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# Beyond Hands Capstone
# Section 004

**End-of-Term Paper**


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# Table of Contents

## Mission Statement of our Team

The mission of our team is to enhance the quality of life for amputee drummers by restoring drumming functionality.

## Value Proposition Statement for Prosthetic Users

Our team has created low-cost drumming prosthetics that provide higher playing accuracy and coordination, is faster to adapt, and reduces muscle fatigue compared to existing drumming prosthetics.

## Executive Summary of Project Progress and Future Plans

Beyond Hands is a project that aims to enable and empower those who are differently-abled to be able to drum using comfortable, easy to use, and adaptable prosthetics. Existing drumming prosthetics in the market are either too expensive or are not accurate. Beyond Hands aims to create low-cost drumming prosthetics that operate accurately. The team has honed in on a crucial aspect of drumming that is paramount to a drummer's success: the difference between a double stroke and a single stroke. With a tighter grip on the drumstick, the drummer could play more rigid, controlled beats, which are known as single strokes. With a looser grip on the drumstick, the drummer could enable for the drumstick to play quicker, less controlled notes, known as the double stroke. The double stroke occurs when the drumstick strikes the drum pad, and since the user has a relaxed grip, the drumstick rebounds and strikes the drum pad in a quick succession, until the drummer tightens their grip to restrain the drumstick from striking the drum pad. To address the single and double stroke differentiation, the team has explored variable stiffness, which is a change in the material stiffness of a given material. Through the team's rapid prototyping process, a functional drumming prosthetic that accomplishes the single and double stroke differentiation was realized. We hope that its introduction can improve people's ability to express themselves through drumming, which can enhance quality of life.

## Framing the Issue: Recreational Prosthetics and Existing Solutions

### Recreational Prosthetics: Limited Options and Efficacy

The prevalence of upper-limb prosthetics have vastly improved over time to perform many functions. However, research for recreational prosthetics, such as prosthetics for music or sports, has not been a main focus of engineers and researchers. This has led to limited options of recreational prosthetics as well as prosthetics that are not effective and accurate. In particular, there are only a few retail options for drumming prosthetics, which can be expensive, ineffective, and can cause muscle fatigue due to the repeated use of the prosthesis. Beyond Hands is working to create a drumming prosthesis that can improve the user's quality of life while maintaining a high-level of drumming functionality. The prosthetic is also low cost and decreases user fatigue.

### Existing Drumming Prosthetics: Georgia Tech Drumming Prosthetic

Beyond Hands aims to improve upon current drumming prosthetics available by introducing a low-cost solution. Many existing drumming prosthetics are expensive. For instance, a drumming prosthetic created by researchers in Georgia Tech has myoelectric control of the prosthetic through a system of motors, microprocessors, a rotating gear and spring mechanism, and many electronic components to achieve variable stiffness for the drummer (Figure 1) (Bretan, M. et al., 2016). The Georgia Tech myoelectric drumming prosthesis is fully capable of fulfilling all of the needs of a drummer. However, the device costs over $3,000, factoring in the research, production, and assembly of the myoelectric device. Beyond Hands aims to fulfill all of the needs of a drummer for a lower cost.

**Figure 1:** Georgia Tech Myoelectric Drumming Prosthesis (Bretan, M., Gopinath, D., Mullins, P. & Weinberg, G. A Robotic Prosthesis for an Amputee Drummer. *arXiv:1612.04391 [cs]* (2016)).

**Existing Drumming Prosthetics: The Paradiddle**

The Paradiddle, which is an open-sourced, 3D printable design, is another existing drumming prosthetic that addresses the issues of low-cost materials and functionality. The Paradiddle achieves variable stiffness actuation through the adjustability of the spring-like mechanism that is attached to the socket (Figure 2) (Siguang Ma, D., 2018). However, this design has a few flaws that would make the prosthetic inconvenient for the user and could lead to the user to abandon the prosthetic. For example, the stiffness is controlled by the movement of the leg, which is inconvenient for the user because this could impede on the playing ability of the drummer. Additionally, since this is a mechanical system with no electrical control, the movement is entirely dependent on the user, and this could cause for high fatigue after long periods of usage. To test the effectiveness of the Paradiddle, the team worked on replicating the design and this will be discussed in a later section.

**Figure 2**: Paradiddle Drumming Prosthesis (Siguang Ma, D., Paradiddle, an open-source 3D-printed drumming prosthesis. *designboom | architecture & design magazine*, 2018,, accessed: September 20, 2018).

**Existing Drumming Prosthetics: TRS Drumming Prosthetic**

The TRS drumming prosthetic is a purely passive prosthetic that requires the user to manually control the movement of the drumstick using the forearm and upper arm muscles without electrical assistance (Figure 3) (TRS Prosthetics, 2018). This can be tiring for the drummer, especially since the drummer has no way to implement double stroke without precise inputs from the user. The double stroke is also difficult to achieve with the TRS drumming prosthetic, and the prosthetic is also difficult to fine-tune to cater to the drummer's desired stiffness.

**Figure 3:** TRS Drumming Prosthesis (TRS Prosthetics, Music – Drum Stick, accessed: September 20, 2018)

## The Biomechanics of Drumming: Normal Drumming vs Prosthetic Drumming

### Non-Amputee Drumming: Muscle Mechanics and Movement

Drumming can involve a variety of muscles including leg, back, pectoral, abdominal, shoulder or arm muscles. For the purpose of focusing on the areas of the arm that actuate the drumstick, we will focus on the biomechanics involved in the lower arm, wrist and hand. The principal motion involved in the execution of a stroke, i.e. moving the drum stick up and down, is a wrist extension or flexion. The muscles involved in this movement are the brachioradialis, flexor carpi ulnaris, extensor/flexor carpi radialis and the extensor digitorum.

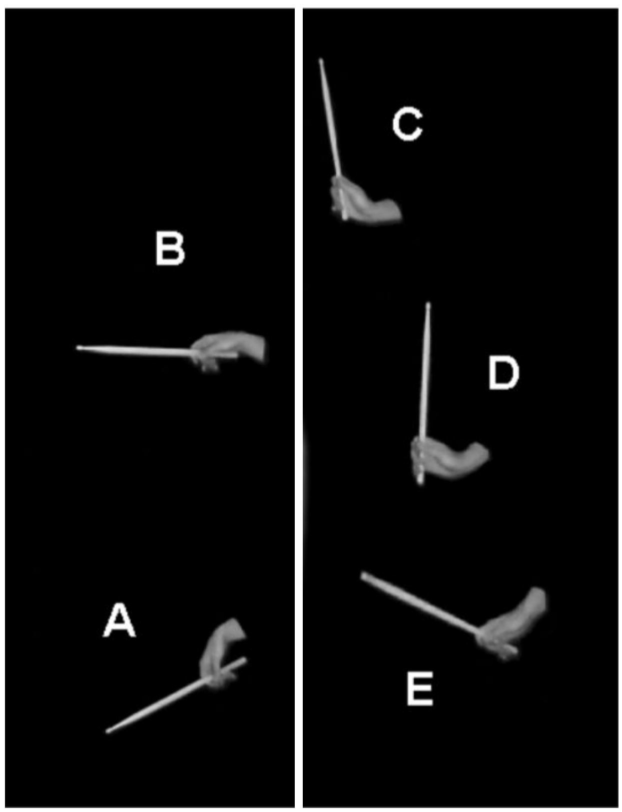



**Figure 4**: Orientation of the drumstick and hand during the successive stage of a stroke (Dahl, S. (1997). Measurements of the motion of the hand and drumstick in a drumming sequence with interleaved accented strokes: A pilot study. *Report Speech, Music and Hearing, Quarterly Progress and Status Report*, 1-6.)

Moreover, to achieve a double stroke, drummers usually have to stiffen their wrist and have to open their fingers to allow for the drumstick to bounce freely. These two actions involve muscle contraction in the forearm.

Finally, it is common for drummers to use the pronation/supination of the forearm and hand to reach different drums/cymbals or achieve different sounds. Pronation and supination are the movements that allow to flip the palm face down or up respectively. These movements are possible through the structural arrangement of bonds and muscles in the forearm.

