2.74 | 99th | 1.08 |



***[5.3]** Anthropometric data: Thumb Breadth [6, Bibliography]*

### 4.3.3 Height

The centreline of the operating controls shall be located in a range between 400 and 1200 mm from the floor (see Figure 3).

**Note:** The specified limits are the minimum and maximum, and might not be ideal for all applications. For effective user access, care should be used when locating controls close to the 400 or 1200 mm limits, especially when a complex action or manipulation is required.

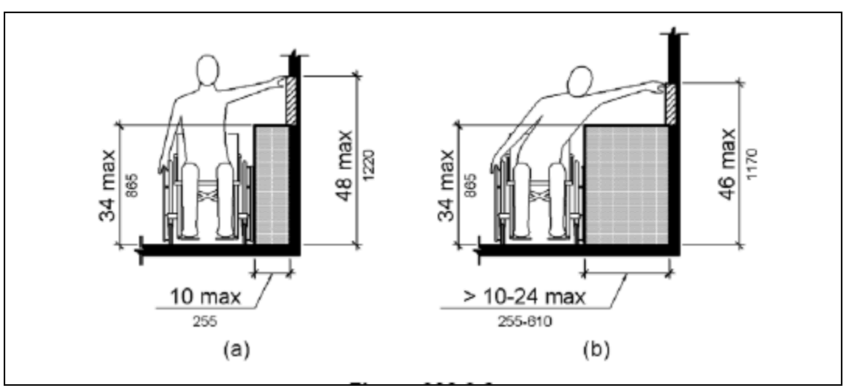
***[6]*** *Height of operating controls from CSA/ASC B651 Accessible Design for the Built Environment [6, Bibliography]*

**308.3.2 Obstructed High Reach.** Where a clear floor or ground space allows a parallel approach to an element and the high side reach is over an obstruction, the height of the obstruction shall be 34 inches (865 mm) maximum and the depth of the obstruction shall be 24 inches (610 mm) maximum. The high side reach shall be 48 inches (1220 mm) maximum for a reach depth of 10 inches (255 mm) maximum. Where the reach depth exceeds 10 inches (255 mm), the high side reach shall be 46 inches (1170 mm) maximum for a reach depth of 24 inches (610 mm) maximum.

**EXCEPTIONS:**

1. The top of washing machines and clothes dryers shall be permitted to be 36 inches (915 mm) maximum above the finish floor.
2. Operable parts of fuel dispensers shall be permitted to be 54 inches (1370 mm) maximum measured from the surface of the vehicular way where fuel dispensers are installed on existing curbs.

**Figure 308.3.2**




**Obstructed High Side Reach**

***[7]*** *Reach distances from ADA Accessibility Standards [7, Bibliography]*

**PHYSICAL CHARACTERISTICS**

- Finish : Powder Coat paint
- Compliant with US ADA standards for vending equipment.

**ENVIRONMENT**

- Indoors only; Infinity Xtreme versions available from your Seaga distributor for outdoor use.

***[8]** Vending machine standards from Ambient and Refrigerated Models SERVICE and PARTS MANUAL [1, Bibliography]*

**228 Depositories, Vending Machines, Change Machines, Mail Boxes, and Fuel Dispensers**

**228.1 General.** Where provided, at least one of each type of depository, vending machine, change machine, and fuel dispenser shall comply with 309.

**EXCEPTION:** Drive-up only depositories shall not be required to comply with 309.

> **Advisory 228.1 General.** Depositories include, but are not limited to, night receptacles in banks, post offices, video stores, and libraries.

**228.2 Mail Boxes.** Where *mail boxes* are provided in an interior location, at least 5 percent, but no fewer than one, of each type shall comply with 309. In residential *facilities*, where *mail boxes* are provided for each *residential dwelling unit*, *mail boxes* complying with 309 shall be provided for each *residential dwelling unit* required to provide mobility features complying with 809.2 through 809.4.

***[9.1]** Vending machine standards from American with Disabilities Act [7, Bibliography]*

**309 Operable Parts**

**309.1 General.** *Operable parts* shall comply with 309.

**309.2 Clear Floor Space.** A clear floor or ground *space* complying with 305 shall be provided.

**309.3 Height.** *Operable parts* shall be placed within one or more of the reach ranges specified in 308.

**309.4 Operation.** *Operable parts* shall be operable with one hand and shall not require tight grasping, pinching, or twisting of the wrist. The force required to activate *operable parts* shall be 5 pounds (22.2 N) maximum.

**EXCEPTION:** Gas pump nozzles shall not be required to provide *operable parts* that have an activating force of 5 pounds (22.2 N) maximum.

