Violin Prosthetic

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Violin Prosthetic

This document contains information regarding a lower arm prosthetic that was designed for an 11-year-old violin player named Sam. Sam was born without fingers or a thumb on this right hand—the hand that holds a bow when playing the violin. Sam currently has a prosthetic that consists of a bow rigidly attached to a wrist brace. This prosthetic was successful in allowing Sam to learn the basics of playing the violin. However, the prosthetic allowed Sam to only use 30 percent of the length of the bow. In order for Sam to progress in his violin ability, it is necessary that he be able to use a larger portion of the bow. Additionally, the connection between Sam’s original prosthetic and the bow caused damage to the wood of the bow.

The intention behind this prosthetic was to allow Sam to utilize a larger portion of the length of the bow, and comfortably play the violin for an extended period of time. It was also important that the violin prosthetic not cause any damage to the violin bow. The following document outlines the design process of a violin bow prosthetic that successfully achieved the goals stated above. This includes research, developing design constraints and considerations, and the decision making process leading to the final product.

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1 Introduction

Sam, an 11-year-old violin player was born without fingers or a thumb on his right hand. In order to learn the basics of violin, he currently uses a custom made prosthetic that allows him to hold a violin bow. However, his current prosthetic does not allow for the bow angle to change relative to his wrist, and thus, he cannot perform many techniques that are important to him furthering his violin skills. Specifically, his prosthetic allows Sam to use only a small percentage of the bow. For this project, a prosthetic was designed for Sam with the goal being to allow Sam to replicate full wrist motion such that he can keep the bow perpendicular to the violin strings and use an increased percentage of the length of the bow. The prosthetic needs to be light and comfortable so that Sam can play for extended periods of time.

2 Problem Understanding

Studying existing designs for prosthetic bow devices, both patented and not, facilitates better understanding of user needs and existing design limitations. Additionally, codes and standards are important to research in order to ensure proper implementation of a new prosthetic.

2.1 Existing Devices

The new prosthetic design can draw insight from existing devices created for similar applications. The devices in this section share similar functionalities with the new prosthetic and have relevant designs. They all involve prosthetics for violin players with varying degrees of physical impairment.

2.1.1 Existing Device #1: Manami Ito’s Prosthetic Bow

Figure 1: Manami Ito playing the violin with her prosthetic bow (Source: My Modern Met).

Link: https://www.youtube.com/watch?v=MYezcuVwUU4
Description: Manami Ito’s prosthetic bow allows her to play the violin, even though she is missing her right arm. The prosthetic is harnessed to her shoulder joint with straps across her back and a strap looped around her other shoulder. Wires run along her back and follow the strap connecting one shoulder to the other. The prosthetic works with a tension based system such that when the wires along her back are flexed, the prosthetic elbow joint triggers and moves. This allows her to control the motion of the prosthetic elbow with intentional movements of her opposite side shoulder. A custom-made bow grip is attached to the end of this prosthetic which grips the bow while allowing free rotation about the axis of the prosthetic forearm. A small rod is attached vertically to her violin on the side of the strings opposite her prosthetic. This rod ensures that the bow does not slip too far down the strings and gives her more control over the angle between the bow and the violin.

2.1.2 Existing Device #2: Sam’s Current Prosthetic

Description: The current prosthetic consists of a store-bought wrist brace which attaches to the bow. The wrist brace is secured on the wrist with several velcro straps. The bow is rigidly attached to the brace such that it is always at the same angle with respect to the forearm (close to, but not quite, 90 degrees). The user can control the bow both by utilizing their shoulder joint and their elbow joint. However, if the user holds their violin in a standard position, the bow significantly changes angles with respect to the violin strings whenever the elbow bends. In order to maintain proper technique, the user is limited to controlling the violin bow with just their shoulder joint. Consequently, the user has limited motion of the arm in order to maintain an approximately 90 degree angle between the bow and the strings.
2.1.3 Existing Device #3: Isabella Nicola Cabrera Violin Prosthetic

Figure 3: Isabella Nicola Cabrera playing the violin with her prosthetic bow (Source: My Modern Met).

Link: Washington Post Article

Description: Isabella Nicola Cabrera’s current violin prosthetic is made of 3D-printed plastic and attaches to her upper arm. Velcro straps allow for finer adjustments and dismounting of the prosthetic. The violin bow is rigidly attached to an adjustable mount at the far end of the prosthetic for occasional adjustments. Cabrera, born without a left hand or part of her forearm, uses muscles in her left arm to control the prosthetic. Movement is enabled by a joint at her elbow, which allows her to use her shoulder muscles. While she is able to move the bow perpendicular to the strings, she is limited to about half the total length of the bow. Further, a lack of a pivot point akin to a wrist joint limits total possible motion.

2.2 Patents

Patents serve to record technological achievements in many areas of society, including medical prosthetics. Highlighted in this section are two patents which demonstrate a few of the ways in which prosthetics enable users to play violin.

2.2.1 Mechanical Prosthetic Hand

(US20170266020A1)

This patent is for a mechanical prosthetic hand [1]. The size of the hand is adjustable and the fingers can be operated individually or together as they are attached by cables. The prosthetic is hollow and lightweight, making it comfortable for the user. The hand attaches to a sleeve worn by the user.
2.2.2 Forearm Prosthesis  
(SU145981A1)

This prosthetic was developed in 1960 to ensure that the user’s hand would be able to turn and rotate when playing the violin [2]. At the elbow joint, there is a guide disk connected by a propeller and a rotary sleeve. This allows the bow to move in the right direction when the elbow joint is rotated.

2.3 Codes & Standards

This section highlights two international standards that are relevant to this project. These standards ensure the safety of the customer and the quality of the product.
2.3.1 External Limb Prostheses and External Orthoses: Requirements and Test Methods
(ISO 22523)

The international standard ISO 22523 specifies requirements and test methods for external limb prostheses and external orthoses [3]. This applies to the prosthetic design as it is being attached to Sam’s arm, an external limb. Two important considerations that are outlined in the standard include the specification of strength requirements and allowable materials.