### Prosthetic Drumming: The Need for Motion Recovery and Restoring Functionality

Having a transradial limb difference, or an amputation below the elbow, tremendously decreases the range of motion an individual can achieve. Neither wrist nor finger motion are available and the ability for pronation and supination is greatly reduced. Since these motions are so essential in playing the drums, limiting them presents a challenge. The drummer has to compensate with fast elbow rotation and a wider range of shoulder movement, which can induce fatigue and introduce inaccuracy. Therefore, a drumming prosthetic has to enable the drummer to regain, at least in part, the range of motion given by the wrist and fingers.

## User Research for Drummers and Survey Results

An online survey was conducted to gain a better understanding of the drumming community. The surveys are intended to guide the design process and delineate design criteria for drumming prosthetics. A total of 79 drummers were surveyed from an online drumming community and the complete survey can be found in the Appendix.

The goal behind the surveys was to gather information on general playing styles, drumstick grips most often used while playing the drums, drumstick feedback, and other necessary hand movements during performances while playing. Although the question of different drumstick grips (American, Traditional, German, and French grips) was asked, the team wanted to focus on addressing single and double stroke modulation before pursuing different drumstick grip types. There will be future efforts to address the different drumstick grips in future prototyping iterations.

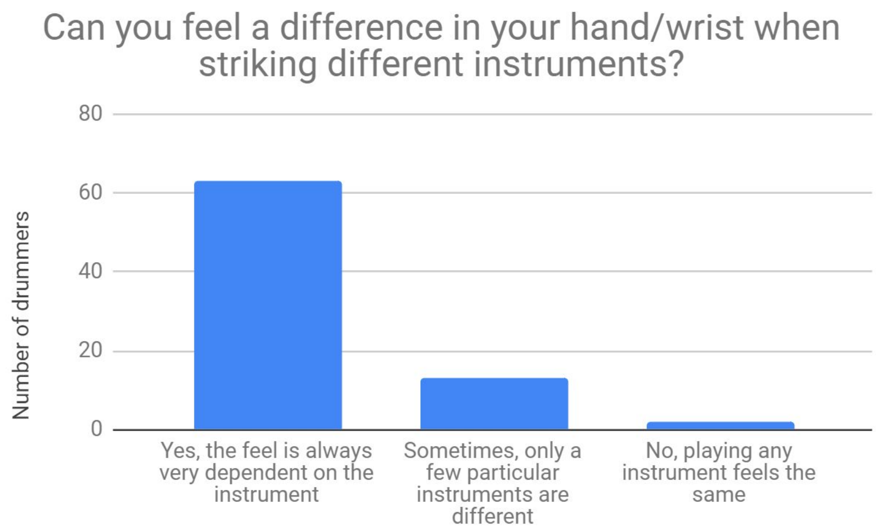



**Figure 5.** Instrument dependency for drumming feedback indicated by number of drummers interviewed

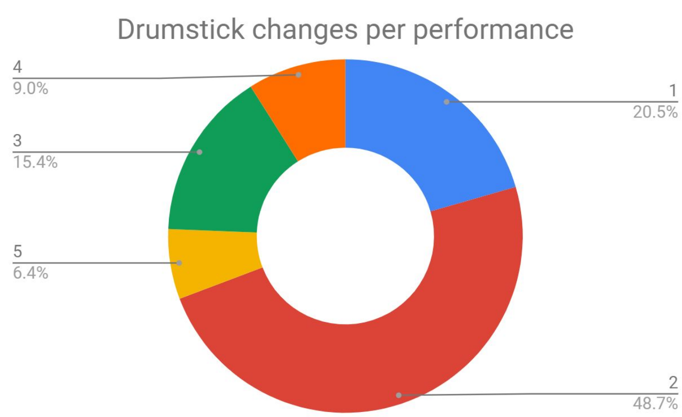



**Figure 6.** Frequency of drumstick changes mid-performance on a scale of 1-5, 1 indicating "I have never had to change sticks mid-performance" and 5 indicating "This is a fairly common occurrence"

Another important factor to consider in the prosthetic design, was ease of replacing the drumstick during use. Certain designs could require drilling or modifying the stick, which is not possible mid-performance. However, survey results indicated ability to easily switch sticks is not an important design factor as 69.2% of surveyed indicated they rarely change drumsticks mid-performance (score of 2 and below) (Figure 5). The results from our survey also indicated that 60.5% of people break one or two drumsticks per year. Therefore, we decided that this consideration was not critical for our design.

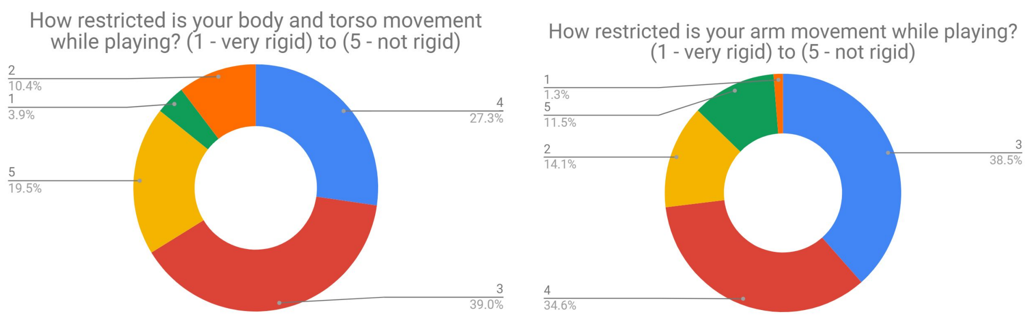



**Figure 7.** Rigidity of drummer's body (Left) and arms (Right) on a scale of 1-5, where 1 indicates "very rigid" and 5 indicates "not rigid at all"

The final aspect taken into account was rigidity of the player's body and arms. Many upper-limb prosthetics follow a body-powered mechanism involving a cable system that tenses and releases as the distance between the two shoulders or alternatively the angle of the arm changes. Because of the popularity of such a mechanism, it is a high contender for actuating the variable stiffness of the drumming prosthetic. However, implementing a body-powered mechanism would require an area of the body to be rigid or controlled. As the results indicated, less than 16% of dummers consider either their arms or body to be fairly rigid (ranking of 2 or less) while playing (Figure 7). Therefore, a body-powered cable system may prove to be difficult to implement.

### Brainstorming and Metrics for Drumming Prosthetic Design

Based on a combination of user research and team discussion, the team has determined metrics that the drumming prosthetic had to meet. Ultimately, the design metrics chosen, from most to least important, were: coordination and accuracy, fatigue, low-cost, and fast to learn. A MATLAB application was developed to determine coordination and accuracy statistics. After conducting a drumming test with a study subject, fatigue can be gauged by survey and electromyogram (EMG) recordings. To obtain these measurements, users will complete a series of playing tests during which their rate of improvement will be tracked, and they will also complete post-test surveys. This would enable for our team to assess the ease of learning. The testing protocol link is included in the Appendix.

## Literature Review of Variable Stiffness for Variations of Drumming Strokes

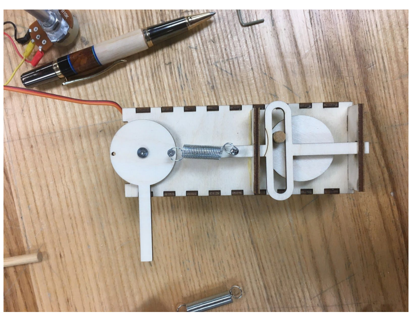
### Variable Stiffness, Single Stroke, and Double Stroke

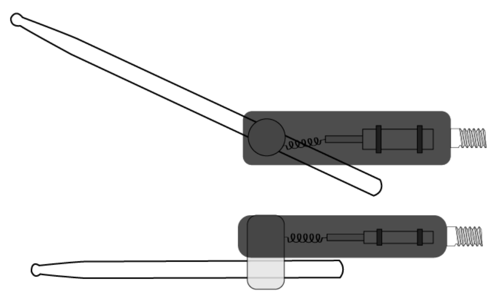
Drumstick grip is crucial to a drummer's play style. With a tighter grip on the drumstick, the drummer could play more rigid, controlled beats, which are known as single strokes. With a looser grip on the drumstick, the drummer could enable for the drumstick to play quicker, less controlled notes, known as the double stroke. The double stroke occurs when the drumstick strikes the drum pad, and since the user has a relaxed grip, the drumstick rebounds and strikes the drum pad in a quick succession, until the drummer tightens their grip to restrain the drumstick from striking the drum pad again.

