Wheelchair Adaptive Devices for Quad Tennis

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Abstract

The client requires a suite of assistive devices for use in a quadriplegic tennis league as a result of his condition, Becker Muscular Dystrophy. The two main goals of this project are to design and fabricate a tennis ball serving system and an optimized tennis racket grip. Some important criteria for these designs are client safety, ease of use, and accuracy. After evaluating a range of brainstormed ideas with a design matrix, the team elected to move forward with a compressed air system to launch the tennis ball and a series of elastic bands around the racket handle for a supported grip. Testing of the racket grip proved successful for an initial prototype, but the tennis ball launcher failed to complete the task of launching the ball. Future work of the designs will focus on optimizing the tennis grip for comfort and developing a working model for the serving system.

Introduction

Motivation

The design project client has Becker Muscular Dystrophy (BMD), which is a genetic muscular disorder that is characterized by the progressive weakening of muscles in both upper and lower extremities. According to the Center for Disease Control, 1 in every 7,250 males between five and twenty-four years of age will develop either Becker Muscular Dystrophy or the closely related, yet more severe, Duchenne Muscular Dystrophy.[1] Although BMD is not currently curable, there are a variety of treatment options that may help patients remain mobile for a longer period of time. For example, one important component of treatment is occupational therapy, in which patients learn to use adaptations to simplify everyday life. Physical therapy is another important component of retaining mobility as it stretches and strengthens tight muscles and prevents further muscle and joint damage. Furthermore, a form of therapy that is especially relevant to the design project is recreational therapy. Recreational therapy allows patients to participate in leisure activities, socialize, and form a support group with individuals of varying abilities.[2]

The client enjoys playing quadriplegic wheelchair tennis, which is a division of tennis in which players must have a permanent disability that results in the substantial loss of function in at least three extremities.[3] The International Tennis Federation (ITF) and United States Tennis Association (USTA) allows players to use any assistive devices to help facilitate gameplay.[3,4] While being active in the sport, the client has continuously experimented with a variety of assistive devices to improve his ability to play. Currently, many of these experimental devices do not produce the results that the client wants, and the client does not have access to materials or methods to develop viable devices to resolve some of the impairments noticed while playing the sport. There is a need for a design team to design and fabricate such assistive devices for the client so that he can use quality and safe assistive devices while on the tennis court. These devices would improve the client's overall ability to play the game and avoid any hassles that the client currently encounters, such as missed serves or lost tennis racket grip. If successful, these devices could be marketed to other quadriplegic tennis players and expanded to fit other adaptive sports.

Current Devices

One of the most common issues that quadriplegic tennis players struggle with is maintaining an adequate grip on their tennis racket. As a result, a common method employed is the use of athletic tape to secure the racket to their hand (figure 1). Although this method is effective for many players, it does not suit the needs of the client because it greatly limits the range of motion in the wrist, which is his main source of power during gameplay. The client has experimented with other methods, such as the use of rubber bands and Velcro straps; however, these methods have proved ineffective. There are a variety of devices that are on the market for off-court serving systems. An example of one of these portable tennis ball machines is the Lobster Elite 2 Freedom Ball Machine (figure 2). Although this machine is good for a practice setting, it lacks the consistency that the client needs during a game.

Figure 1: Athletic Tape Commonly Used to Secure Hand to Tennis Racquet[5]

Figure 2: Lobster Elite 2 Freedom Ball Machine[6]

Problem Statement

The client has Becker Muscular Dystrophy, and is active in the USTA's quadriplegic tennis league. In the quadriplegic league, players are allowed the use of assistive devices, in addition to their wheelchair, to aid them during the match. Assistive devices can vary greatly from player to player as each person's condition is unique to them, but the client requires an optimized tennis racket grip and an accurate tennis ball serving system. This equipment must be attached to the client's wheelchair in order to prevent interference with play. The client has requested that we design these assistive devices in order to improve their level of play, and eventually that of other individuals in the quadriplegic tennis league.

Client Information

Dan played tennis on the high school tennis team as well as recreationally into his college years until age 23. At this point he could still stand and walk, but he could not move as fast as the other people on the court. Dan attended Stanford University and received a bachelor's degree in civil engineering in 1997. He then became a certified java programmer and now works as a web developer for Wet Sand. He did not learn about adaptive sports until later in his life and did not start playing wheelchair tennis until 2006. After struggling to even hit the ball over the net, he played in a quadriplegic wheelchair tennis tournament later that year and made his decision to sell his apartment and things to travel around the US playing wheelchair tennis. That year he did not win a single quad match, but he started working on his world ranking and thoroughly enjoyed all of the traveling that he got to do. He won his first match in South Africa, and in 2009 he finally got to play in the "A" division, winning both the singles and doubles matches. He is a veteran of the quadriplegic tennis circuit who is continually improving his game.

Background

<u>*Biology and Physiology Research*</u>

Becker Muscular Dystrophy (BMD) is caused by a genetic mutation that results in the insufficient use of dystrophin, a protein that is responsible for maintaining the structural integrity of muscles by providing a link between the muscle cytoskeleton and extracellular matrix (figure 3).[7] Inheritance of BMD is X-linked recessive, which consequently makes males the most susceptible group to developing the disease.[8]

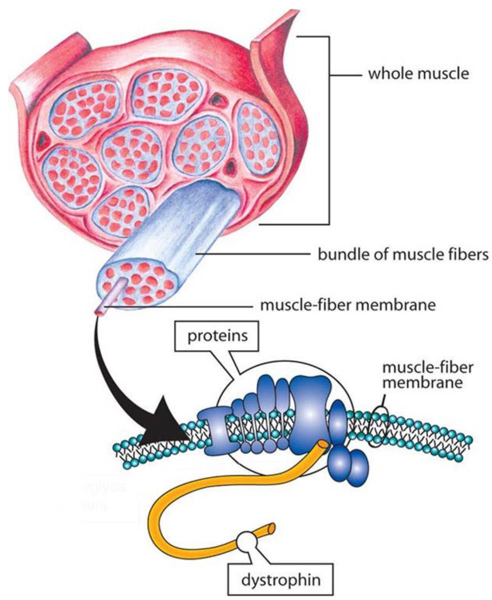


Figure 3: Dystrophin protein within the muscle-fiber membrane[9]

Muscle weakness is typically first noticed in the upper legs, pelvis, upper arms, and shoulders (figure 4). Unlike the closely related Duchenne Muscular Dystrophy, cognitive and cardiac impairments are typically not prevalent; however, when they are, they are usually much less severe. The muscular disorder usually appears by the time the patient is 11 years old; however, it may appear as late as age 25. The rate of disease progression varies greatly from patient to patient. Some individuals remain mobile until their mid-thirties, while others need a wheelchair by the time they are teenagers.[8] The Center for Disease Control estimates that 90% of males from the ages of 15-24 with either Duchenne or Becker Muscular Dystrophy use wheelchairs on a regular basis.[1] In terms of a long-term outlook of the disorder, most patients with BMD live into their mid-forties and fifties due to heart and breathing complications.[2]

Figure 4: Typical muscle groups affected by BMD[10]

Quadriplegic Wheelchair Tennis Background

Quadriplegic wheelchair tennis was founded in 1976 and is considered one of the most rapidly growing wheelchair sports in the world. Since its beginning in 1992, the International Tennis Federation's (ITF) Wheelchair Tennis Tour has grown from 11 international tournaments to 160 global events that occur each year.[4] Wheelchair tennis follows the same rules as the able-bodied version of the game, with the exception of allowing players to let the ball bounce twice before returning the ball to the opponent. Furthermore, the ITF and United States Tennis Association (USTA) allows players to use any assistive devices to help facilitate gameplay.[3,4] Assistive devices may be attached to the racket, as long as any modifications do not alter the physical characteristics of the racket in order to enhance performance.[3] Furthermore, the USTA stipulates that the overall racket length should not exceed 29 inches (73.66 centimeters).[3] The USTA permits players to use off court serving systems or another individual to throw the ball towards the player; however, the player must use the same serving method for the entire duration of the match.[3]

Specifications

General Specifications

The combined cost for both assistive devices must not exceed $500. Each device must also comply with all USTA regulations. Specifically, a rule the USTA has in the quadriplegic tennis league limits the number of exposed logos a player may have on their person/wheelchair.