2.3.2 Description of Upper Limb Prosthetic Components
(ISO 13405-3:2015)

The international standard ISO 13405-3:2015 sets restrictions for components of upper limb prosthetics [4]. The standard defines the methods of socket suspension as well as the types of wrist, elbow and shoulder units that can be used. This applies to Sam’s prosthetic as the prosthetic is being attached to an upper limb. The standard can be used by both the manufacturer to describe their product and the consumer to provide feedback.

2.4 User Needs

While some of the needs for a product solution may be understood from the problem statement, an interview with the customer enables greater clarity for the designers. Additionally, a customer interview allows for a tailored solution that can increase total shareholder value. This section includes a summary of the interview conducted for this project and a compilation of the customer’s needs, prioritized by importance.

2.4.1 Customer Interview

Interviewees: Sam and his violin instructor
Location: A Violin Studio, St. Louis, MO
Date: September 6th, 2019
Setting: Both Sam and his instructor were prepared with their respective violins and bows. Sam stood at the front of the room, his instructor sitting on a chair adjacent to the interviewers. The interview lasted for approximately thirty minutes.

Interview Notes:

How long has Sam been playing violin?
- Playing violin for seven years.
- Using current prosthetic for four years.

What is the main function you want the new prosthetic to improve upon?
- The ability to use more of the bow. Right now Sam can use less than half of the bow while playing. To play at a higher level, he will need to be able to use more of the bow.

Are there any other functions that would be useful to add to the new prosthetic?
- The ability to “bounce” the bow on the violin. Right now he doesn’t have the fine motor control to perform this action.
- The ability to attach the bow to the prosthetic closer to the "frog" of the bow without damaging it.
- The ability to twist/rotate the bow as it goes up and down the violin would also be nice.
- Not opposed to a prosthetic that has pieces that attach to other parts of his arm.
- Having the bow stem (frog) closer to his hand.

How does the current prosthetic work?
- Attached with a flexible, velcro wrist brace.
- A metal piece with a clamp is inserted into the brace and the bow is screwed in.
- The bow moves with his shoulder movements and rotates with forearm rotation, not the usual wrist rotation.

What are some major drawbacks of the current prosthetic?
- The metal in the brace does not allow wrist movement so he can only use part of the bow.
- The screws that lock the bow in place also damage the bow.
- Pushing hard on the bow causes it to slip loose at times.
- Currently hunches shoulder to hold the violin at a more optimal angle to the bow, would be better in the long run to have proper form to hold the violin.

What do you like about the current prosthetic?
- The flexibility is comfortable for him to play with, especially with the sock.
- The lightness of the prosthetic allows him to play for long periods of time because his arm is not weighed down.
- Has not had to adjust the prosthetic much, but would like the ability to do so.

Any irritation or hot spots with the current prosthetic?
- No irritation or hot spots.
- Material is flexible and he wears a sock underneath the prosthetic.
- His older prosthetic was made of plastic, rigid, and heavy, which was uncomfortable.

What range of wrist motion would he need?
- The wrist motion would mostly be in the plane of his upper arm to keep the bow perpendicular to the violin in order to use more of the bow.
- The ability to move the wrist up and down would allow Sam to bounce the bow and twist the bow.

Is Sam able to put on the current prosthetic easily and quickly?
- The wrist brace can be equipped easily and he has no complaints about the time that it takes.
Does he have any limitations to his movement?
  – He has full functionality in his wrist and can move it in all directions needed to play the violin.
  – Right arm is shorter than the left.

Are there any things to consider in terms of longevity of use (specifically regarding possible development of Sam’s arm)?
  – Unsure how his arm will develop in the future.
  – His right arm has less muscle.
  – Is only 11 so will most likely grow a lot.
  – Currently uses a half-size violin will eventually move to larger sizes of violin with longer bows.

How does he transport the prosthetic?
  – Used to have a bag for it until his dog chewed it up.
  – Now carries it with his sheet music but would consider putting it in his violin case.

Are there any preferences for the color of the new prosthetic?
  – His favorite color is orange but a more subtle color would probably be better.

Are there any durability concerns?
  – Has used his current prosthetic for the past 4-5 years, but would like the new prosthetic to last a long time.
  – Has a dog that has had access to the prosthetic in the past.
  – Has younger siblings that could also have access to the prosthetic.

2.4.2 Interpreted User Needs

From the information gathered in the interview, the customer needs are defined. These needs cover the general functions or properties of the prosthetic that are deemed necessary or important. A rating of five means the need is deemed of the most importance and a rating of one means it is of the least importance.
Table 1: Interpreted Customer Needs

<table>
<thead>
<tr>
<th>Need Number</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The prosthetic allows the use of more of the bow length</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>The prosthetic does not damage the bow</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>The prosthetic is lightweight</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>The prosthetic is comfortable</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>The prosthetic is easy to put on</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>The prosthetic is portable</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>The prosthetic allows wrist movement</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>The prosthetic is durable</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>The prosthetic is adjustable</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>The prosthetic allows proper shoulder posture</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>The prosthetic is child safe/safe to use</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>The prosthetic can pluck the violin strings</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>The prosthetic has an appropriate appearance</td>
<td>2</td>
</tr>
</tbody>
</table>

2.5 Design Metrics

From the interpreted user needs, design metrics can be defined. As the prosthetic is developed, it will be compared to the design metrics and improved as needed.

Table 2: Target Specifications

<table>
<thead>
<tr>
<th>Metric Number</th>
<th>Associated Needs</th>
<th>Metric</th>
<th>Units</th>
<th>Acceptable</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,4,6</td>
<td>Total weight</td>
<td>kg</td>
<td>&lt; 0.3</td>
<td>&lt; 0.15</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Amount of bow that can be used</td>
<td>percentage</td>
<td>&gt; 60</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>2,8</td>
<td>Decrease in radius of bow at connection after one month of use</td>
<td>percentage</td>
<td>&lt; 10</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>3,4,5,9,10</td>
<td>Rating of comfort by Sam</td>
<td>avg. score</td>
<td>&gt; 3/5</td>
<td>&gt; 4/5</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Time it takes to equip prosthetic</td>
<td>s</td>
<td>&lt; 120</td>
<td>&lt; 60</td>
</tr>
</tbody>
</table>
3 Concept Generation

With a more nuanced understanding of the customer’s needs and how these needs are translated into design metrics, several concepts can be developed in order to visualize various solutions for the violin prosthetic. The generation of various concepts and the assessments of how each concept would fit the customer’s needs is detailed in the following sections.