In the case of a drummer with a prosthetic, there needs to be a methodology to mimic a human hand grip. The team has determined that modulating the drumstick's rotation and behavior was important. To achieve a change in the drumstick rotation and behavior, the team explored variable stiffness actuation, which is a concept that enables for the user to tighten or loosen the elastic element, such as a spring or a bungee cord, attached to the drumstick that influences the drumstick's rotation such that the drummer could perform a single or double stroke based on the stiffness of the elastic element. A study done by Kim et al. validated that the double stroke can be achieved based on a range of stiffnesses of the elastic element (Kim, Y., Garabini, M., Park, J., Bicchi, A., Drum stroke variation using Variable Stiffness Actuators, 2014, IEEE Conference Publication, 20th September 2018).

**Linear Actuation: Theory and Design**

Single spring actuation can also allow for the change in variable stiffness. By using a single spring attached to a linear actuator, the spring can elongate or undergo compression, which would change the effective stiffness of the elastic element attached to the drumstick. Through experimentation (Figure 8), there was a noticeable difference in the elastic element stiffness depending on the position of the spring. The Linear Actuator Prototype section below discusses the prototype that was created from this principle.





**Figures 8 and 9:** Validation of Stiffness Change Model (Left), Linear Actuator Prototype Schematic (Right): Side View (Top), Top View (Bottom)

**Twisted String Actuation: Variable Stiffness through Winding Strings**

This is a method where two antagonistic bungee cord elements are twisted and wound together. This would change the stiffness of the bungee cord elements based on the degree of twisting that occurs, while also inducing a length change of the bungee cord system depending on how many twists are in the system. The twisted string actuation concept is illustrated in Figure 10.

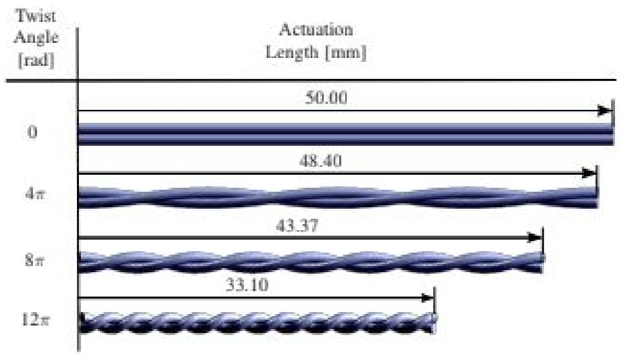



**Figure 10:** Twisted String Actuation (Palli, G., Pan, L., Hosseini, M., Moriello, L. & Melchiorri, C. Feedback linearization of variable stiffness joints based on twisted string actuators. in *2015 IEEE International Conference on Robotics and Automation (ICRA)* 2742–2747 (2015). doi:10.1109/ICRA.2015.7139571, Accessed: March 1, 2019)

**Cam and Follower: Changing Stiffness through Pushing on the String**

The second design involves a cam and follower. A cam profile controlled by a rotary actuator translates rotational motion into linear motion by pushing on a follower (Figure 11). This linear follower will pull on a bungee cord to create different degrees of stiffness in the cord, if modelling the bungee as a linear spring system. This design is a lower-cost alternative to implementing a fully electronic linear actuator as rotary actuators are less expensive.

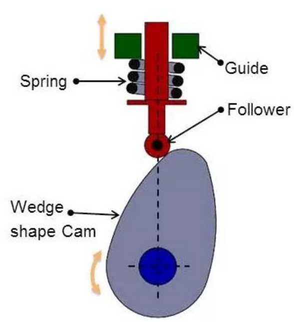
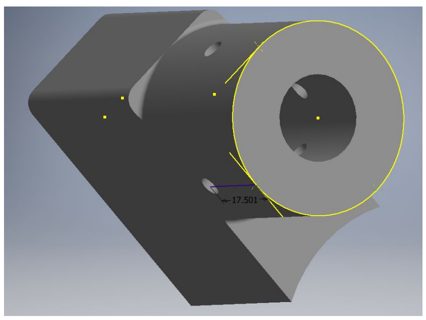


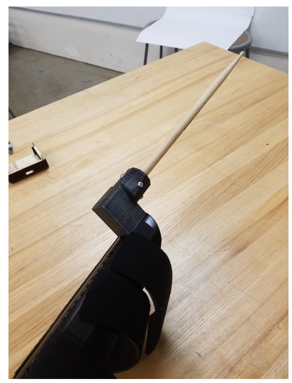

**Figure 11:** Cam and follower system (Soni, V., Cam and Follower Mechanism And their Types. Accessed: March 1, 2019)

# Design and Prototyping Process for the Drumming Prosthetics

### Stiff Prototype for Baseline Testing and Comparison

A stiff drumstick prototype was created as a baseline, or control, against which functional prototypes may be compared. This stiff prototype is an adaptor piece that was 3D printed with a mount that attaches to a brace. Figure 12 depicts the CAD model for the adaptor, and Figure 13 depicts the assembled stiff drumming prototype.

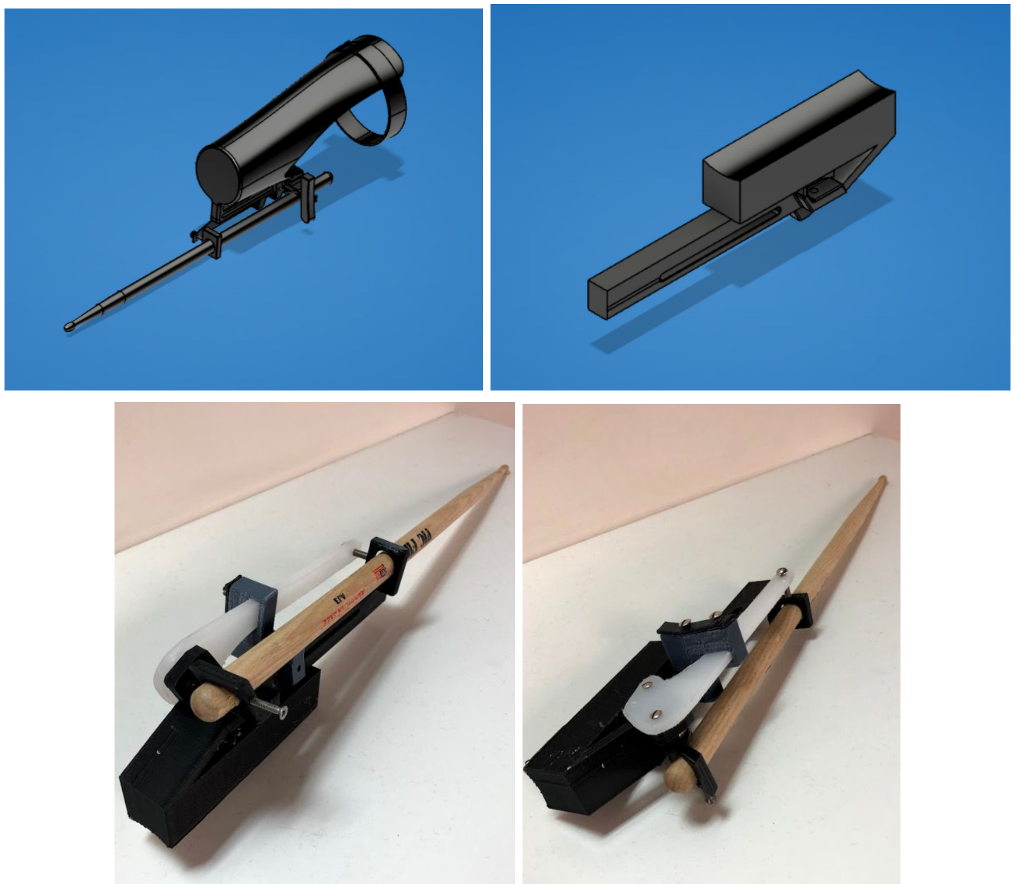




**Figures 12 and 13**: CAD model (left), Stiff Drumstick (Right)

### Paradiddle Prototype for Drumming Prosthetic Comparison

As previously mentioned, the Paradiddle drumming prosthesis is an open source, 3D printed design from Dominic Siguang Ma. The prosthetic provides variable "bounciness" by moving a lever along a plastic arm; the further out the fulcrum point, the less flexible and "bouncy" the arm attached to the drumstick is (Figure 14). The mechanism's pin system is operated by pressing and pushing along the user's leg, thereby moving the fulcrum point along the plastic arm. Additionally, as an open source project, the parts are easy to acquire and assemble. Therefore, this design incorporates many of the aspects our group hopes to implement, including variable stiffness for different strokes, making this prosthetic a reasonable benchmark for comparison.