***[9.2]** Vending machine standards from American with Disabilities Act [7, Bibliography]*

**GLOBAL ENCLOSURE STANDARDS WITHIN THE ELECTRICAL INDUSTRY**

**ENCLOSURE IP RATINGS**

| First Numeral IP | Test | Second Numeral IP | Test |
|---|---|---|---|
| 0 | No protection | 0 | No protection |
| 1 | Protected against solid objects up to 50 mm, e.g. accidental touch by hands | 1 | Protected against vertically falling drops of water, e.g. condensation |
| 2 | Protected against solid objects up to 12 mm, e.g. fingers | 2 | Protected against direct sprays of water up to 15° from vertical |
| 3 | Protected against solid objects over 2.5 mm, e.g. tools and wires | 3 | Protected against sprays to 60° from vertical |

***[10]** Vending machine standards from Global Enclosure Standards [10, Bibliography]*

12VAC5-421-1430. Vending machine doors and openings.

A. Vending machine doors and access opening covers to food and container storage spaces shall be tight-fitting so that the space along the entire interface between the doors or covers and the cabinet of the machine, if the doors or covers are in a closed position, is no greater than one-sixteenth inch or 1.5 millimeters by:

1. Being covered with louvers, screens, or materials that provide an equivalent opening of not greater than one-sixteenth inch or 1.5 millimeters. Screening of 12 mesh to 1 inch (12 or more mesh to 2.5 centimeters) meets this requirement;

2. Being effectively gasketed;

3. Having interface surfaces that are at least one-half inch wide or 13 millimeters; or

4. Jambs or surfaces used to form an L-shaped entry path to the interface.

B. Vending machine service connection openings through an exterior wall of a machine shall be closed by sealants, clamps, or grommets so that the openings are no larger than 1.5 millimeters or one-sixteenth inch.

***[11]** The maximum closing gap between the vending machine covering and exterior surface from Virginia Law [19, Bibliography]*

(i) Being covered with louvers, screens or materials that provide an equivalent opening of not greater than 1.5 millimeters or 1/16 inch. Screening of 12 or moremesh to 2.5 centimeters (12 mesh to 1 inch) meets this requirement.

(ii) Being effectively gasketed.

(iii) Having interface surfaces that are at least 13 millimeters or 1/2 inch wide.

(iv) Jambs or surfaces used to form an L-shaped entry path to the interface.

(2) Vending machine service connection openings through an exterior wall of the machine, shall be closed by sealants, clamps, or grommets so that the openings are no larger than 1.5 millimeters or 1/16 inch.

***[12]** The maximum closing gap between the vending machine covering and exterior surface from Pennsylvania Law [20, Bibliography]*

## Fundamental concepts of friction and lubrication affecting textile fibers

### 2.15 Rolling friction

In addition to sliding, one can also move materials by rolling. The great advantage of rolling a body over sliding is that the friction in rolling may be two or more orders of magnitude lower than that in sliding. The greatest application of this concept is made in the use of ball and roller bearings, in which the balls or rollers are free to roll in a groove called a race without any shaft or trunnion to support them.

It was thought that low friction in rolling was due to minute slips between ball and surface; however, studies have shown that although slip did occur, it contributed only a small part to the rolling resistance. This is supported by the fact that lubricants that reduce sliding resistance had little effect on total rolling resistance [3, p 131]. The underlying mechanism governing rolling friction is again the deformation of the bulk discussed in the previous section. If a hard ball is rolled over a soft metal plate (Fig. 2.7(a)) it produces a groove by displacing metal plastically. If one measures the force required to displace metal, it is found to equal the observed rolling friction. This also illustrates why lubricants have so little effect on the latter. Consider now the set up shown in Fig. 2.7(b) in which a hard steel ball is rolled over a flat rubber sheet. Although no permanent groove is formed, work is still lost. In rolling, the ball deforms rubber ahead of it and does work; but much of this deformation is recovered at the rear as the ball is urged forward. As alluded to earlier, no material is ideally elastic, some energy (due to elastic hysteresis caused by internal friction between rubber molecules as they rub over each other) is lost. The amount lost will vary, a bouncy rubber may recover 95% (Fig. 2.8(b)), whereas a "soggy" rubber may recover only a small amount (Fig. 2.8(c)) and lose most of the work expended. Ball bearings are made of hard steel and the devices are designed so that the stresses are small, i.e. they lie within the elastic region. This gives very small rolling resistance ($\mu \sim 0.001$). Theoretically, the total frictional resistance is given by the sum of the forces due to adhesion and deformation (equation 2.6):

***[13]** Passage from Chapter 2 "Fundamental concepts of friction and lubrication affecting textile fibers" from the textbook "Friction in Textile Materials" page 37 - 66 [24, Bibliography]*

- **Other Protective Equipment**: An eyewash fountain and deluge shower should be readily available in the work area.