3.1 Mockup Prototype

The mockup utilizes a ball bearing in order to replicate the wrist motion needed to play the violin without use of fingers or a thumb on the player’s right hand. It implements the idea of stoppers fixed to the brace so that the bow does not swing out of the necessary range of motion.

![Figure 6: Close up view of mockup.](image)

![Figure 7: Top view of prosthetic mockup.](image)
3.2 Functional Decomposition

The violin prosthetic must meet certain functional criteria defined during the Problem Understanding. The necessary functions are shown in Fig. 8. The overall purpose of allowing Sam to play the violin without fingers or a thumb can broken down into smaller functions. These functions must be accomplished in order to achieve the overall goal.

Figure 8: Function tree for Violin Prosthetic, hand-drawn and scanned.
3.3 Morphological Chart

A morphological chart provides a way to visualize different solutions to a problem. In designing the violin prosthetic, several concepts fulfill the same functions in different ways. Figure 9 provides a means to brainstorm and outline each of these concepts.

![Morphological Chart for Violin Prosthetic](image)

Figure 9: Morphological chart for Violin Prosthetic.

3.4 Alternative Design Concepts

Combining solutions from the Fig. 9’s morphological chart in realistic and holistic solutions, four violin prosthetic concepts were developed and are shown and detailed in the following section. Each of the concepts fulfills the functions that were deemed necessary through the interview with Sam.
3.4.1 Coupled Prosthetic, Concept One

Figure 10: Initial sketch of Coupled Prosthetic.
Figure 11: Final sketch of Coupled Prosthetic.

Solutions from morph chart:

1. Prosthetic is adjusted with velcro
2. Bow is coupled with upper arm
3. Ball bearings
4. Use of elbow
5. Wrist brace forms interface with forearm
6. Pizzicato is not feasible

Description: This prosthetic design is connected to the arm in two places. A flexible wrist brace serves as the interface between the forearm and the bow grip. The wrist brace is adjustable using velcro straps. The bow attaches to the wrist brace via a padded screw that tightens the bow into place. To allow the bow to rotate with respect to the forearm, the wrist brace has a ball bearing at the connection between the bow and the forearm. A brace fitted with velcro around the upper arm guides the bow onto the violin using a tube. The rod holding the tube is connected to the arm brace with a hinge to keep the bow in line with the violin. This mechanism would keep the angle between the bow and the strings consistent, allowing Sam to access more of the bow’s length.
3.4.2 Wrist Rotation Prosthetic, Concept Two

Figure 12: Initial sketch of Wrist Rotation Prosthetic.
Figure 13: Final sketch of Wrist Rotation Prosthetic.

Solutions from morph chart:

1. Prosthetic is adjustable with velcro
2. Stoppers on the violin
3. Wrist rotates the bow
4. Wrist tilts the bow
5. Potential for pizzicato

Description: This prosthetic design is based off of the assumption that Sam’s current wrist motion and strength is sufficient to control the motion of a violin bow. With this concept, the bow is clamped in such a way that it is below Sam’s palm, as is the natural position for a violin player. This way, Sam can control the rotation of the bow and he will also be allowed use of the full bow length. Attached to the violin would be stoppers that would ensure that bow would stay in the proper position on the strings. Foam grips would connect the wrist brace to the bow, as well as the stoppers to the violin, in an attempt to prevent any damage to the bow.
3.4.3 Bearing Prosthetic, Concept Three

Figure 14: Initial sketch of Bearing Prosthetic.
Figure 15: Final sketch of Bearing Prosthetic, further developed as a mockup.

Solutions from morph chart:

1. Prosthetic can slide onto arm
2. Stoppers at "frog end" of bow control it
3. Ball bearings allow for bow rotation
4. Wrist brace or 3D printed
5. Potential for pizzicato via 3D printed chip

Description: A commercial wrist brace forms the foundation for this prosthetic concept. A ball bearing, securely mounted onto the brace, is an integral part of this design, as it allows for free 360 degree rotation of the bow attachment with respect to the arm attachment. A 3D printed piece will be sewn to the wrist brace to mount the outer ring of the bearing. The inner ring of the bearing will be mounted to a clamp which will hold the rod of the bow. Additionally, two end-stops, attached to the bearing, limit the range of motion for the bow to a level of rotation that will prevent the bow from swinging dangerously out.
3.4.4 Ball Joint Prosthetic, Concept Four

Figure 16: Initial sketch of Ball Joint Prosthetic.
Solutions from morph chart:

1. Prosthetic is adjusted with velcro
2. Ball joint for rotation about the x axis
3. Ball joint for rotation about the y axis
4. Wrist brace interface with arm
5. Guitar pick pizzicato attachment

Description: A commercial wrist brace serves as the base of this prosthetic. It can be interfaced with Sam’s arm and easily adjusted using velcro straps. A ball joint equipped with a clamping mechanism is sewn onto the wrist brace such that the bow can be attached. The clamping mechanism consists of a 3D printed grip which hinges open and closed to attach to the rod of the bow. The grip has a padded inner circumference to avoid damage to the bow. Once the bow is secured into place, it can be easily placed on the violin strings and will rotate about both the x-axis and the z-axis. A guitar pick is attached using string to the base of the wrist brace to allow Sam to perform the pizzicato technique.
4 Concept Selection

The following section outlines the logic behind decisions that will be made in the concept selection. Important project criteria will be determined and mathematical models will be utilized to make informed and logical decisions regarding the violin prosthetic.

4.1 Selection Criteria

The Selection Criteria section serves to quantify the relative importance of specific design aspects. An Analytic Hierarchy Process (AHP) results in the weighting of each design criteria relative to the other criteria in terms of importance. Each of the criteria are ranked against each other on a scale of 1/9 to 9, with 9 being significantly more important, 1/9 being significantly less important, and 1 being of equal importance. This AHP chart is shown in Fig. 18.