As a result, all devices shall be devoid of logos, so as not to infringe on this rule. A full write-up of the product design specifications for both designs can be found in Appendix A.

Design Specifications - Serving System

The client has requested that the serving system be mounted to the wheelchair (figures 5-6) so that it does not get in the way of play and is accessible. It is critical that the serving system can consistently launch the tennis ball to a height of 42” and a location 36” horizontally from the wheelchair for the client to hit. Since the client uses his wheelchair outside of tennis, he has also asked that the serving system be easily detachable from the wheelchair. Another specification of the client was that the device be adjustable such that the angle and height to which the ball is launched can be altered. The serving system should be able to withstand normal operating conditions such as heat, cold, and humidity. It is also necessary that the serving system be simple for the client to operate. For example, having a button for the client to push to launch the ball would be acceptable, whereas having the client exert a significant amount of force to launch the ball would not.

Figures 5-6: The client’s current power wheelchair (seated) and wheelchair on loan for design purposes (empty)

From a safety and reliability standpoint, the serving system must not cause the client’s arm, hand, or body any injury during the launching phase. The device also cannot throw off the balance of the wheelchair in such a way that it is more prone to tipping, especially when the tennis ball is being launched from the serving system. The serving system should be extremely reliable with regards to location consistency as previously mentioned, but it should also have a reliable launching activation mechanism. For example, if a button is pushed to activate the serving system, then the button should not regularly malfunction. On the flip side, the serving system should not randomly activate when the client isn’t using it.

The barrel of the serving system will be cylindrical in shape and approximately 7-8 cm in diameter so that it can accommodate a tennis ball of 6.7 cm diameter. The serving system should be compact to reduce its weight and the chances of it interfering with play. If the device is too big or protrusive it will hit the client's racket during his backswing. The weight of the serving system is fairly lenient so long as it does not inhibit the mobility of the client or throw off the balance of the wheelchair.

Design Specifications – Tennis Racket Grip

The client specified that the optimized tennis racket grip must improve their ability to keep a firm grip on the racket without sacrificing wrist mobility or endurance. In particular, the client emphasized that the grip should hold the fourth and fifth digits securely to the racket (figures 7-8). This is due to the fact that those are the two fingers that are most often displaced from the grip when the racket contacts the ball. The grip must also be able to withstand normal playing conditions, such as perspiration, heat, cold, and humidity. For example, the human body temperature ranges from 97.7°F to 99.5°F and sweat has a pH slightly below 7, so the grip should not be adversely affected by either of these environmental factors.

Figure 7: The client's tennis racket during normal grip

Figure 8: The client's tennis racket when force is applied from ball contact

In regard to safety and reliability, the grip should not cause any abrasions or other injuries to the client during the course of play. This effectively means that the grip must be made of a smooth material that will give the client a comfortable and enjoyable playing experience. In addition, the grip should not deform or be impacted in any way by the pressure applied by the client. The maximum grip strength of a typical adult male is approximately 110 pounds, but, due to the client's BMD and the fact that the average tennis player does not grip the racket with the standard maximum force, the grip will only need to withstand 80 pounds of force at most.

With respect to size and weight, the client currently uses a racket handle between 4 ¼ to 4 ⅝ inches in circumference, including the grip. Thus, the assistive grip should be relatively small so that it is able to fit onto a racket handle of this circumference. Finally, the grip needs to be extremely lightweight to avoid limiting the client's range of motion or slowing him down.

Design Inspirations

Prototype Design Research (Design Inspiration) - Serving System

Current projectile launching systems were looked at in order to see if they could be modified to fit the given design specifications. The launching systems weren't necessarily related to tennis in any way.

The first projectile launching system researched was the pneumatic potato gun. As seen in figure 9 below, there are three main components to the pneumatic spud gun -- the air tank, the release valve, and the barrel. The air tank stores either compressed air or CO_2. The valve separates this compressed gas from the barrel where the potato is held. When the user opens the valve, the compressed gas, which is at a high pressure, rushes into the barrel and expels the potato from the gun.

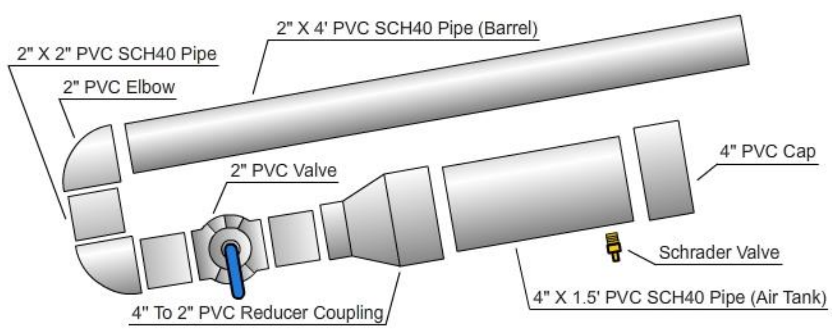


Figure 9: Pneumatic potato gun schematic[11]

The second projectile launching system researched was the castor wheels system used in modern soccer passing machines (figure 10). This launching mechanism works by spinning two castor wheels at very high speeds so that when a ball with a diameter slightly smaller than the space between the castor wheels is pushed through, it is ejected outward at a high speed.

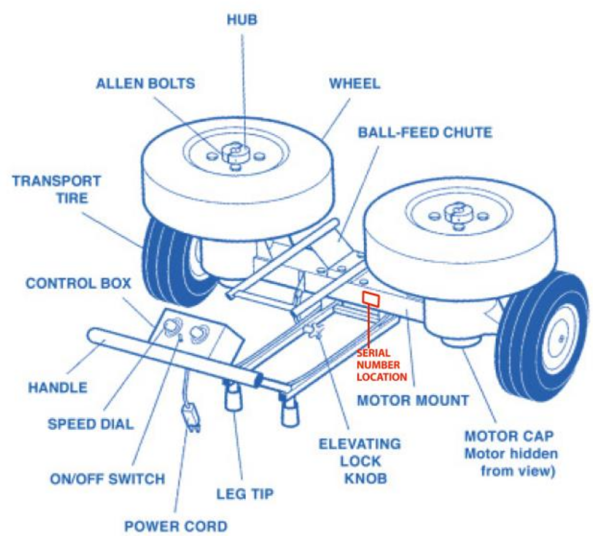


Figure 10: Soccer passing machine layout[12]

The third projectile launcher looked at was the NERF gun. A NERF gun is operated by pulling a piston back against the force of a spring and temporarily holding it in place (figure 11). This increases the volume of air held in the chamber of the gun. When the piston is released, it decreases the volume of the chamber once again, which causes an increase in air pressure. The increased air pressure pushes the projectile out of the gun.

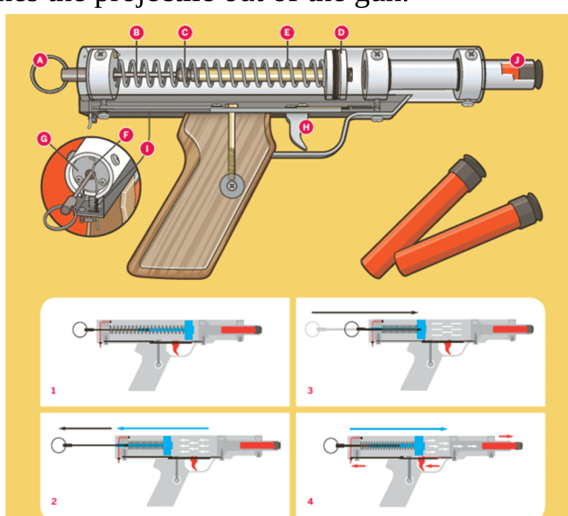


Figure 11: NERF gun infographic[13]

Prototype Design Research (Design Inspiration) – Tennis Racket Grip

Current grip and hand supports were looked at for inspiration to see if they could be modified to fit the design criteria.