## Section 9 - Physical and Chemical Properties

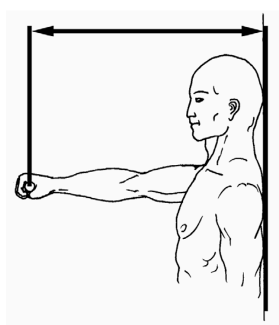
**9(a) Appearance (physical state, color, etc.):** Metallic Gray
**9(b) Odor:** Odorless
**9(c) Odor Threshold:** NA
**9(d) pH:** NA
**9(e) Melting Point/Freezing Point:** ~2750°F (~1510°C); Coating: ~2750°F (~1510°C)
**9(f) Initial Boiling Point and Boiling Range:** Coating: ~1700°F (~927°C)
**9(g) Flash Point:** NA
**9(h) Evaporation Rate:** NA
**9(i) Flammability (solid, gas):** Non-flammable, non-combustible
**9(j) Upper/lower Flammability or Explosive Limits:** NA
**9(k) Vapor Pressure:** NA
**9(l) Vapor Density (Air = 1):** NA
**9(m) Relative Density:** 7.85 g/cc; Coating: 7.14 g/cc
**9(n) Solubility(ies):** Insoluble
**9(o) Partition Coefficient n-octanol/water:** ND
**9(p) Auto-ignition Temperature**: NA
**9(q) Decomposition Temperature**: ND
**9(r) Viscosity:** NA

**NA** - Not Applicable
**ND** - Not Determined for product as a whole

*[14] Density of Galvanized Steel from the Safety Data Sheet of Galvanized Steel from United States Steel Corporation [25, bibliography]*

**Functional Grip Reach**

| FEMALE N = 2208 Centimeters | | Inches | MALE N = 1774 Centimeters | | Inches |
|---|---|---|---|---|---|
| 68.61 | **Mean** | 27.01 | 75.07 | **Mean** | 29.55 |
| 3.39 | **Std Dev** | 1.33 | 3.68 | **Std Dev** | 1.45 |
| 83.20 | **Maximum** | 32.76 | 92.10 | **Maximum** | 36.26 |
| 57.50 | **Minimum** | 22.64 | 62.60 | **Minimum** | 24.65 |
| | **Percentiles** | | | **Percentiles** | |
| 61.51 | 1st | 24.22 | 67.26 | 1st | 26.48 |
| 62.12 | 2nd | 24.46 | 68.04 | 2nd | 26.79 |
| 62.55 | 3rd | 24.63 | 68.55 | 3rd | 26.99 |
| 63.19 | 5th | 24.88 | 69.28 | 5th | 27.28 |
| 64.26 | 10th | 25.30 | 70.45 | 10th | 27.74 |
| 65.03 | 15th | 25.60 | 71.27 | 15th | 28.06 |
| 65.66 | 20th | 25.85 | 71.93 | 20th | 28.32 |
| 66.22 | 25th | 26.07 | 72.52 | 25th | 28.55 |
| 66.72 | 30th | 26.27 | 73.05 | 30th | 28.76 |
| 67.19 | 35th | 26.45 | 73.54 | 35th | 28.95 |
| 67.64 | 40th | 26.63 | 74.02 | 40th | 29.14 |
| 68.08 | 45th | 26.80 | 74.49 | 45th | 29.33 |
| 68.51 | 50th | 26.97 | 74.95 | 50th | 29.51 |
| 68.95 | 55th | 27.15 | 75.42 | 55th | 29.69 |
| 69.40 | 60th | 27.32 | 75.90 | 60th | 29.88 |
| 69.86 | 65th | 27.50 | 76.40 | 65th | 30.08 |
| 70.34 | 70th | 27.69 | 76.92 | 70th | 30.29 |
| 70.87 | 75th | 27.90 | 77.50 | 75th | 30.51 |
| 71.46 | 80th | 28.14 | 78.15 | 80th | 30.77 |
| 72.15 | 85th | 28.41 | 78.91 | 85th | 31.07 |
| 73.03 | 90th | 28.75 | 79.87 | 90th | 31.45 |
| 74.36 | 95th | 29.27 | 81.31 | 95th | 32.01 |
| 75.24 | 97th | 29.62 | 82.25 | 97th | 32.38 |
| 75.90 | 98th | 29.88 | 82.94 | 98th | 32.65 |
| 76.97 | 99th | 30.30 | 84.03 | 99th | 33.08 |



*[15] Anthropometric data: Buttock height, Sitting shoulder height, functional grip reach [6, Bibliography]*

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