![AHP Chart](image)

Figure 18: AHP to determine scoring matrix weights.

4.2 Concept Evaluation

The Concept Evaluation section uses a Weighted Scoring Matrix (WSM) to quantify one concept’s criteria compared to the others. Using the AHP values of each criteria’s relative importance, an overall score may be calculated for each concept. The highest scoring concept best meets the criteria when normalized for importance. Note that for this specific analysis, the criterion of “functionality” includes the feasibility of the prosthetic on the client. The WSM is shown in Fig. 19.
4.3 Evaluation Results

To determine which concept would be pursued of the four, analyses from both the AHP and WSM were considered. From the AHP, the most important criteria was manufacturability followed closely by functionality. This was because the prosthetic design needs to be feasible given a limited amount of time and resources. Additionally, the prosthetic should improve on Sam’s current model by giving him the ability to rotate the bow and use more of its length.

Following functionality and manufacturability was comfort, portability, durability, and lastly, aesthetic. It was apparent through the customer interview that Sam should be able to use the prosthetic for extended periods of time, and thus it should be comfortable. Portability was important since Sam needs to be able to transport the prosthetic within his violin case to play it at lessons and at school. The prosthetic needs to be durable, so that it functions for many playing sessions without the need for repair, and aesthetic design was chosen as a criteria so that Sam will like the look of the prosthetic. Taking this into account, the WSM was made and the four designs were ranked based on the criteria.

The best idea, according to the WSM, was the concept that used Sam’s wrist motion to move and rotate the bow. This idea was closely followed by the concept that used a ball bearing to mimic wrist motion. The design ranked third used a ball joint and this would not allow Sam to put any pressure on the bow. The idea ranked fourth was the coupling device which would not be feasible to manufacture and may also be less comfortable for Sam. Based on the assumption that Sam does not have the wrist strength to pursue the highest ranked design concept, the second highest ranked design with the ball bearing was ultimately chosen. The scores from the WSM for the first and second options were close enough that this decision was justified. This concept currently did not include the ability to perform pizzicato. However, this function was not deemed necessary for the final product.
4.4 Engineering Models/Relationships

Figure 20 depicts the optimal angle for the stoppers so that Sam can use 70 percent of the bow while ensuring that the bow is playing in the correct position on the strings. The lengths and angles used in the final relationships are labeled on the diagrams.

Two limiting cases were considered in this model. The limiting case where Sam’s arm is fully extended determines the minimum necessary angle between Sam’s forearm and the bow such that...
the bow remains in the playable range. The other limiting case, with Sam’s arm fully contracted, helps to determine the maximum necessary angle. With these angles, the design can use the geometry from the schematics to determine the necessary ratios, \( r_1:h \) and \( r_2:h \).

Figure 21 is a mathematical representation of the violin bow interaction with the strings on the full violin. The purpose of this model is to determine the reaction forces on the user as they apply force on the bow to make music.

Figure 21: Mathematical model to calculate the reactionary forces on the user.

The following forces and moments are shown in Fig. 21: \( M \) is the moment applied by the user, \( F_{arm} \) is the vertical force applied by the user, \( F_{string} \) is the reaction force of the violin strings on the bow string, and \( F_g \) is the weight of the bow. Through an interpretation of Newton’s laws of motion, a vertical force balance and moment balance can be represented.

Figure 22 models the necessary tensile strength of the string that will hold the entire device to the wrist brace. The model accounts for the mass of each component, and the force of gravity that will be acting on them. An assumption is made in this model that the strings will be perfectly aligned with the y-axis, which is close to the actual situation, where the face of mass, \( m \), is flush with the plane of the palm of the player’s hand.
5 Concept Embodiment

The following section outlines the development of the selected concept, the Bearing Prosthetic. The models developed in the previous section were applied to this concept, and proof-of-concept models were developed based on this solution.

5.1 Initial Embodiment

The initial prototype was designed based on the previous mock-up and theoretical models that were developed. The WSM shows that using a ball bearing is an acceptable way to mimic wrist motion. In Fig. 23, 24, and 25, the CAD model drawing of the initial prototype is displayed.

Figure 22: Model to determine the necessary tensile strength of the string.
Figure 23: Exploded view with callout to Bill of Materials (BOM).
Figure 24: Assembled isometric view with BOM.
Figure 25: Assembled projected views with overall dimensions.
Initial Prototype Components
1. Wrist Brace (interface between user and mechanism)
2. Plastic Ball Bearing (serves as a frictionless rotational platform for the bow)
3. 3D Printed Bearing Interface (interface between Plastic Ball Bearing and Wrist Brace)
4. 3D Printed Clamp with Bearing Connector (interface between Plastic Ball Bearing and Bow)
5. Felt (serves as a softer contact material for the Bow)
6. Hex Screw (to tighten 3D Printed Clamp with Bearing Connector)
7. Wing Nut (to tighten 3D Printed Clamp with Bearing Connector)

Design Rationale for the 3D Printer Bearing Interface Clamp’s Stopper Locations

Part of this design is the location of the stoppers on the bearing interface. These stoppers serve to keep the bow from swinging freely, posing a danger to the user and others, and to allow the user to apply pressure to the bow and the violin. The location of the stoppers on the bearing interface are defined per the model shown in Fig. 20. The location is defined by an angle, $\theta_{max}$, referring to the maximum angle theta can make between the bow and the forearm [rad], and may be calculated by Eq. 1.

$$\theta_{max} = \frac{x^2 - L_L^2 - (0.3L)^2}{-2L_L(0.3L)}$$  \hspace{1cm} (1)

where $x$ is the distance between the elbow of the user and the fingerboard at the waist of the violin [m], $L_L$ is the length of the forearm of an eleven-year-old human male [m], and $L$ is the length of the bow [m]. Approximated values for these quantities are shown in Table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_L$</td>
<td>0.228</td>
</tr>
<tr>
<td>$L$</td>
<td>0.743</td>
</tr>
<tr>
<td>$x$</td>
<td>0.711</td>
</tr>
</tbody>
</table>

Using the values of Table 3 in Eq. 1 results in a stopper location of 3.97 rad, or 25.0° from the center line.