**Figures 14-17:** Original Paradiddle design (Upper Left), modified Paradiddle design without the built-in socket (Upper Right), Paradiddle Prototype Top View (Lower Left), Paradiddle Prototype Side View (Lower Right)

Our prototype attachments are being mounted on an arm brace. Because the team wanted to have the Paradiddle fit on the arm brace, the socket pictured in Figure 14 was removed, and replaced with a panel to be compatible with the arm brace (Figure 15). The top of the panel was threaded with ½” holes for attaching to the socket. It was assumed using our socket instead of the original 3D printed one would have no effect on the prosthesis’ performance. Parts were 3D printed following CAD modification and then assembled. The flexible plastic arm was cut from polycarbonate and fitted with an AJ4 drumstick held in place by screws (Figures 16 and 17).

**Beyond Hands First Design: Body-Powered Prototype**

Many body-powered prostheses exist in the market today and are widely used by amputees since they are cheap, easy to use, and can provide haptic feedback to the user through the tightness of the cable. We, therefore, wanted to build a proof-of-concept prototype to see if it would be possible to drum using such a prosthesis. To come up with our design, we did some research on the numerous devices available and figured out what type of mechanism would work best for us. The designs shown in Figure 18 were particularly useful.

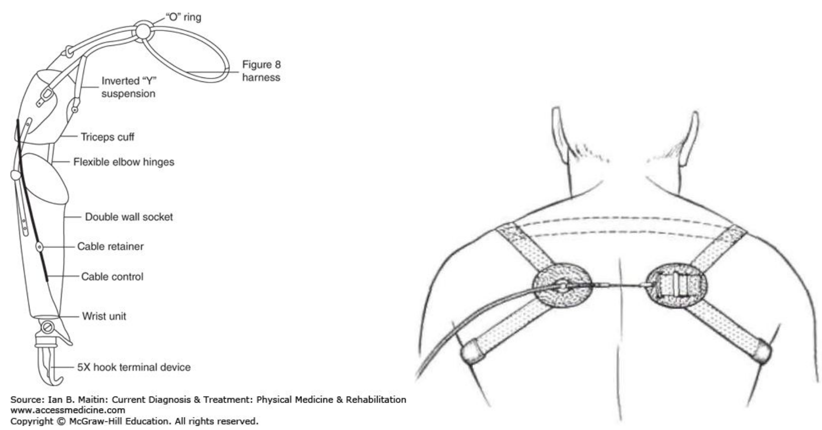



**Figure 18:** Body Powered Prosthesis (Left), Harness for Shoulder Actuated Device (Pursley, R.J., Harness patterns for upper-extremity prostheses. Artificial limbs, 2 3, 1995, 26-60, accessed: December 14, 2018). (Right)

The harness was made out of cotton straps and leather for the pads. The pieces were sewn together using a traditional sewing machine (Figure 19). The cable was the most critical aspect of the design. We started by using threaded fishing wire passing through a flexible tube but realized that the tube was too flexible which generated friction with the thread and impeded the motion. We, therefore, decided to use a bike brake cable, since it provided a strong inner cable with a non-flexible and lubricated outer tubing. After fixing the tubing and the cable to the harness, we attached the other end to a linear spring that was itself connected at the back of a drumstick. The drumstick was placed in a rotating holder and fixed to our socket. The entire setup can be seen worn by a user in Figure 20. To actuate the drumstick, the user swings his/her arm up and down. Depending on the position of his/her shoulders, the spring will extend (shoulders at rest) or contract (shoulders pulled backward). This will change the strength of "grip" around the drumstick to create different types of motion, meaning that when the spring is extended it creates a tight grip around the drumstick, whereas when the spring is at its resting length, the grip is looser. ("Grip" in this context refers to the mimicry of a normal drummer's grip using spring actuation of the prosthetic.) With a looser grip, the user can generate double stokes and with a tighter grip, he/she can create louder and more precise sounds. Since we wanted the fatigue to be the lowest possible, we made the resting position of the shoulders correspond to the tight grip since the tight grip is used more often.

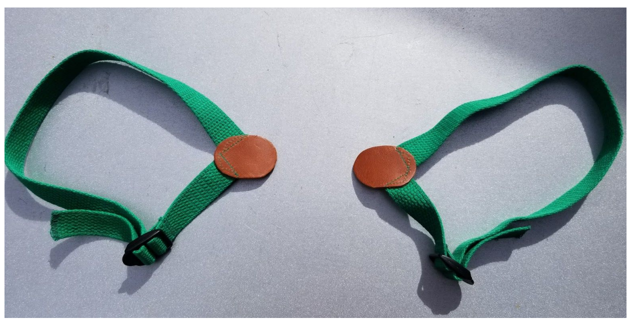


**Figure 19:** Body Powered Prosthesis Harness

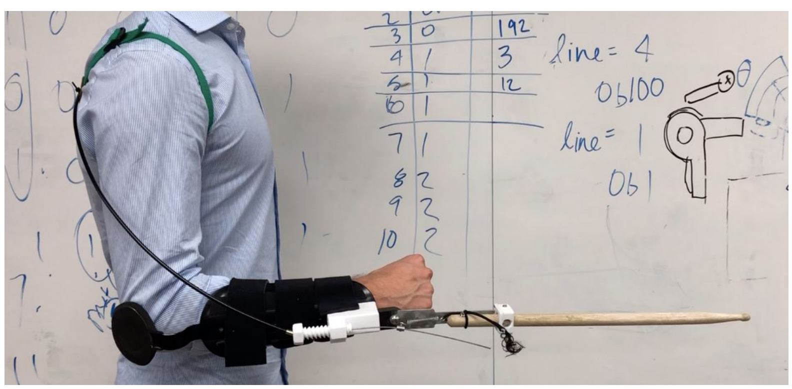



**Figure 20:** User wearing the body powered prosthesis

**Beyond Hands Second Design: Linear Actuator Prototype**

The linear actuator mechanism is composed of a spring, a linear actuator and a rotating shaft. The spring is fixed to the shaft at one end and fixed to the linear actuator at the other. The drumstick is also attached to the rotating shaft (Figure 9).

When the actuator is pulled, the spring extends, which reduces the range of rotation of the bar, and therefore of the drumstick. Therefore, by playing with the position of the linear actuator, the user can obtain different response of the drumstick depending on what he/she wants to achieve. Depending on the length of the spring the drumstick will be able to rotate more or less freely and generate double taps in one case or louder and more precise sounds in the other case. A mathematical model of this mechanism has been developed and can be found in the Appendix. This model allows us to understand how the drumstick will move depending on the stiffness of the spring.

For our works-like prototype, we 3D printed a casing that can contain the actuator, spring and shaft mechanism and that can be attached to the socket. Two bearings have been mounted on the sides of the box to allow the bar to rotate. We also 3D printed a holder for the drumstick, that is fixed to the shaft.

**Figure 21:** Linear Actuator Prototype

**Beyond Hands Third Design: Twisted String Prototype**

A prototype was created using the twisted string concept based on Figure 10. This prototype consists of a redesigned drumstick holder, a motor with motor mount, bungee cord, and electronics. The electronics include a microcontroller (Arduino), Myoware, electrodes, and batteries (not pictured). To actuate the prosthetic, the user performs a forearm muscle flex, which would then wind or unwind the bungee cord. This causes a change in the length of the bungee cord thus changing the stiffness of the prosthetic to enable for a single or double stroke (Gaponov, I. et al., 2016). Thus, there are stiff and nonstiff conformations for the twisted string prototype (Figure 23, Figure 24).