The first design researched was a tennis glove (figure 12). This tennis glove design claims to reduce the strain placed on the hand while increasing the user's grip strength using an "anatomical pad system." The glove also utilizes terrycloth mini-towels to help reduce hand moisture. Finally, the glove has a tight grip around the wrist to support it without limiting its motion.

Figure 12: Typical tennis glove worn during play[14]

The other grip design researched was elastic and resistance bands (figure 13**)**. The elastic properties of these bands were explored to see if they could be used to hold the client's hand securely to the racket handle.

Figure 13: A variety of exercise resistance bands of varying strength[15]

Preliminary Designs - Serving System

Compressed Air Cannon

The compressed air tennis ball launcher (figure 14) is a series of tubes made of PVC piping that uses compressed air or CO_2 as a means of propulsion. The system consists primarily of an Arduino, a button/trigger, a tube feeding system and a CO_2 canister. The Arduino is programmed to generate a current that passes through an analog potentiometer resistor, and the resulting voltage is used to determine whether the high speed solenoid valve on the CO_2 canister is open or closed. A potentiometer is useful for this design, as it will allow for manual adjustment of CO_2 flow rate out of the canister. Once the CO_2 is released from the canister, it will be diverted in two directions, one for launching the tennis ball in the breach and the other to load a new tennis ball from the feed tube. The tubes and canister will be built around the wheelchair in order to allow for the best fit.

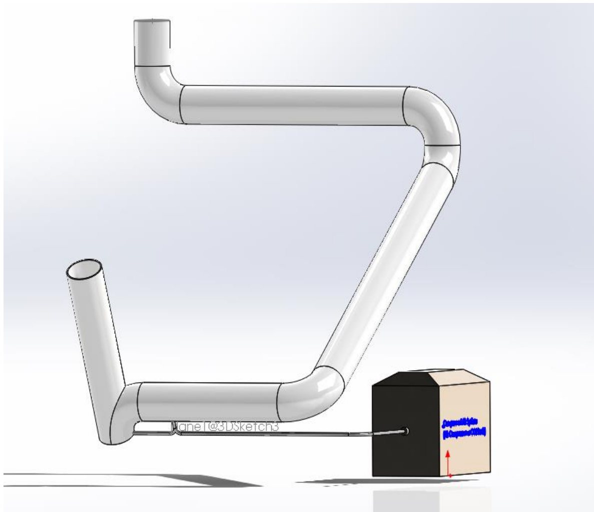


Figure 14: Compressed Air Cannon design model

Caster Wheel Platform

Most current ball launcher designs use a caster wheel system (figure 15), which consists of a pair of wheels running in the same spin direction, but opposite rotation direction. A tennis ball is placed inside the gap between the wheels, and is launched a certain distance depending upon the velocity at which the wheels are spinning. This system will use an Arduino and potentiometer to control the on/off condition of the wheels and their motor. There are safety plates covering the spinning wheels in order to prevent the user from injuring himself on the fast moving wheels. One drawback of this design is the duration of time necessary for the wheels to reach optimal spin speed necessary to launch the tennis ball. These wheels would be about 8 inches in radius in order to provide sufficient launch force without becoming too big.

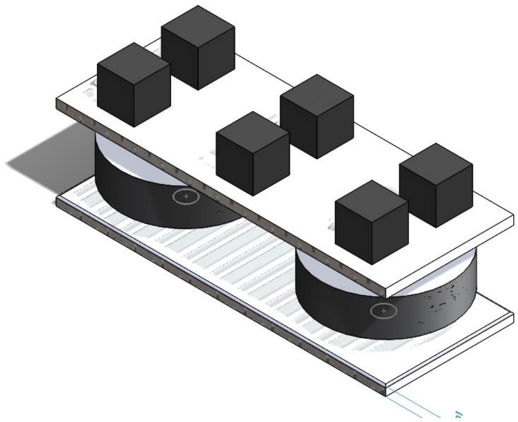


Figure 15: Caster Wheel Platform design model

Loaded Spring Gun

The last of the initial designs was a launcher that used compressed spring energy for propulsion (figure 16). For this design, a box containing a spring is attached to the side of the client's wheelchair and a cable is attached to the spring inside the box. This cable runs from the box to an electric winch that is powered by the onboard wheelchair battery. This winch will draw back the spring on which the tennis ball has been placed, creating significant tension. When the client is ready, the spring will be released, thus launching the ball to the optimal height for the client. One issue raised with this design is that the stress and forces of the spring loaded launch may increase the wear and tear on the design as well as the wheelchair itself, leading to greater maintenance and replacement expenses.

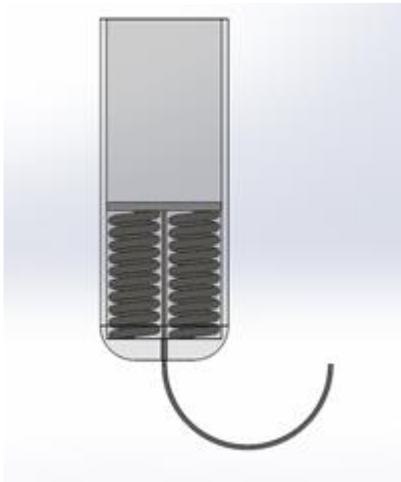


Figure 16: Loaded Spring Gun preliminary design model

Preliminary Design Evaluations/Final Design – Serving System

Design Matrix Criteria

Eight categories were created to rank the possible serving system designs. Each category was given a certain weight to signify its importance in determining the final preliminary design. These categories were then inputted into a design matrix (table 1) and evaluated to determine the best design.

Client Input was given a weight of 10/100. This includes the client's personal comfort and input on the design. This input can be related to a variety of factors, such as the ergonomics of the chair, game play ability, custom fit, and general opinions.

Client Safety was given a weight of 20/100. The top priority of this project is to ensure that the final deliverable does not pose a threat to the client's safety. Some important safety factors necessary in the serving mechanism are chair stability, structural integrity against internal and external forces, and general safety.

Accuracy was given a weight of 15/100. The tennis ball serving mechanism must be able to launch the ball in a precise manner within the client's desired range. As reflected by the weighting, this is one of the most important categories.

Fabrication was given a weight of 10/100. The design must be able to be produced using equipment the team can get access to.

Ease of Use was given a weight of 15/100. Since the client has Becker Muscular Dystrophy, the design must be accessible to the client and not require a significant amount of muscle exertion

Cost was given a weight of 10/100. The client is using personal funds to fund this project, making it extremely necessary to decrease project costs in order to prevent a significant financial burden on the client.

Durability was given a weight of 10/100. The design must be able to withstand general tennis play conditions such as weather, wear and tear, and game play.

Adjustability was given a weight of 10/100. The design must be able to be customized to client's personal preferences as well as those of other users.

Design Matrix

Criteria (weight)	"Air Cannon"- Compressed Air		"The Launcher"- Caster Wheels		"The Spring Gun"- Compressed Springs	
Client Input (10)	5	10	4	8	5	10
Client Safety (20)	4	16	3	12	3	12
Accuracy/Precision (15)	5	15	4	12	4	12
Fabrication (10)	3	6	2	4	3	6
Ease of Use (15)	5	15	3	9	4	12
Cost (10)	3	6	2	4	3	6
Durability (10)	4	8	4	8	3	6
Adjustability (10)	4	8	3	6	3	6
Total (100)	-	84	-	63	-	70

Table 1: Tennis Serving System Design Matrix

The Compressed Air Cannon was given the highest score in every one of the categories. This design proved to be safe, accurate, and easy to use. This resulted in the highest score in the design matrix.

The Caster Wheels design scored high in durability but was not as safe or easy to fabricate/use as the previously mentioned design.