Original concepts call for two stoppers on the Bearing Interface. The other stopper would be located at $\theta_{min}$, referring to the minimum angle theta that may make between the bow and forearm, and on the other side of the centerline of the bow, as shown in Fig. 20. This angle is calculated using Eq. 2.

$$\theta_{min} = \frac{x^2 - L_L^2 - L^2}{-2L_LL}$$  \hspace{1cm} (2)

where the variables are the same as defined for Eq. 1. During construction, a stopper at this location was deemed unnecessary as the location of the clamp limited the motion of the bow such that it would not swing freely and pose a danger to the player.

Finally, the locations of the stoppers may also be represented by the ratio of $d_2$ to $h$, as shown in Eq. 3.

$$\frac{d_2}{h} = \tan(90° - \theta_{min})$$  \hspace{1cm} (3)
which is calculated to be 2.14 and subsequently included in subsequent design decisions.

Design Rationale for the Size of the Ball Bearing

In determining what size bearing to order and design each of the rest of the parts around, the model of stopper locations was extended in order to determine the necessary circumference such that the stoppers could accurately be placed in the position determined above. The diameter of the bearing that was used for the design was 1.13 inches. Thus, with the value of $\theta_{max} = 25.0$ degrees, and a diameter, D, of 1.13 inches, the arc length, s, between the bow’s perpendicular position and the stopper was determined using Eq. 4.

$$s = \frac{D}{2} \theta_{max}$$ (4)

Plugging in the values for $\theta$ and D, it is found that the arc length, s, will be 2.2 in. This is sufficiently long enough such that the stopper will be placed with enough precision, but any larger would increase the weight and cost of the part, which would deter from the design.

Design Rationale for the Position of Clamp on the Bow

To determine optimal position for the clamp to be connected to the bow, the model, seen in Fig. 21, was used. In order to minimize the force that Sam has to exert the length of the bow that is accessible must be maximized. For a bow of length, L, the moment Sam applies to the bow, $M$, the force of gravity on the bow, $F_g$, the normal force of the violin, $F_{violin}$, and the force of Sam’s arm, $F_{arm}$, three equations model the system. Equation 5 shows the moment on Sam’s arm.

$$\sum M_{arm} = M + F_g\left(\frac{L}{2}\right) - F_{violin}L = 0$$ (5)

Equation 6 models the forces in the system in the y-direction.

$$\sum F_y = F_{violin_y} - F_g + F_{arm_y} = 0$$ (6)

Equation 7 models the forces in the system in the x-direction.

$$\sum F_x = F_{arm_x} - F_{violin_x} = ma_x$$ (7)

Prototype Performance Goals

1. Sam will be able to use 70% of the bow and play with good sound quality. Currently, Sam can only use 30% of the bow and being able to use a larger portion of it will allow for better sound quality.
2. Sam will be able to play the violin for more than 5 minutes without readjusting the prosthetic. Sam should be able to use the prosthetic to play violin comfortably for extended amounts of time.
3. Sam will be able to equip and unequip the the prosthetic in less than 4 minutes. It is important that the prosthetic is easy to put on and take off with one hand.

5.2 Proofs-of-Concept

Prior to the creation of the initial prototype, a simplified proof-of-concept was created to show that the ball bearing design would work to produce the desired result. Figures 26, 27, and 28 show the proof-of-concept design.
Figure 26: Proof of Concept.

Figure 27: Proof of Concept.
The proof of concept, seen in Fig. 26, 27, and 28, was an idea for the prosthetic that utilized a ball bearing connected to a wrist brace. In the proof of concept model, the bearing was connected by super glue which was not strong enough to keep the bearing connected to the brace so in the initial prototype the bearing was sewn to the wrist brace. In the proof of concept the team also used a metal bearing which was too heavy to play violin with for more than 5 minutes, which is why a lighter plastic ball bearing was chosen for the initial prototype. The bearing worked well to provide rotation in the bow and as such the team continued with that design in the initial prototype.

In order to actually construct the initial prototype, there were several small details that were not considered in the description of the selected concept from Section 4. This included the materials used for each of the pieces, as well as the position of the stoppers. The position of the stoppers on the ball bearing are described above, and were determined using models. In order to maximize the manufacturability of the initial prototype, the group decided to 3D print as much of the design as possible. The group purchased a wrist brace from Walgreens as it was assumed that this piece of the design will be long-lasting. By purchasing a wrist brace, the group can ensure that it will be comfortable for Sam to wear. The group used a metal hex screw and wing nut because the accessible 3D printers could not print threads fine enough for their purpose. Additionally, the group ordered the ball bearing from McMaster Carr, as it would not have been feasible to design and 3D print a bearing that was functional and inexpensive. The rest of the parts were 3D printed using a Prusa I3 MK2S with PLA.

The only other difference between the drawing of the selected concept and the Initial Prototype is that the group used only one stopper as opposed to two. This was because of a redundancy in using two stoppers and that the clamp design functions as a stopper in both limiting cases.
6 Working Prototypes

6.1 Overview

Two working prototypes were created in the course of this project. They are a culmination of the research and all the design steps taken before their creation. These prototypes aim to improve upon the current prototype that Sam uses and can serve as a better alternative as Sam continues to grow physically and as a violin player. The section will describe both prototypes, their success in meeting the performance goals, and what was learned from each one.