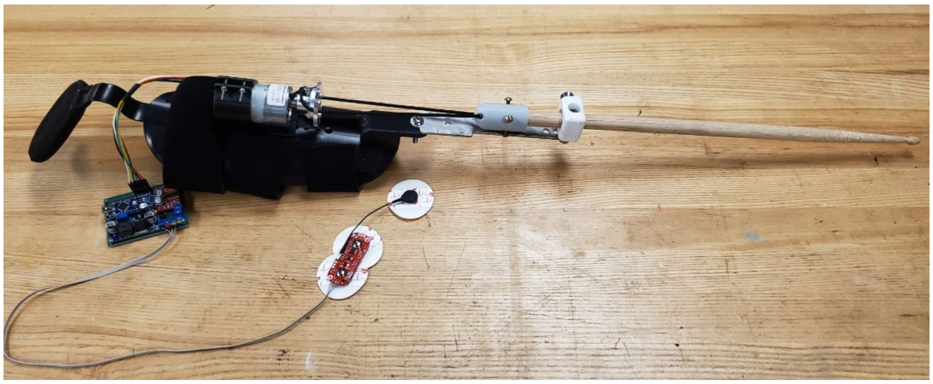


**Figure 22:** Twisted String Prototype with electronics

**Figure 23:** Nonstiff conformation for the Twisted String Actuated Prototype

**Figure 24:** Stiff conformation for the Twisted String Actuated Prototype

**Beyond Hands Fourth Design: Cam Prototype**

This design involves a cam that will block the movement of the bungee cord at a set length along the cord. This will effectively shorten the bungee cord length, by only allowing a certain length of the cord to stretch. This thereby increases the stiffness of the system through a binary switch mechanism. Two types of cam design were investigated: one that pinches the cord (Figure 25a), and one that deflects it (Figure 25b). If the user wants a tight grip for single strokes, the cam blocks the bungee cord thereby reducing the length that can stretch. If the user wants a looser grip for double stokes, the cam rotates, freeing the bungee cord.  These two designs had the goal of reducing the actuation time to get a more immediate stiffness change. encouraging results were obtained after motorizing both prototypes. These designs were more investigative and will be more developed in the coming month.

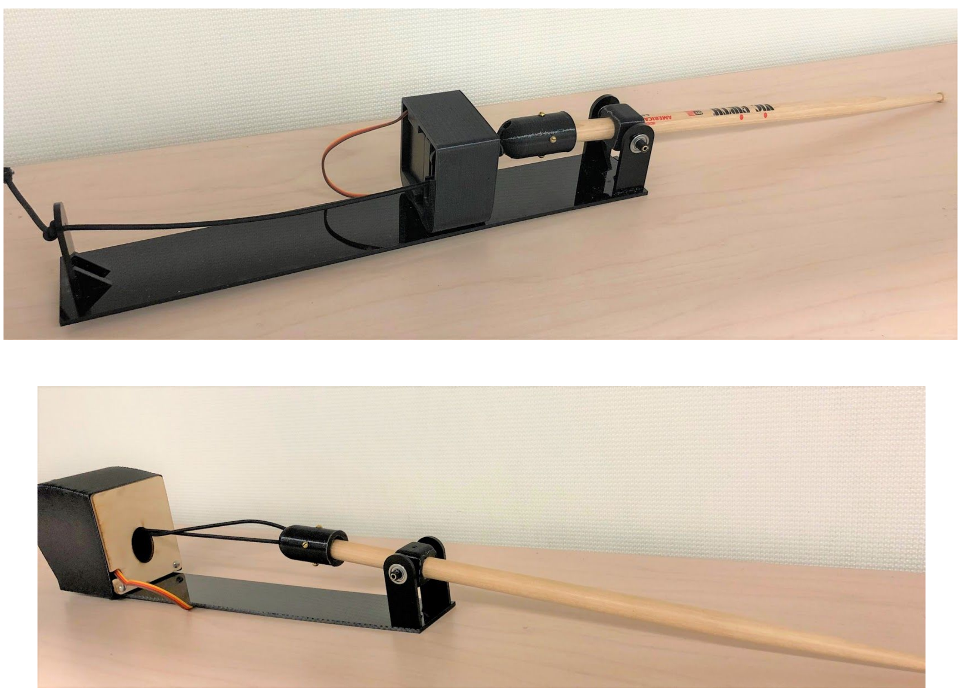


**Figure 25:** Cam System. Prototypes of the bungee cord pinching design (top) and the bungee cord deflection design (bottom).

## User Testing and Results with Non-Amputated Drummers

To test the accuracy and induced fatigue with the prototypes that were created, a testing protocol was created and is included in the Appendix. Baseline testing results were acquired with natural drumming and the twisted string actuated prototype (in the stiff and nonstiff conformations) to compare accuracy and fatigue measurements. Each drumming modality was tested with the jazz groove rudiment for four measures at 60 BPM, 120 BPM, and 180 BPM, thus a total of nine datasets per user were generated. Because of time constraints, the EMG data was not recorded, but will be tested in the future. Thus, the results discussed in this paper are going to be limited to accuracy measures.

### BopPad Accuracy Measurements

Accuracy was measured through a MATLAB script that captures drum strikes on a device known as the BopPad, which aids a musician in maintaining rhythm. Figure 26 is an example of accuracy measurements recorded by the BopPad.

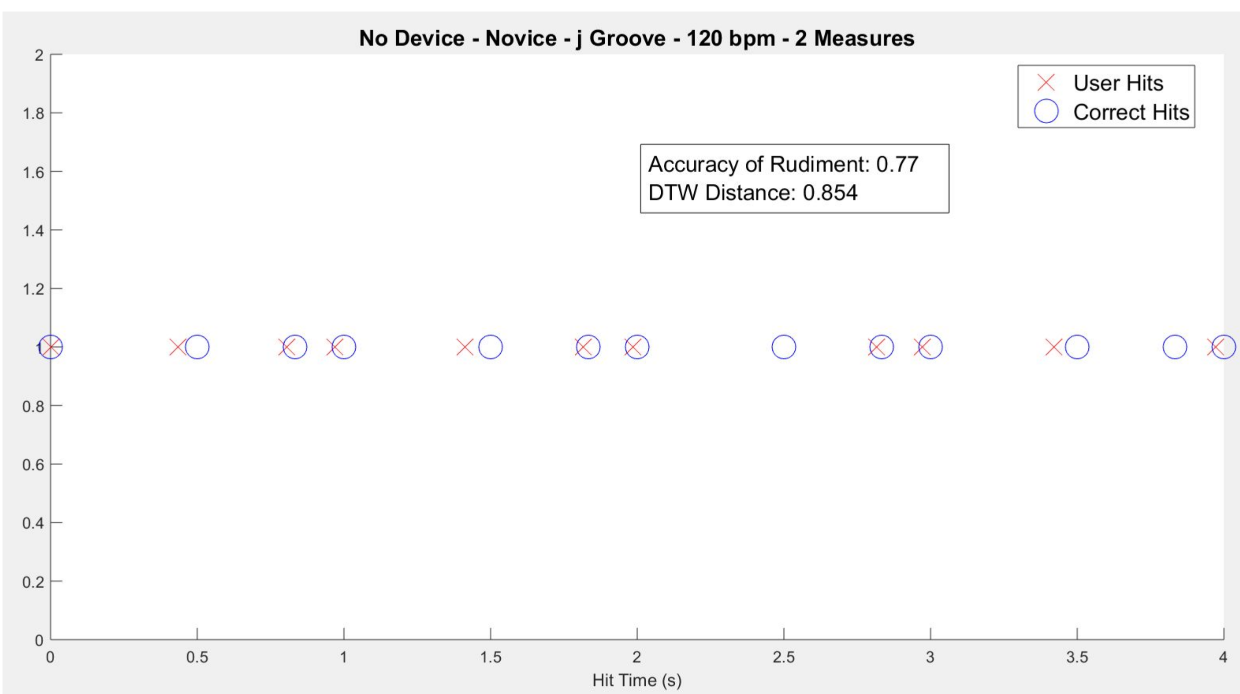


**Figure 26:** The red X's denote a user strike, while the blue circles represent the actual rhythm. This example represents a user that is attempting to play a jazz groove at 120 BPM for two measures, with no prosthetic device.