The Spring Gun was tied with the air cannon in client input, fabrication, and cost, but fell short in regards to accuracy, durability, and adjustability. Adjusting this design would require different springs or a different amount of compression before launching. The springs could also rust which was not an issue in the air cannon.

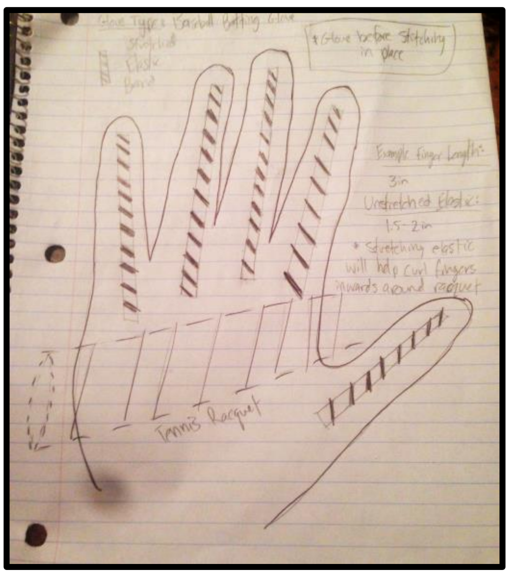
Proposed Final Design

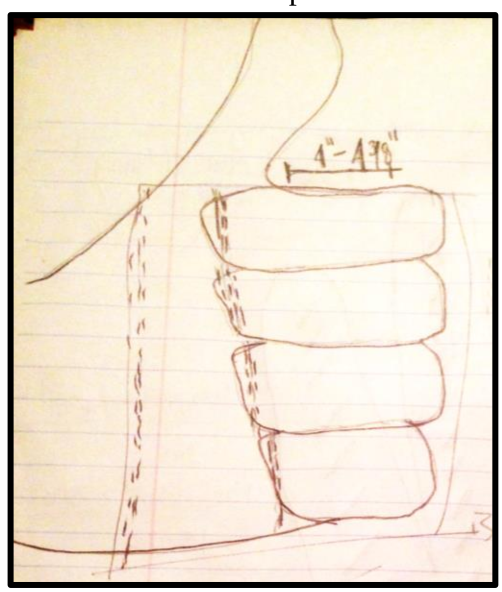
The design selected by the team via a design matrix with relevant criteria was the compressed air cannon. This design won or tied for best in every one of the design criteria, proving to be the most suitable design for the purpose of launching a tennis ball in a quadriplegic league match. Moving forward, the design team will work to research parts, materials and costs associated with fabrication, and eventually the fabrication protocol itself.

Preliminary Designs - Tennis Racket Grip

The Elastic Glove

The elastic glove grip design (figures 17-18) is a sports glove modified with elastic bands. The fingertips of the glove are sewn to the base of the palm so that the player's fingers remained wrapped around the racket throughout play. To account for the stitched area, a glove of one size larger than the client's hand would be used. Elastic would then be incorporated along the inside of each finger in order to hold the fingers taut against the grip. The racket would be slid into the curled fingers by applying some outward force front the fingers and then releasing when the racket was positioned. This design would be very comfortable during play and would have ventilation in place via small pores to keep the hand from getting too sweaty. Some concerns with this design are that the glove may be hard to get on in the sewn shape and if any of the elastic were to break or wear-out, the whole glove would have to be replaced.





Figures 17-18: Elastic Glove preliminary design model

Racket Cords

One current method of quadriplegic tennis racket grip supports is using rubber bands to wrap around the hand. Racket cords (figure 19) uses this idea in an altered method to hold the hand tight against the grip using vertical elastic bands. It uses clamps that would fit tightly against the racket on the top and bottom of the grip and then elastic bands that ran vertically all the way around the grip. The player could fit his hand into as many or as few of the bands as desired for optimal grip. This design would be adaptable to players with varying hand strength and allow for changing the grip if necessary even within the duration of a game. With the extra material on the racket itself, we are concerned with how it may alter the interaction between the ball and the racket.

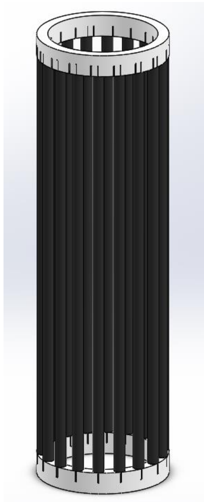


Figure 19: Racket Cords design model

3D Mold

A 3D mold of the client's hand is the basis for this design (figure 20). Coverings for the fingers would be added so that the fingers would be held in place after being slipped into the mold. The design also allows for the mold to be rotated or angled differently on the racket before being fixed in place. This angle could be changed at any point between games. While this allows some flexibility in the grip, the fingers would be fixed in place. This design would succeed in holding the player's hand to the racket, but it may also increase grip size and would not allow for altering the finger positions of the grip after fabrication. It would also not be adaptable for anyone other than the client, unless another 3D mold were to be made.

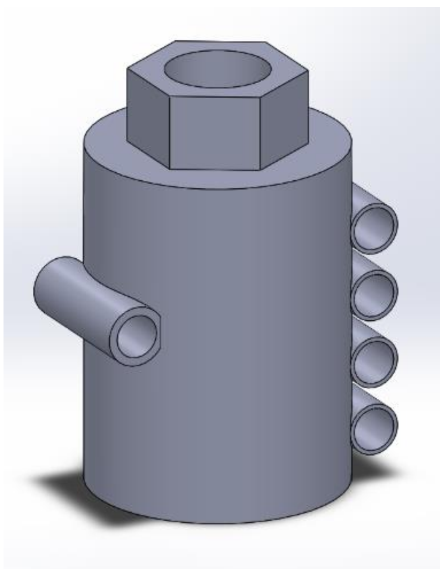
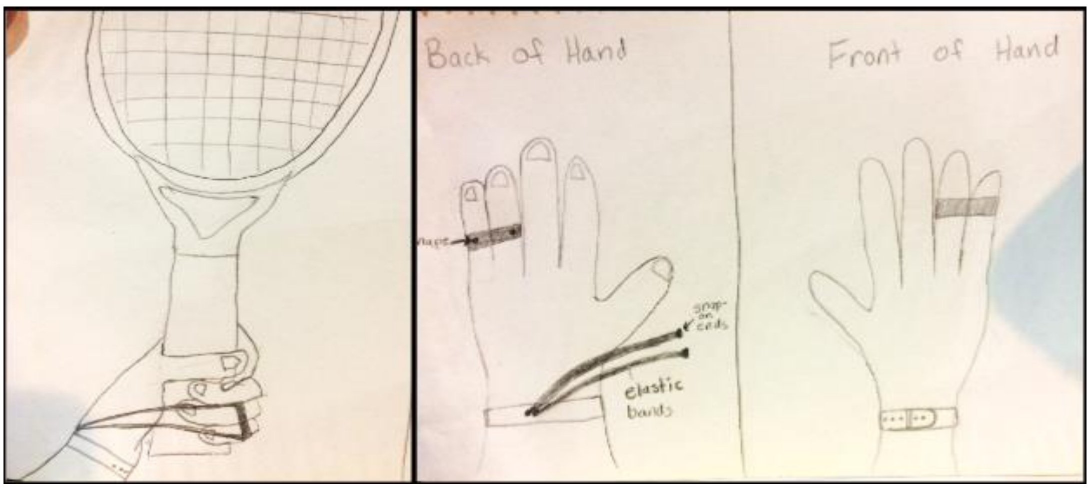


Figure 20: 3D Mold preliminary design model

Spiderman Wrist Mounted Strap

The last design features a thin wrist strap connected by elastic to a band around the fourth and fifth digits (figures 21-23). The elastic attaches to the back of the wrist, which prevents the elastic from changing length and therefore applying a different force with different wrist positions. The detachable elastic from the wrist would allow the player to easily transition between holding a tennis racket and using the hand for something else without having to completely take off the assistive device. Along with this, if parts of this design were ever to break, they could be replaced separately. This design would also be able to be used by most other players. The main concern with this design is that it may affect the ease of mobility of the wrist which is where the client currently gets most of his strength for hitting.