6.2 Initial Prototype

The initial prototype was designed using insight gained from the mock-up and proof-of-concept along with the engineering models. The initial prototype is shown in Fig. 29. The wrist brace is store bought to ensure a comfortable and adjustable fit for Sam. The white piece attached to the wrist brace is the interface between the wrist brace and the plastic bearing. This interface is sewn to the wrist brace using small holes located around the base of the interface and is stabilized with tabs that run half an inch up and down the length of the wrist brace from the base of the interface. Behind the yellow clamp in Fig. 29 is the stopper on the bearing interface. It restricts the rotation of the bow to increase the control the user has on the movement of the bow. The clamp, the yellow piece shown in the figure, is attached to the bearing by squeezing the prongs, fitting them into the inner diameter of the bearing and releasing which then locks the clamp in place on the bearing. To remove the clamp, the process is reversed. The bow attaches to clamp by sliding through the open end of the clamp until it fits into the felt-padded circular end of the clamp. Then a hex screw is inserted into one side of the open end so that the threaded end of the screw protrudes on the opposite side and a wingnut can be used to tighten it into place. There is a hexagonal indent located on the side with the hex head so that it is held in place while the wingnut is tightened. The clamp is designed so that it can be quickly removed from the wrist brace and stay attached to the bow while it is being transported in the violin case. It is still easy to remove the bow from the clamp by unscrewing the hex screw from the clamp and sliding out the bow.
The initial prototype was tested to see if it would meet the performance goals determined earlier in the project. The first performance goal was enabling the use of 70% of the bow length. The second goal was to play without readjustment for 5 minutes. The third goal to be able to equip and unequip the prosthetic in less than 4 minutes. The first performance goal was easily met. Using the rotation of the bearing on the wrist brace, the initial prototype allowed the full length of the bow to be used. The second goal was not completely met because some adjustment was necessary during the testing of the prototype. This was not viewed as a major issue and was attributed to unfamiliarity with the wrist brace and prototype in general. Further practice with the prototype and putting on the wrist brace would reduce the need to adjust the prototype while in use. The third performance goal was achieved well under the time limit. The pronged clamp was very quick to equip, but squeezing the prongs with the bow attached while connected to the wrist brace was a little difficult and required some awkward movement, and thus, it was more difficult to remove.

The performance goals were mostly met with success; however, other areas to improve upon were noticed during these tests. The initial prototype did not include a stopper on the body of the violin to help control the motion and angle of the bow. After these tests, the necessity of this feature was apparent. The prototype could be used but fine motor control and accuracy was hard to obtain. Additionally, the clamp extended too far from the wrist brace. This required the user to hold their arm at an angle too high for optimal movement and comfort. With these improvements in mind, work began on the design of the final prototype.

6.3 Final Prototype

Moving forward from the initial prototype demo, there were several major changes that were carried out for the final prototype. The most impactful change was adding a spoke to attach to
the violin itself to keep the bow running on a track at an ideal angle with the strings. This spoke was inspired by research of Manami Ito’s prosthetic, outlined in section 2.1.2. Additionally, the connection between the bow clamp and the bearing was redesigned. The interface was changed from a snap fit to a dovetail interface. This change allowed for easier connection and disconnection of the bow piece to the wrist brace piece, as it got rid of the awkward finger motion necessary in the initial prototype. This also worked to move the bow closer to the palm of the user’s hand. This allowed for a more comfortable and relaxed shoulder position, as the bow was now located in a more natural violin playing location. Finally, the spoke on the wrist brace-bearing interface was removed. With the addition of the spoke on the violin, this spoke became unnecessary in controlling the movement of the bow while playing the violin. It actually ended up hindering the mobility of the bow based on its dimensions.

The final prototype can be seen in the figures below. Figure 30 shows the wrist brace, bearing interface, bearing and clamp interface. Figure 31 shows the clamp. The clamp is tightly lined with felt in order to reduce damage to the bow. The wing-nut design and the felt both allow for this clamp to be adjustable and adaptable to various bow sizes. The dovetail interface is lined with tape in order to increase the friction between the two pieces.
The final prototype was assessed against the same performance goals used for the initial prototype. These performance goals include use of 70% of the bow length, ability to play for 5 minutes without readjustment, and to equip and unequip the prosthetic in less than 4 minutes. All three of these performance goals were easily met. The user has the whole length of the bow for playing. The new dovetail fit between the Bow Clamp and the Bearing Interface significantly increased the fine motor control of the bow. By practicing with it in advance, the user does not need to readjust the prosthetic during use. Finally, the user is easily able to equip the prosthetic in less than 4 minutes. Further, the vertical stopper on the violin allowed for the application of much higher pressure. As such, the user may make much louder sounds on the violin.

7 Design Refinement

7.1 FEM Stress/Deflection Analysis

A standard mesh, of medium density, is sufficient for an analysis of this order. Each mesh cell has an Element Size of approximately 0.0344 in. and a Ratio of 1.5. The loads in the simulation reflect those applied by the bolt on the bow clamp. When the clamp is tightened around the bow, the bolt exerts an evenly distributed force on each side of the clamp. It is estimated that 1.3 N of force is required to secure the bow in the clamp. The load can be seen in the purple and orange arrows in Fig. 32, where the bolt interfaces with the clamp. The shape fit, the part of the clamp which interfaces with the bearing and wrist mount, serves as the fixed reference for this analysis. As such, it is considered fixed and free of any lateral motion or displacement. The accuracy of this analysis is confirmed by observation of stress concentration and displacement locations. First, the maximum stress should occur in the round part of the clamp due to the geometry. This is shown in Fig. 33. Second, the maximum displacement should occur at a free end of the clamp, where it is forced downward to lock the bow in place. This is replicated in the simulation, as shown in Fig. 34.

Even though the object is physically constructed from PLA plastic, ABS was used in this simulation as it is closest material to PLA available in SolidWorks.
Figure 32: Unloaded model with mesh, loads, and boundary conditions.
Figure 33: Model with load applied and resultant stress shown.

Figure 34: Model with load applied and resultant deflection shown.

Figure 33 shows that a maximum stress of 0.42 MPa will occur in the clamp. As this occurs on
the concave part of the clamp, it is compressive. The compressive yield strength of ABS plastic is approximately 7.58 MPa [5]. Thus, using the compressive failure scenario for the material, the factor of safety is approximately 18 for this part. This factor of safety means that the clamp is significantly safe from an engineering perspective.

The clamp is designed such that the two free ends bend toward one another to secure the violin bow in place within the part. As such, the design allows for these free ends to deflect to the point of contact with one another. It is physically impossible to deflect beyond this condition, as the ends cannot simultaneously occupy the same space. To this end, there is no deflection which can damage the part.