The accuracy (measured on a scale from 0 to 1) is calculated through an algorithm that incorporates dynamic time warping, which calculates the temporal distance between two sequences. In this case, the algorithm calculates the time differences between the user strikes (red X's) and the actual, accurate rhythm (blue circles). The more the user strikes deviate from the accurate rhythm, the lower the accuracy.

**EMG Fatigue Measurements**

To measure user fatigue, an EMG is used to detect muscle signals. The EMG device that is used is called the MyoWare. The electrodes that are attached to the Myoware are placed directly onto the surface of the skin at the muscle areas of interest. While the user is playing, the muscle signals were monitored, and the muscle contractions (represented by spikes in the datasets) were observed as the user played.

**Results**

A total of nine tests were performed for three users in our group. Before testing, the team discussed that the testing would be more productive if each tempo was tested with both the stiff and nonstiff conformations of the twisted string actuated prototype, rather than changing stiffnesses mid-test. For natural drumming (without the aid of a prosthetic), the accuracy for all three tempos for all three users ranged from **76% to 100%** accuracy. Figure 27 shows a dataset that has achieved this accuracy range. Table 1 shows the accuracy results for natural drumming.

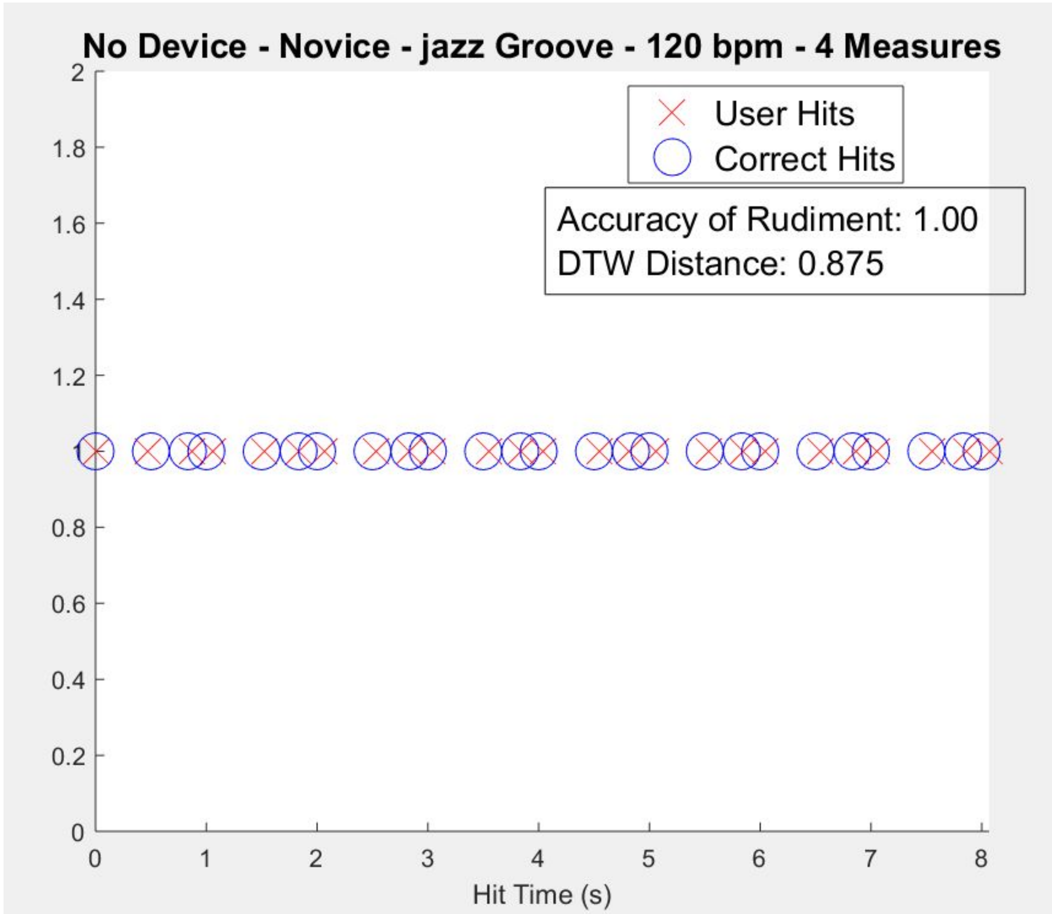



**Figure 27:** 100% accuracy for natural drumming at 120 BPM, 4 measures

For the twisted string actuated prototype in the unstiff conformations, the accuracy varies based on the user, stiff and nonstiff conformations, and the tempo. Table 1 below shows the accuracy results for each test. These results are discussed in the **Discussion** section below.

| | **User 1** | **User 2** | **User 3** |
|---|---|---|---|
| **60 BPM, Natural Drumming** | 96% | 100% | 76% |
| **120 BPM, Natural Drumming** | 100% | 88% | 92% |
| **180 BPM, Natural** | 100% | 100% | 100% |

| Drumming | | | |
|---|---|---|---|
| **60 BPM, Nonstiff** | 76% | 100% | 80% |
| **60 BPM, Stiff** | 100% | 32% | 4% |
| **120 BPM, Nonstiff** | 80% | 100% | 40% |
| **120 BPM, Stiff** | 80% | 96% | 32% |
| **180 BPM, Nonstiff** | 40% | 56% | 60% |
| **180 BPM, Stiff** | 80% | 60% | 44% |

**Table 1:** Accuracy results for natural drumming testing and twisted string actuated prototype testing

## Discussion: Designing, Prototyping, and Testing

Through the fall semester, the team cemented the design criteria for a drumming prosthesis based on our survey results. To stand out from and improve upon existing prosthetics, ours needed to enable higher playing coordination and accuracy, reduce fatigue, be lower cost, and be faster to learn.

Each prototype developed had its own merits and drawbacks. The stiff version without any "bounciness" provides a good baseline for comparison, despite causing muscle fatigue very quickly. The Paradiddle can only achieve a small range of stiffnesses and had a difficult assembly, but did fit many of the same criteria we aimed to implement. It was easy to source parts for our body-powered prosthetic and it provides the user with instant feedback felt in the cable running across the shoulders. However, it generated a lot of fatigue. It would also need to be built more robustly for further testing.

The twisted string prototype is able to achieve the variable stiffness that we wanted. According to user feedback, the prototype was easy to learn, as it did not take more than 30 minutes to get accustomed to. However, the actuation is not instantaneous, so the transitioning time between a single and double stroke needs to be decreased in future prototypes. The cam design aims to decrease this actuation time and will be tested by users in the future.

**Rationale of Testing Methods and Decisions**

Before testing, the group wanted to readily change the stiffness of the prototype to achieve single or double stroke while playing. However, after constructing the twisted string actuated prototype, the team saw that the single and double stroke could be achieved regardless of whether the bungee cord was wound or unwound. This was suspected to be because of the ball bearing design used for the rotation of the drumstick, which vastly reduced the damping experienced in the previous prototypes. This improvement allowed for the user to perform single and double strokes easily, depending on how hard the user strikes. Therefore, rather than using the bungee cord to modulate single stroke and double stroke, the winding and unwinding of the bungee cord could be used to adjust the resonant frequency of the double stroke, fine-tuning the rebound of the drumstick according to the tempo being played. Thus, the testing was centered around comparing the effectiveness of both stiff and nonstiff bungee cord positions for different tempos, rather than focusing on whether single or double strokes can be achieved, since the ball bearing design was able to achieve this difference.