Figures 21-23: Spiderman Wrist Strap preliminary design model

Preliminary Design Evaluations/Final Design – Tennis Racket Grip

Design Matrix Criteria

Seven categories were created to rank the possible tennis racket grip designs. Each category was given a certain weight to signify its importance in determining the final preliminary design. These categories were then inputted into a design matrix (table 2) and evaluated to determine the best design.

Client Input was given a weight of 10/100. This includes the client's personal comfort and input on the design. This input can be related to a variety of factors, such as the ergonomics of the chair, game play ability, custom fit, and general opinions.

Client Safety was given a weight of 20/100. The top priority of this project is to ensure that the final deliverable does not pose a threat to the client’s safety. Some important safety factors necessary in the grip design are ability for circulation in the hand/wrist, risk of equipment malfunction, and risk of overheating.

Comfort was given a weight of 20/100. The client must be comfortable using the design for the extent of a tennis match, which is generally around 3 hours.

Fabrication was given a weight of 10/100. The design must be able to be produced using equipment the team can get access to.

Mobility was given a weight of 20/100. The design must allow for a firm grip without sacrificing degrees of freedom in the wrist and other aspects. Being able to make adjustments to the positions of the hand or fingers on the racket to improve play during a game is a plus.

Cost was given a weight of 10/100. The client is using personal funds to fund this project, so it is extremely necessary to decrease project costs in order to prevent a significant financial burden on the client.

Durability was given a weight of 10/100. The design must be able to withstand general tennis play conditions such as weather, wear and tear, and game play.

Design Matrix

Criteria (weight)	Elastic Glove		Racket Cords		The Mold		Spiderman Wrist Strap	
Client Input (10)	4	8	5	10	3	6	4	8
Client Safety (20)	5	10	4	8	5	10	3	6
Comfort (20)	5	20	4	16	3	12	3	12
Fabrication (10)	4	8	5	10	2	4	5	10
Mobility (20)	3	12	4	16	3	12	3	12
Cost (10)	4	8	5	10	3	6	4	8
Durability (10)	3	12	3	12	4	16	3	12
Total (100)	-	78	-	82	-	66	-	68

Table 2: Tennis Racket Grip Design Matrix

The Elastic Glove was given the highest scores in client safety and comfort as it would fit as a sports glove, which is made to be comfortable during athletic activities. It scored lower in mobility and durability, however, since the hand position is sewn in place and the elastic bands may stretch out throughout use. This resulted in the elastic glove being a close second in the matrix.

The Racket Cords' simple and effective design scored the highest in multiple categories, including client input, fabrication, mobility, and cost. The client liked the simplicity of it and how the hand grip could be altered during play. The fabrication would be relatively simple and few materials needed would lead to a low cost.

The Mold scored high in client safety and durability as it would be built to last a lifetime, but it would not allow for mobility in the grip and would also not be as cost effective or as easy to fabricate as the other designs, which led this to be the lowest scoring design.

The Spiderman Wrist Strap scored the highest in fabrication due to its simple design but it did not score as high in client safety, comfort, mobility, or durability due to the elastic bands running across the wrist.

<u>Proposed Final Design</u>

The racket cords were chosen to be the final preliminary design. This design scored the highest in the design matrix and was also the client's favorite. The team created a test prototype using rubber bands and duct tape on the grip of a racket (figures 24-25). The design was found to be effective in securing the hand to the racket in a comfortable fashion. The ability to use as many or as few of the bands as desired allows the user to create a personalized grip. The elastic bands must be tight against the racket in order for this design to be effective, so the shape of the racket handle will need to be taken into consideration when designing the base system.

Figure 24-25: Initial prototype of Racket Cords design

Fabrication

A full bill of materials used for both the serving system and grip support can be found in Appendix B. The total cost of both designs amounts to $379.10. Given an initial budget of $500, the designs were able to be completed within the budget constraints.

<u>Serving System</u>

Theory:

The work-energy principle in dynamics can be utilized to determine the initial velocity of the tennis ball needed to reach a peak height of 48 centimeters. The work-energy principle balances the energy of a system between two states by converting energy into either potential energy, kinetic energy, or work. For the tennis ball, it is assumed to be dragless (i.e. the air exerts no force on the ball to collect work and slow the tennis ball down) and converts from its initial launch velocity at the end of the tube to zero velocity at its peak height for serving. The kinetic energy of the tennis ball at state 1 is half its squared velocity multiplied by its mass, and the potential energy of its peak height (where velocity is zero and thus so is kinetic energy) at state 2 is its mass multiplied by the gravity constant and the ball's height. Thus, the equation in question is $\frac{1}{2}m_{ball}V_o^2 = m_{ball}gh_{peak}$. Since all variables are known except for the initial velocity, it can be solved for to determine the necessary launching velocity.[16]

A pneumatic mechanism is used to lift the tennis ball in the air to this initial launching velocity. The source of power in launching the tennis ball lies in the pressure differential between a source of compressed air and atmospheric conditions (figure 26). A free-body diagram of the tennis ball in the launching tube accounts for the atmospheric pressure and weight pulling the ball down and the subsequent inlet pressure needed to overcome these forces and propel the ball out of the launching tube (figure 27). A force balance on the tennis ball shows $m_{ball}a_{ball} = (P_{inlet} - P_{atm}) * A_{ball} - m_{ball}gcos(\theta_{launch}) = F_{ball}$. This force balance is converted to work on the ball in the work-energy principle, where the work is the integral of the force balance on the ball over the distance traveled, which in this case is simply the length of the launching tube. Thus, accounting for the dimensions of the launching tube, a second work-energy balance shows: $F_{ball}L_{tube} = \frac{1}{2}m_{ball}V_o^2 + m_{ball}gh_{tube}$. This simplified model does not account for frictional or drag effects on the flight on the tennis ball or dynamic and enthalpic effects of the fluid itself, which may greatly factor in during experimental testing.[17] The EES (Engineering Equation Solver) code for these equations can be viewed in Appendix C.

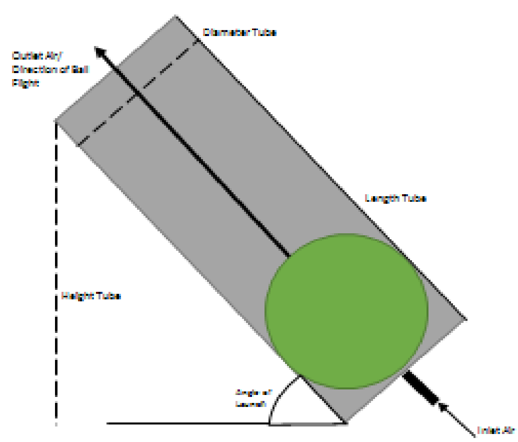


Figure 26: Diagram of tennis ball within launching channel

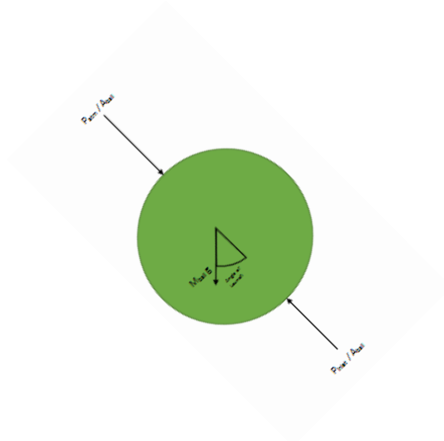


Figure 27: Free body diagram of tennis ball during work process

Materials:

The launching mechanism for the tennis ball consists of three main components: a storage tank for high pressure compressed air, an airline to regulate the pressure and bulk flow of the pneumatic transfer, and a launching tube for ball placement and launching initiation. Each component requires specific consideration for materials based upon the normal and peak operation expected during their use.