7.2 Design for Safety

The following section explores various safety concerns including a ranking of how each concern should be prioritized based both on the severity of the concern and also the likelihood of an incident. Further, the following section discusses how these concerns can and should be mitigated. It is important to analyze the risks of the product so that improvements can be made and the final product will be safe for the user, or if necessary, the safety concerns can be brought to the attention of the user to ensure safe usage of the Violin Prosthetic.

7.2.1 Risk #1: Choking

Description:
The small 3D printed parts such as the clamp or the stopper on the violin could be a potential choking hazard if they are swallowed. The screw in the clamp could also be a choking hazard. This risk would only occur if the screw that is used to attach the clamp to the bow came loose and the clamp was to fall off. Since Sam has a dog that may get a hold of the bow, this could cause the screw to come loose.

Severity:
The severity is catastrophic as choking on a piece could lead to serious injuries or suffocation. This is the worst type of injury that could be induced from the prosthetic.

Probability:
The probability is seldom since, if used as intended, the clamp should always be connected to the bow.

Mitigating Steps:
In the Violin Prosthetic, the clamp mechanism is designed to mitigate the risk. It is intended to be permanently attached to the bow, and as a result, the small pieces should seldom be floating around. This risk could further be mitigated if the clamp were to be permanently attached to the bow in a way that eliminates the need for a screw. A higher infill percentage could also make the parts stronger and less likely to break into smaller pieces.

7.2.2 Risk #2: Sharp Plastic

Description:
The 3D printed pieces have potentially sharp edges that could cut someone. If the pieces fracture or break, the resulting sharp edges may also cause a cut. If the prosthetic is subjected to rough treatment, the likelihood of it breaking increases.

Severity:
The severity is critical because the cut could be severe and the chemicals from the material
could go into the cut. Some micro pieces of plastic could also go into the cut. This injury in not
catastrophic because this type of injury can be healed.

**Probability:**
The probability is unlikely since the edges of the 3D printed pieces have been filleted and the
pieces themselves cannot be broken easily, as they are printed with a high infill percentage.

**Mitigating Steps:**
To mitigate this risk, small parts could be combined so there are fewer sharp edges. The edges
will also be filleted so that they are not as sharp and a higher infill percentage will make the parts
stronger so they are less likely to break.

### 7.2.3 Risk #3: Bow hits someone

**Description:**
When the user is first mounting the bow on the violin, the bow can swing around and hit the
user or someone around the user.

**Severity:**
The severity is negligible since the bow will not be moving at a high speed and will produce
minimal injuries if it does hit the user.

**Probability:**
The probability is likely since the bow moves freely and quickly around on the bearing. However,
the spoke addition to the prosthetic limits the span with which the bow can swing, thus decreasing
the probability.

**Mitigating Steps:**
To prevent this, a spoke has been 3D printed onto the bearing itself and will subject the bow to
limited spans of motion.

### 7.2.4 Risk #4: Violin spokes poke someone

**Description:**
The spokes on the violin are tall and as such, could potentially poke the user or someone around
the user. This is unlikely to happen when the user is playing the violin.

**Severity:**
The severity is marginal since the spoke will not be able to severely injure anyone. The injuries
would be minimal and easy to recover from.

**Probability:**
The probability is seldom since the spoke is not in a position where it is likely to injure someone.

**Mitigating Steps:**
Making the spoke very visible will reduce the risk of it injuring someone. This can be done by
printing the spoke in a bright color. Additionally, the edges of the spoke could be filleted in order
to decrease the severity of this potential occurrence.

### 7.2.5 Risk #5: Thread connection on bearing holder fails

**Description:**
The bearing holder is sewed to the wrist brace. If a weak thread is used, the bearing, and as such
the bow could fall and injure the user or someone near the user. The thread could also fail if the
wrist brace is treated roughly.
Severity:
The severity is marginal since the bow falling will not be able to severely injure anyone. The bow will not be falling from a large height and it is very light.

Probability:
The probability is seldom since the thread used is strong and the bearing is sewn in multiple times.

Mitigating Steps:
By using a strong thread, the bearing holder, and as such the bow, will be strongly attached to the wrist brace. Multiple rounds of sewing can also help to make the attachment stronger.

Figure 35 displays the Heat Map for the potential safety risks in the design.

Figure 35: Safety risk heat map.

As shown in Fig. 35, the choking hazard is the highest priority hazard since it has the highest risk severity. Although it has a low likelihood of happening, steps need to be taken in order to prevent choking or suffocation. The next two priorities to look at are the violin spoke poking someone and the thread connection failing. Both of these risks have a lower severity and could possibly occur. The fourth priority is the potential that sharp plastic from the 3D printed pieces may cut someone. The likelihood of this happening is very low but the severity of the injury is high. The lowest priority would be the bow hitting someone. Although this injury is likely, the severity is negligible and solutions have already been implemented to prevent this.
7.3 Design for Manufacturing

Draft Analysis

The part used for the draft analysis is the interface between the wrist brace and the bearing that the bow rotates with. Almost all of the features on this part were on the positive draft face of the part so they were edited to have a positive draft. The only features that received a negative draft were the holes on the skirt of the part. While the positive and negative drafts were being added the functionality of the part was kept in mind and remained unhindered by the draft. Figure 36 shows the part before and after draft was added.

![Draft Analysis Diagram](image)

Figure 36: Before and after draft images from Bearing Interface Using SolidWorks "Draft Analysis".