**Qualitative Results**

Qualitatively throughout testing, users were asked about their perceived fatigue and general comfort during the testing procedure. For all users, the perceived fatigue induced by the twisted string prototypes proved to be significantly less than the body-powered prototype (Figure 20). Users were also asked whether the stiff or nonstiff positions of the twisted string prototype was more intuitive and generally more comfortable for each tempo, independent of accuracy scores. Table 2 below shows each user’s response to this question for each tempo.

| | **User 1** | **User 2** | **User 3** |
|---|---|---|---|
| 60 BPM | Unstiff | Unstiff | Unstiff |
| 120 BPM | Unstiff | Stiff | Unstiff |
| 180 BPM | Stiff | Stiff | Stiff |

**Table 2:** Qualitative responses to which modality was more intuitive and more comfortable for the user while playing each tempo

These responses suggest that at slower tempos (60 BPM and 120 BPM), the unstiff conformation is generally more favored (when the bungee cord is untwisted), and at faster tempos (180 BPM), the stiff conformation is more favored.

**Quantitative Results and Observations**

Even though the qualitative feedback suggests that the unstiff conformation is preferred at lower tempos, and the stiff conformation is preferred at higher tempos, the quantitative data is varied across all users.

At 60 BPM, User 1 has a better accuracy with the stiff conformation than with the nonstiff conformation, which contradicts the notion that an unstiff conformation was intuitive for User 1 at 60 BPM. However, the qualitative responses for Users 2 and 3 were consistent with the qualitative results for the 60 BPM tempo.

For the 120 BPM tempo, the quantitative results compared to the qualitative responses are only consistent for User 3, who demonstrates an 8% increase in improvement in the nonstiff conformation at 120 BPM over the stiff conformation, and has stated that the unstiff conformation was more favored for the 120 BPM tempo. On the contrary, User 1 has experienced no increase or decrease in accuracy when using both the stiff and nonstiff conformations. User 2 states that the stiff conformation was intuitive for

120 BPM, but demonstrates a 4% decrease in accuracy when using the stiff conformation versus the nonstiff conformation.

For the 180 BPM tempo, the qualitative responses are consistent with Users 1 and 2, showing 40% and 4% improvements respectively for the stiff conformation. However, for User 3, there was a decrease in accuracy of 16% using the stiff conformation.

**Sources of Error and Future Improvements**

All of these results demonstrate that the results are not conclusive. However, there are some potential causes of error that could have led to these inconclusive results. First, the encoded positions for the motor and the tuning of the degree of twisting was not optimized for the tempos that we were testing. In future iterations of this prototype, we aim to use a potentiometer to vary the stiffness, rather than having a binary switch. The design could also be further optimized by taking into account the varying user striking forces and experience levels of the user.

Another source of user error is the adaptivity of the user to the prosthetic while testing. This could present some bias in the results, depending on the order of testing, as the user could improve on their drumming as they are playing. Although this bias could not be eliminated, this could be circumvented by either allowing for the user to accustom themselves to drumming before testing, or by lengthening the rest periods between each test.

Some improvements that could be made to the testing procedure is to simply do more tests. Because of time constraints this was not considered, but in the future, more tests will be performed to get a larger sample size for each individual to make definitive conclusions. Another improvement is to recruit more users for testing, as this would also allow for more definitive conclusions, as stronger correlations could be made with larger sample sizes. Effectively, more work has to be done in both the design of the twisted string prototype and its optimization, and the design of our experimentation. In the future, more able-bodied users and need-knowers would be recruited to give valuable feedback.

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# Appendix

## Definitions for Technical Terminology: Drumming, Prosthetics, Mechanics, and Electronics

**Drumming and Music Terminology**

**Grip:** Refers to a normal drummer's grasp on the drumstick. This could be a relaxed grip, where the drummer releases his/her fingers around the drumstick, or a tight grip, where the drummer has all fingers wrapped around the drumstick.

**Time Signature:** Dictates the number of notes per measure

**Measure:** A unit of music with a set number of notes played based on the time signature

**Rudiment:** Drumming patterns that drummers use to build simple or complex rhythms

**Single Stroke:** The drummer strikes once on the drum, and then returns the drumstick to its original position.

**Double Stroke:** The drummer strikes the drum, and relaxes the hand to enable for the drumstick to rebound. This enables for the drumstick to strike the drum again, without a change in the drummer's hand position. The drummer then returns the drumstick to its original position.

**Jazz Groove:** A drumming rudiment that consists of a sequence of two single strokes, and then a double stroke using a triplet rhythm (schematic of the Jazz Groove shown below)

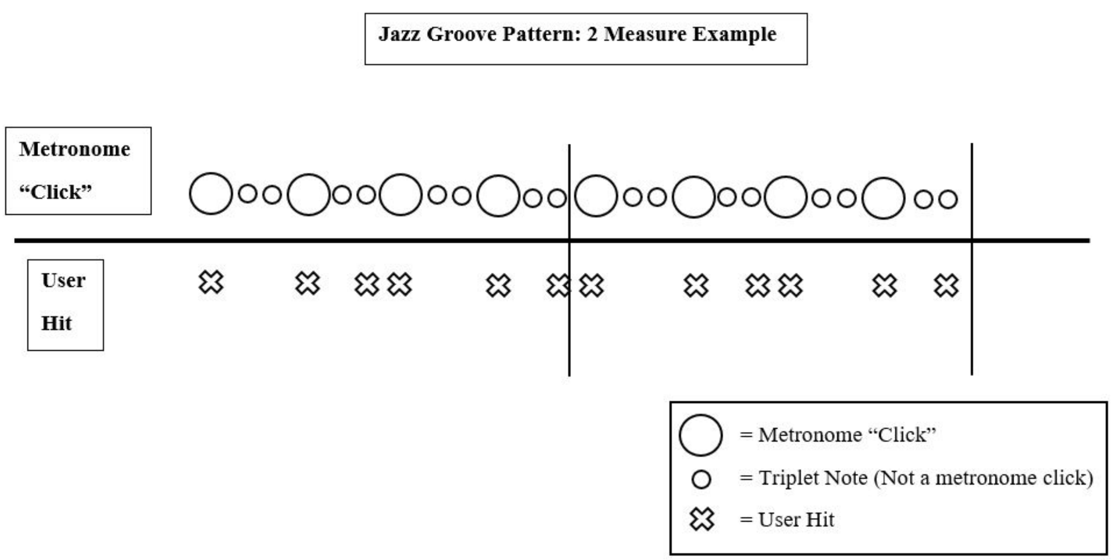



**Figure 23:** Using a 4 notes per measure time signature

**Metronome:** A device used to keep track of the beats per minute (the “speed” of the segment of music)

**Parts of a Drumkit:**


**Figure 24:** Drum kit Components (Standard 5-Piece Drum Kit Parts | Drum Fortress, Accessed March 1, 2019)

**Prosthetics Terminology**

**Passive Prosthetic/Body-Powered Prosthetic:** A prosthetic that is actuated through human movement and mechanics. The prosthetic does not contain moving parts.

**Active Prosthetic:** A prosthetic that contains electronic components. This means that the motion of the prosthetic comes from an external electrical source, such as a battery.

**Myoelectric Prosthetic:** An active prosthetic that registers a muscular signal output from the user, and processes the signals for prosthetic movement. For instance, a user contracts their bicep to control the extension of a prosthetic hand.

**Transradial Amputation:** Amputation that is below the elbow.

**Mechanics Terminology**

**Variable Stiffness:** The change in material stiffness of a given material. For instance, the stiffness of a bungee cord can change based on how much it is stretched.

**Cam and Follower Design:** A cam is a rotating profile that directs an object known as a follower around its profile. The follower is an object that moves around the cam. The purpose of a cam and follower design is to turn rotational motion into linear motion, depending on the profile of the cam.

**Electronics Terminology**

**Actuators:** A device that enables translational and/or rotational motion for a system. For instance, an electric motor is a rotary actuator, while a push-pull solenoid is a linear actuator.

**Sensors:** A device that monitors a physical property. For example, a force sensor measures the amount of force that is placed on the sensor.

**Solenoids:** A coil that uses electric current to create a magnetic field. The magnetic field forces are used to create linear motion. For the purposes of the paper, the solenoid that is mentioned is a push-pull solenoid, which contains a metal piece in the middle (known as a slug) that retracts into the solenoid when the solenoid coil is induced with electricity, which enables for the coil to compress. When there is no induction with electricity, the slug pushes out of the solenoid, and the coil decompresses.