The storage tank selected is a 2.5 gal (9.46 L) air tank from Viair rated for 200 PSI (1379 kPa) with six ¼” NPT attachment ports. Accessories for the tank include a ¼” NPT fill valve (rated for 200 PSI), a 300 PSI pressure gauge, a ¼” NPT 200 PSI pressure relief valve, a ¼” NPT draincock, a ¼” NPT cap, and a ¼” NPT 90° male/male connector to the air line. These accessories are used for the functionality (fill valve and connector) and safety (pressure relief valve and draincock). A volume of 2.5 gal was used to maximize the amount of air stored for serving while still being compact enough to fit on the client’s wheelchair.

The airline delivery component consists of a ¼” NPT solenoid valve, a ¼” NPT pressure regulator rated for up to 200 PSI, a ¼” polyurethane air hose rated for 300 PSI, and a swivel ¼” NPT male coupler. The solenoid valve is used to control air flow from the storage tank by opening its port when current is run through the solenoid. This port is normally closed to hold air within the storage tank, and a circuit can be created to open and close the solenoid valve with the push of a button. A pressure regulator is introduced to regulate the pressure drop from the tank to the launching tube for adjustability and accuracy of the serve. The launching tube and air hose are expected to experience much less stress than the storage tank due to this regulator, but all components were procured with the expectation that it is possible for the mechanism to break. A polyurethane air hose carries the compressed air safely around the wheelchair, ending in a swivel male coupler that allows an easier connection between the air line and the launching tube.

Finally, the launching tube consists of a 10” long 3” diameter schedule 40 PVC tubing rated for 200 PSI with end cap and a quick connect ¼” NPT female coupler with ¼”-⅜” bushing.

These dimensions are based upon the allowances from the diameter of the tennis ball (2.54''/ 6.45 cm) and wheelchair.

Fabrication:

The storage tank system requires no rigorous fabrication. All accessory valves for the tank are wrapped in polytetrafluoroethylene (PTFE) tape at their fittings and screwed tightly into the necessary port using an adjustable wrench (see figure 28 for proper port placement).

Figure 28: Diagram of setup of storage tank and corresponding valves

The first step for fabrication of the air line delivery system consists of connecting the solenoid valve and pressure regulator to the air tank. This step is similar to the fabrication of the air tank valves. The components are screwed together with PTFE tape and an adjustable wrench. The order of components is as follows: air tank, 90° elbow male/male connector, solenoid valve (being careful not to damage the solenoid), male/male connector, pressure regulator, and polyurethane air hose (see figure 29). The air hose is cut to roughly 5.5' (1.67 m) using a hacksaw, but it should be checked against the dimensions of the wheelchair and chosen path to the launching tube and be properly modified. A ¼" NPT hose repair kit is then used to reintroduce a male connector for attachment to a swivel ¼" male coupler.

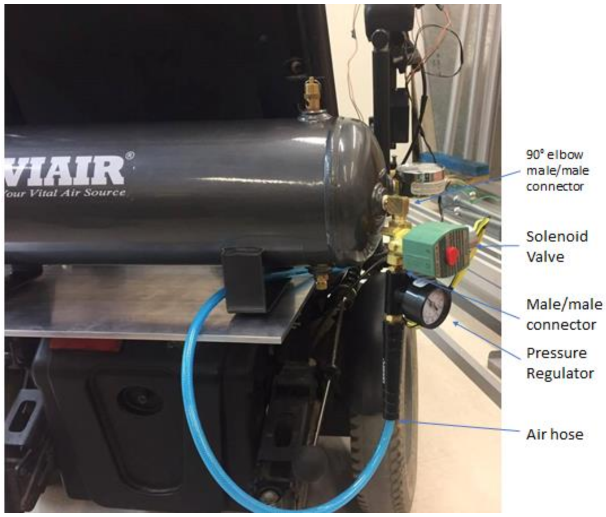


Figure 29: Diagram of air delivery line and components

The PVC pipe for the launching tube was cut to 10” and then cut at 45° at one end using a drop saw. This 45° cut is to keep the PVC opening level with the ground while at the placed at the angle of serving. The PVC end cap is drilled through at the center on a drill press using a ½” drill bit. The quick connect ¼” NPT female coupler is then fitted through this hole and capped on the other side by the bushing. An adjustable wrench tightens the two pieces together around the drilled hole, and the completed assembly is checked for any possible leakage areas. The PVC tube and end cap are then permanently connected with PVC primer and cement (rated for pressures of 180 PSI). The swivel male coupler can then be inserted and detached from the launching tube assembly with ease (figure 30).

Figure 30: Attached launching tube with air delivery line inserted at quick connect coupler

Solenoid Valve Circuitry

Materials:

The electronic circuit controlling the solenoid valve/compressed air output is initially constructed on a breadboard using basic circuit elements that are readily available on websites such as Sparkfun and Digikey. The two initial components of the circuit are the breadboard and Arduino circuit. The Arduino code used in the circuit can be seen in Appendix D. The wiring used in the circuit is #24 AWG Solid Tinned Copper from General Cable. Other notable components of the circuit are a Fairchild TIP41C Field Effect Transistor[18], a 1kΩ resistor, a mechanical switch and the ASCO 8262H020 24V/DC Solenoid Valve. The circuit schematic for this design can be seen in figure 31 below. After breadboard assembly and testing, the components are soldered into an Adafruit Through Hole PCB.

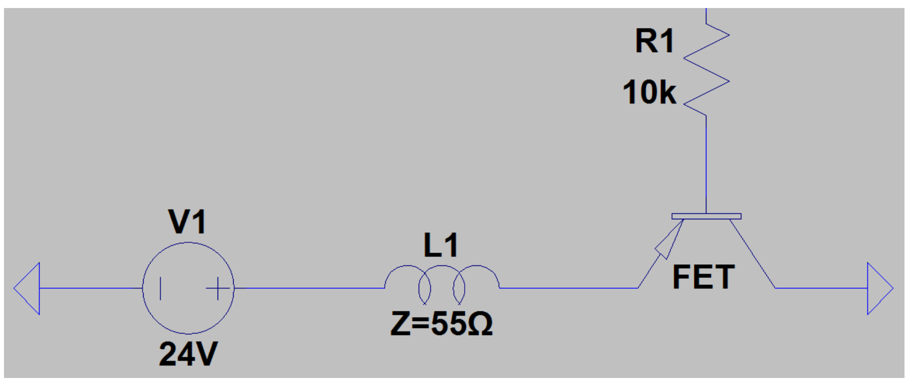


Figure 31: Solenoid Valve/Arduino Circuit schematic

Fabrication:

The first step of the circuit fabrication is to assemble the components onto the breadboard and connect it to the 24V power source for testing. In order to test the functionality of the circuit, the solenoid valve is replaced with an LED light to avoid wear and tear on the valve. Once testing is completed, the components are then removed and soldered into the PCB in the same configuration.

Storage Tank Holding Platform

Materials:

In order to attach the storage tank to the client's wheelchair, a flat plate is designed to insert and lock on a horizontal back bar. The only materials required for this design include a 9" by 17" by 0.25" (22.86 cm by 43.13 cm by 0.635 cm) aluminum flat plate for holding and two #385 x 5/16" x 2" x 3-¾" coarse zinc-plated U-bolts for attachment to the wheelchair. Aluminum is a strong yet lightweight metal that will reduce the moment produced on the wheelchair when attached. This will decrease the effect the attachment system has on the mobility of the client's wheelchair and will not cause the wheelchair to tip. The U-bolts are necessary to attach the plate securely to the round bar on the wheelchair.

Fabrication:

A SolidWorks model of the aluminum plate and U-bolt attachment (figure 32) is created to visualize placement of platform on the wheelchair. Measurements are made to roughly account for symmetrical U-bolt attachment, which are later modified to transition to the geometry of the wheelchair.