DFM Analysis

The part used for the Design for Manufacturing (DFM) analysis is the attachment on the violin body that constrains the bow movement to the right area of the bow. The violin body attachment was chosen for this analysis because it has a specifically designed shape with holes on multiple surfaces in multiple directions and angled surfaces. The two types of manufacturing processes analyzed were injection molding and mill/drill only, shown in Fig. 37 and Fig. 38, respectively. For the injection molding analysis, the part failed because the wall thickness was both thinner than the designated minimum wall thickness in places and thicker than the designated maximum wall thickness in other places. For the drilling/milling analysis, the part failed because there were holes that had flat bottoms, fillets on a vertical extrusion, and the hole sizes did not match standard hole sizes.
7.4 Design for Usability

The Violin Prosthetic, as it is designed in this report, is made specifically for the customer, Sam. However, if the prosthetic were to be produced for a broader customer base, the usability of the prosthetic could be impacted by different potential impairments of the user. Several impairments are addressed in the following section. The prosthetic is examined specifically with regards to each impairment to determine whether they might affect usability, how this would occur, the magnitude with which it would affect the usability, and when possible, improvements to the prosthetic to address the concerns.
1. Vision Impairment:
   In order to use the violin bow prosthetic, there are two connections that are necessary to be made for each use. In order to connect the bow piece to the wrist brace piece, a trapezoidal shape must be slid into a hole of the same shape. This shape fit is large enough (0.5 in. at its widest point and 0.25 in. at its narrowest point) that it will not cause eye strain, and thus the usability of this piece would be largely unaffected by a vision impairment such as presbyopia. The minimal affect that a vision impairment might have would be that it might take a slightly longer amount of time to connect these two pieces, however this increased length of time would most likely not cause the equipping speed to exceed a reasonable amount of time. The spokes that fit into the piece that clamps onto the side of the violin connect with a shape fit. The circular shape is 0.08 in. wide, and thus should be simple to find even if vision is impaired. Were this device to be mass produced for a population with multiple occurrences of visual impairment, it might be useful to increase the size of the shape fits and modify textures on the parts such that the user would have a better idea of where the parts lie relative to each other when connecting them.

2. Hearing Impairment:
   When playing the violin, the pressure being applied by the bow determines the sound level produced as well as the quality of the sound. Being hearing impaired might make it difficult for a violin player to hear these sound artifacts, and thus, they would have to rely on the consistency of the pressure that they apply to the bow when playing the violin. The nature of the Violin Prosthetic is that the pressure is applied through a series of connections between the forearm and the bow. As a result, it is more difficult for the user to identify exactly how much pressure they are applying to the strings through the bow without listening to the sound being produced. Potentially, the Violin Prosthetic could be modified to improve the percentage and consistency of pressure that is applied through the prosthetic such that the player can be sure that the force that they are applying is transferring to the strings in a predictable way.

3. Physical Impairment:
   Ideally, the demands on the players arm of the Violin Prosthetic match the demands that playing the violin without a prosthetic would have on the players arm. The prosthetic was designed in such a way that the connections that need to be made for each use are simple connections, requiring no intense use of any particular muscle. However, some of the permanent pieces could cause pain when being equipped on the violin, as both the clamp on the violin itself and the clamp on the bow are attached using screws. These screws are relatively small and could potentially cause pain for a person with a physical impairment, such as arthritis.

4. Control Impairment:
   By the nature of the Violin Prosthetic, the bow rotates freely, as it is connected to a bearing joint. There is a stopping mechanism on the bearing, however there is a range in which the bow can swing back and forth. Thus, if the violin player experienced a control impairment that would decrease the amount of focus needed to safely mount the violin bow onto the instrument, the bow could swing dangerously and the pointed end could hurt the player or a person standing near by.

8 Discussion
8.1 Project Development and Evolution

Does the final project result align with its initial project description?

– The final product does indeed align with the initial description. The description calls for an improved prosthetic which enables Sam to refine his skills as a violinist. The final version of the prosthetic gives Sam more control over the violin bow and allows him to use a larger portion of it.

Was the project more or less difficult than expected?

– The project difficulty was as expected by the team. Actual work hours on the project are slightly higher than the initial expected quantity, but are not significant.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

– The team could have spent more time designing the vertical stopper placed on the violin. This stopper became crucial to the overall success of the project. As such, a more refined design could have allowed for an easier time reaching the design goals. The time spent to design and refine other parts of the prosthetic may be considered worthwhile, as doing so enabled a more complete final product.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

– From a design perspective, significant time was spent in creating the fit between the Bearing Interface and the Bow Clamp. This connection, if not done properly, would result in a loose bow that could not be controlled. The most tedious part of assembly, however, involved sewing the Bearing Interface onto the Wrist Brace. This task could only be done by one person at a time and required close attention to detail to ensure a tight fit.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

– The team is satisfied with the design concept selected, as it is able to meet all criteria and is an improvement over the existing prosthetic. Furthermore, the simplicity of the design makes it easy to repair and replace in the future, if needed.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

– The codes and standards of multiple types of prosthetic designs were researched. They were then narrowed down by what was most relevant to Sam’s needs. These standards were taken into account when brainstorming different designs.

Was your group missing any critical information when it generated and evaluated concepts?

– It would have been particularly useful to have enlisted the assistance of somebody who actually played the violin so that we could understand which aspects of the design would be most important. One critical piece of information that we were missing was the strength of Sam’s wrist muscle, and whether or not it could support or control the bow.
Were there additional engineering analyses that could have helped guide your design?

- It would have been helpful to have accurate measurements of the weight of the violin and of the bow. This information would have resulted in the models being more accurate as the weight and length were estimated in the original calculations. It would also have been helpful to know the extent of Sam’s wrist strength. This would have been included in the calculations done when finding the required wrist strength to play the violin with the added prosthetic weight.

If you were able to redo the course, what would you have done differently the second time around?

- It would have been helpful to begin the CAD process earlier so that we could go through several more iterations of each of our 3D printed parts. Each piece ended up serving the function that we needed, but were not optimized for weight or shape, and this could have been improved with an increased amount of iterations.

Given more time and money, what upgrades could be made to the working prototype?

- The next step in designing this prosthetic would have been to add a spoke to the bearing holder to keep the bow in the correct range of motion when it is being placed on the violin and being taken off the violin. The spoke on the violin would also be made longer to ensure that it keeps the bow in the correct range of motion at all times. Another improvement would have been to make the equiping of the spoke on the violin easier and possible a permanent addition.

8.3 Team Organization

Were team members’ skills complementary? Are there additional skills that would have benefited this project?

- Each team member brought to the table skills that others didn’t have. This made it so that people were able to specialize and work on things that they had the most experience with. It would have been useful to have a team member with a more complex understanding of violin musicianship.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

- This project allowed the team to develop skills in biomechanics and think about mechanics from the perspective of the human body. The design process was challenging, innovative, exciting, and rewarding, and overall it inspired the group to explore more projects in this field.
Bibliography