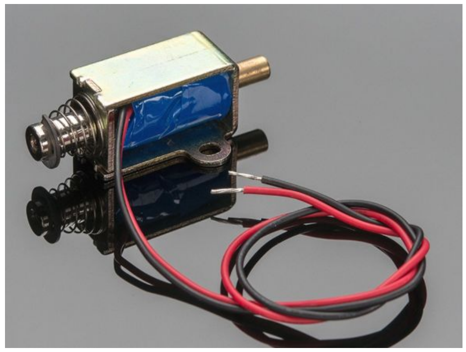


**Figure 25:** Push-Pull Solenoid (Industries, A. Small Push-Pull Solenoid - 12VDC. Available at: https://www.adafruit.com/product/412., Accessed: March 1, 2019)

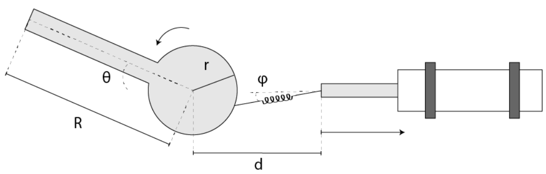
**Microcontroller:** A compact computer that enables for the control and monitoring of electronic components. For instance, an Arduino, which is a microcontroller, can be used to encode motor positions.
**EMG:** Otherwise known as electromyogram. This is an electrical reading of the muscle signals using a myoelectric sensor (the Myoware, in our case), and electrodes.

**Miscellaneous Terminology**
**Works-like Prototype:** An early-stage prototype that focuses on meeting a certain functional requirement without regarding appearance or aesthetics.
**Looks-like Prototype:** An early-stage prototype that focuses on appearance, and is a representation of the appearance of the final prototype.
**Need-Knowers/Differently-Abled:** Technical/awareness terminology for people who are affected by a certain condition. In this report, need-knowers/differently-abled individuals refer to people who have an amputation.
**Non Need-Knowers:** Technical/awareness terminology for people who are not affected by a certain condition. In this report, non need-knowers are individuals who do not have an amputation.

## Drummer Survey

https://goo.gl/forms/zKn0wTxuYshMclrD3

**Single Spring Mechanism Mathematical Model**




Restoring torque as a function of $d$ and $\theta$:

$$T = -k(l - l_0) r \sin(\theta + \phi)$$

$$\frac{l}{\sin\theta} = \frac{r}{\sin\phi} = \frac{d}{\sin(\theta + \phi)}$$

$$T = \underbrace{-krd(1 - \frac{l_0}{d - r}}_{\kappa} \theta = \kappa\theta$$

**Approximate moment of inertia**

$$J = \int_{\frac{-1}{3}l}^{\frac{2}{3}l} m\kappa^2 dx = \frac{1}{9} m l^2$$

Approximate angular frequency. Treat as harmonic oscillator $\ddot{x} + \omega^2 x = 0$

$$T = J\ddot{\theta}$$

$$\ddot{\theta} + \frac{\kappa}{J}\theta = 0$$

$$\omega = \sqrt{\frac{\kappa}{J}}$$

## Baseline Testing Protocol

https://docs.google.com/document/d/1UZAwI2EeMY6VXJ_GdQLVtIxnvLXusC0ZeU0C_jFFPes/edit

## Additional Literature Review for Variable Stiffness (Not Used for Prototyping)

### Antagonistic Variable Stiffness using Motor Control

Antagonistic variable stiffness is a method where two opposing cables, springs, or strings are positioned opposite relative to a link such that the different forces exerted by the actuation mechanisms (i.e. motors) change the stiffness, as shown in Figure 26**.**

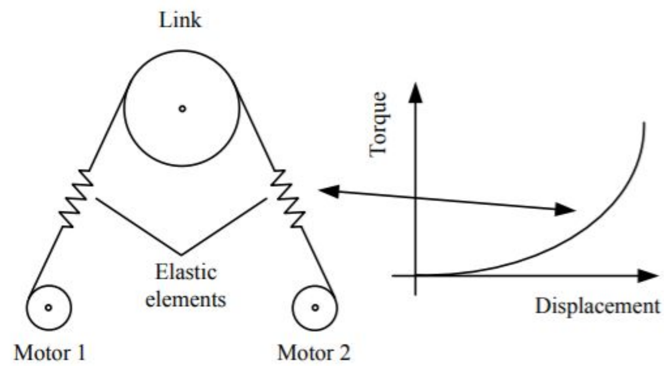



**Figure 26:** Antagonistic variable stiffness via motor control (Petit, F. *et al.* Bidirectional antagonistic variable stiffness actuation: Analysis, design amp; Implementation. in *2010 IEEE International Conference on Robotics and Automation*, 2010, 4189–4196, accessed December 14, 2018).

This method is able to induce a change in stiffness because the elastic elements provide a non-linear torque displacement behavior through the elongation or contraction of these elements via the motors (Petit, F. *et al.* Bidirectional antagonistic variable stiffness actuation: Analysis, design amp; Implementation. in *2010 IEEE International Conference on Robotics and Automation*, 2010, 4189–4196, accessed December 14, 2018).

**Rotational Variable Stiffness using Torsional Springs**

Using torsional springs is another method in which variable stiffness can be achieved. Depending on how much the torsional spring is rotated, the stiffness of the mechanism changes. This was tested by the creation of a high-resolution prototype of this mechanism (Figure 27)**,** where motors attached to the bottom of each gear mechanism modulate the stiffness of the drumstick through antagonistic variable stiffness actuation.

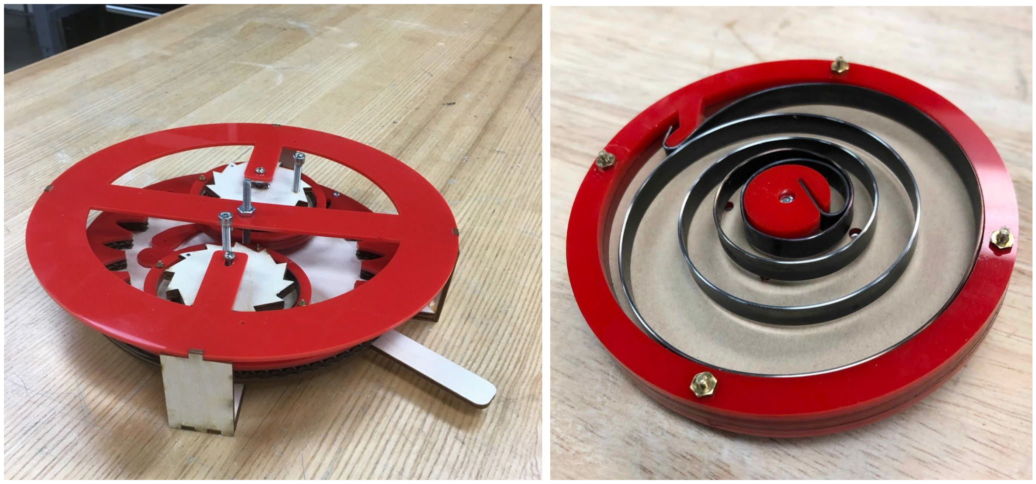


**Figure 27:** High-resolution prototype of antagonistic rotational springs for variable stiffness

## Section Contributions

**David Asnaghi:** Design and Prototyping: CAD Modeling, Body Powered Prototype
**Lucie Derbier:** Design and Prototyping: Body Powered Prototype, Linear Actuator Prototype
**Elizabeth Gomes:** Interview Process, Design and Prototyping Introduction, Paradiddle Prototype, Cam and Follower section, Conclusion, Future Directions
**Alva Liang:** Definitions**,** Executive Summary, Framing the Issue Introduction, Literature Review, Stiff Prototype, Baseline Testing, User Testing and Results with Non-Amputated Drummers, Discussion, Paper 1 revisions, Paper 2 revisions
**Pooja Rao:** Summary, Existing Drumming Prosthetics, Body Powered Prototype, Future Work