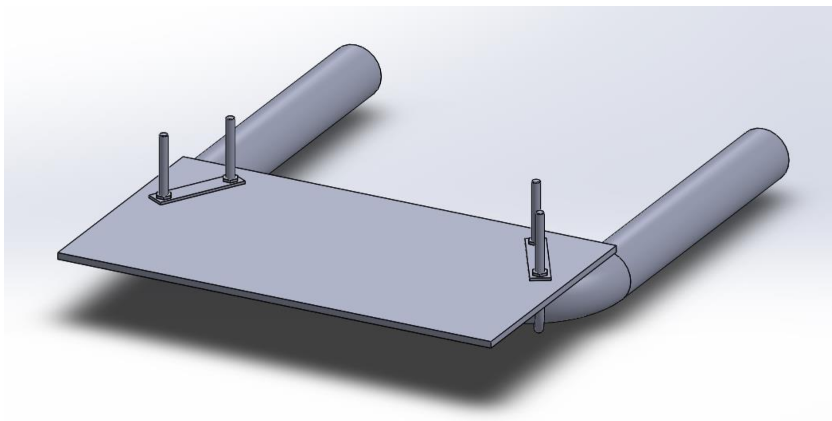


Figure 32: SolidWorks model of platform

The aluminum flat plate is already ordered to the specifications of the wheelchair placement site (see figure 33). Two 1" long by 0.5" deep notches are roughly sawed into the plate at 4.5" and 11.5" from the left edge using a bandsaw in order to account for protrusions from the wheelchair that can be used to stabilize the plate. The notches are then filed down to specification using a straight file and steel wool.

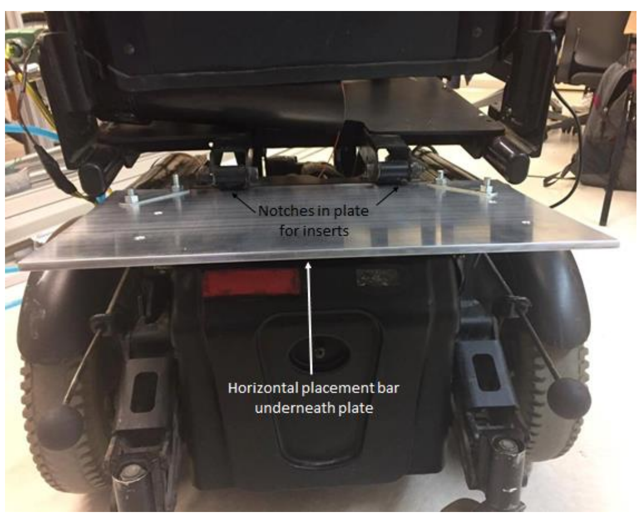


Figure 33: Profile of platform highlighting placement and notch positioning

Four 11/32” holes are drilled into the plate to account for the dimensions of the U-bolts and to optimize grip against the horizontal wheelchair bar. Likewise, four 5/16” holes are drilled to provide attachment of the air tank base, which comes with four ¼” threaded bolts and rubber grips for the attachment sites between the tank and plate. The tank holes were fabricated such that the draincock of the air tank hangs off the edge of the platform. These eight holes are then filed and countersunk to provide leniency in attachment placement. The placement of these holes can be viewed in figure 34. The plate is then polished using steel wool, and the U-bolts are cut to provide flush placement against the plate and pipe.

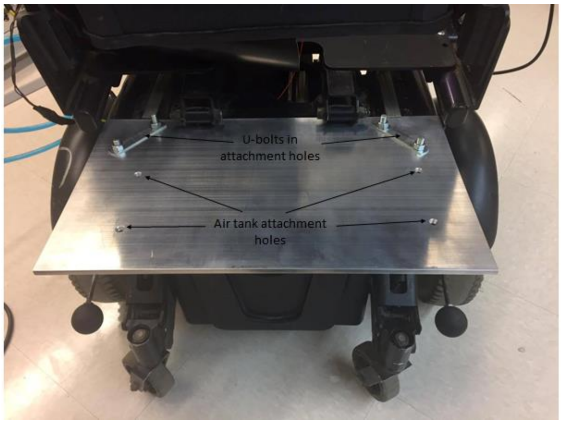


Figure 34: Profile of platform highlighting hole placement

<u>*Launching Tube Holder*</u>

Theory:

The two primary design criterion for the launch tube attachment system are to allow the client to freely adjust the angle at which the launch tube is positioned in order to determine an optimal launch angle, as well as be easily detachable from the wheelchair when not in use. To enable flexibility for the angle of launch, a support system that involved turnbuckles would be a good option because of the ease of adjusting the turnbuckles’ overall length. After consulting the College of Engineering shop staff, a triangulated arrangement of turnbuckles would be the best option for the launch tube attachment. Triangulation is common method that is used in the design of structural supports due to the very stable geometry of a triangle. Triangles do not collapse when subjected to a force because the angles are fixed based on the relative length of the side opposite the angle.[19]

Materials:

The triangulated turnbuckle attachment system consists of four main components: three 4-¾” x 5/32”. zinc-plated turnbuckles (enable adjustability of the angle of launch), a 5” extension spring (functions as a secondary support), six 3/16” diameter steel washers, and two steel c-channels cut to the dimension of the wheelchair and launch tube.

Fabrication:

The steel channels are cut to fit the dimensions of the wheelchair and the launch tube using a mill. The c-channel for the wheelchair attachment plate is milled to the dimensions of 7"x 2"x 0.75". The c-channel for the tube attachment plate is cut to the dimensions of 6.5"x2" x 0.55". After the steel c-channels are cut, the abrasive texture of the metal is grinded off using a belt sander in order to prepare the metal surface for welding.

After grinding is finished, four washers are welded to wheelchair attachment channel in the positions indicated in figure 35. Before welding the washer intended for the attachment of the spring, the washer is fed through the eyelet at one end of the spring.

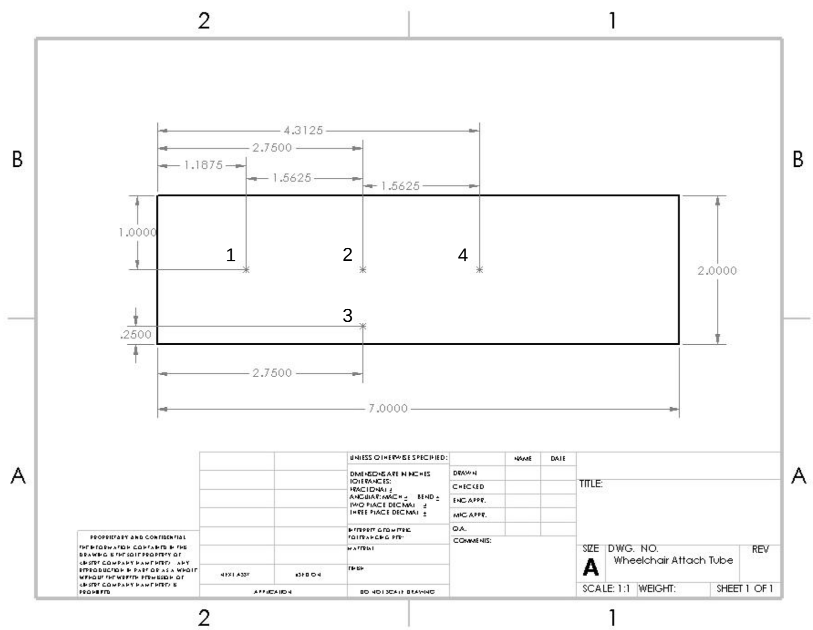


Figure 35: SolidWorks drawing of wheelchair attachment plate. Washers for turnbuckle attachment at positions 1,3, and 4. Washer for spring attachment at position 2.

For the tube attachment channel, two washers are welded to the positions indicated in figure 36. Prior to welding the washer intended for positioning the three turnbuckles, the washer is fed through the eyelets of all of the turnbuckles. Before welding the washer intended for spring placement, the washer is fed through the other eyelet of the spring. All washers are welded so that they are parallel to the shorter side of the c-channel.

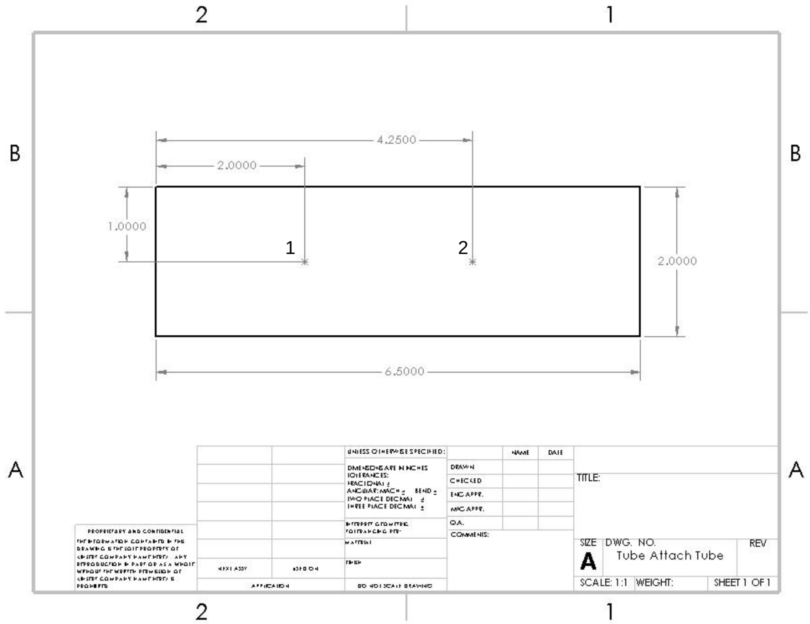


Figure 36: SolidWorks drawing of tube attachment plate. Washer for spring attachment at position 1.Washer for turnbuckle attachment at positions 2.

After welding is complete, the attachment plates with their appropriate hardware are attached to the wheelchair and launch tube respectively using hose clamps. The wheelchair attachment plate is fastened to the 2” bar on the wheelchair directly before the left rear wheel. The tube attachment plate is fastened to the side of the tube that is across from the tube’s outer lip (see figure 37). Finally, the hooked ends of the turnbuckles are attached to their respective washers to complete the attachment.

Figure 37: Launch tube attachment set-up

<u>Grip Support</u>

Materials:

The grip clamps are fabricated from a 6”x12”x1’’ piece of HDPE. This material has a large strength to density ratio and does not significantly change properties from temperature (up to 259 F) or moisture.[20] Four 10/24 screws, washers, and nuts are used for holding the paired pieces together. 30’’ of ½’’ woven elastic is used for the vertical bands around the racket grip. Woven elastic is made of polyester which is mildew resistant and allows airflow from the skin pores.[21] It also does not narrow as it stretches, which decreases the risk to circulation when pressed against the skin.

Fabrication:

The HDPE is first cut into 80 mm x 100mm blocks using a saw. These pieces are then taken to the mill and faced off at the proper dimensions of 85.4mm x 30mm. The mill CNC program is used to mill a half circle with a radius of 30 mm on one side of the piece and the dimensions of the client’s racket on the other side with a 0.25’’ corner radius (see figure 38 and 39).

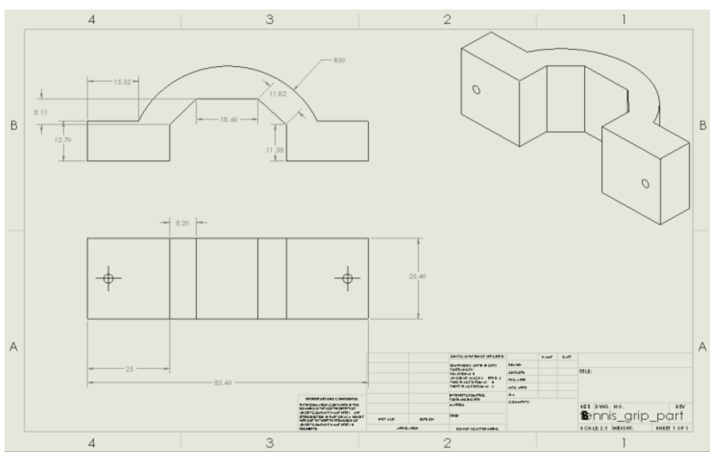


Figure 38: SolidWorks drawing depicts the dimensions of the half-clamps that were fabricated.

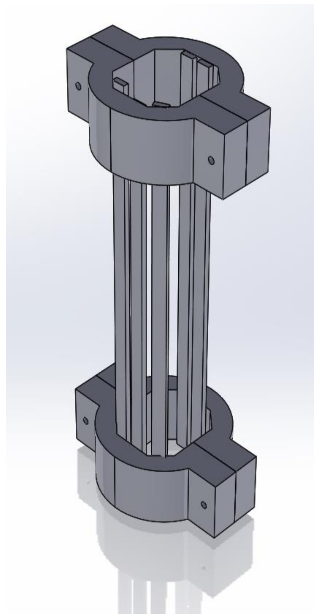


Figure 39: The SolidWorks model of the racket grip design.

Two 3/16'' holes are drilled on each side of the half-clamp 25mm from the inner edge. Four of these half-clamps are made and then attached in pairs at the top and bottom of the racket 6.2'' apart. The woven elastic is cut into 5.5'' strips and then knotted at each side. The knots are placed on the outside of the clamps so that the elastic is stretched flat against the racket handle (see figures 40 and 41).

Figures 40 and 41: The racket grip prototype

Testing & Results

Serving System

Testing Protocol:

Safety goggles and an open area should be used for testing purposes. The air tank should be filled with an air compressor through its fill valve to a max of 170 PSI. The tank should be checked for any air leaks. If leaks are found, testing should be discontinued and the leak resolved. The launching circuit should be connected to a 24 V power source. Testing should determine if the serving system accomplishes the primary objective of consistently launching the tennis ball in the air for serving. A tennis ball should be inserted into the launching tube, and the tube pointed in a neutral direction (i.e. not near anyone or anything). The button should be pressed and the movement of the tennis ball should be recorded.

Additionally, the tank pressure and max output pressure should be recorded for a number of shots (until outlet pressure reaches 20 PSI) to determine a possible relationship between the two to determine the consistency of the serving system over repeated use.

Results:

Using an available air compressor, the air tank was only able to be filled to a max of 90 PSI. No leaks were found to exist in the design. Upon testing, it was found that the tennis ball would not be significantly lifted (i.e. it stayed in place) upon release of air from the tank. Air flow was found to divert around the ball through the gaps between the tennis ball and the tube wall. No further significant testing could be performed on ball movement as the tennis ball does not move.

In regards to testing outlet and tank pressure, a linear regression model was performed on the data collected ($n = 46$). A highly accurate linear relationship between tank pressure and outlet pressure was found ($p < 2.2e-16$), where Outlet PSI = 0.4994(Tank PSI) + 10.94571 (see figure 42).

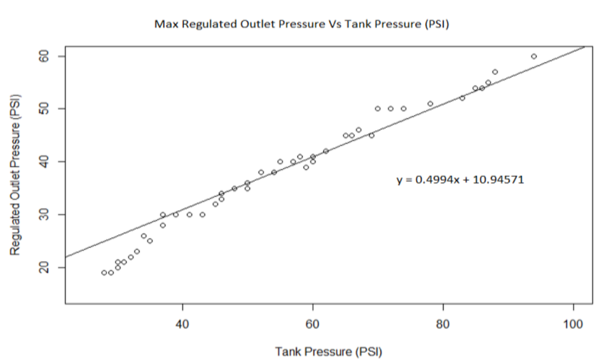


Figure 42: Linear regression model fitted to trial data from outlet and tank pressures

Solenoid Valve Circuitry

Testing Protocol:

It is important to test the circuit design before soldering into the PCB in order to allow for changes to be made if one design did not work well. Once in the PCB, it is more difficult to remove a component that does not work, as they would have to be desoldered. In the initial phases of testing, the solenoid valve is replaced with an LED in order to reduce wear and tear on the valve. In order to test whether the solenoid valve would be activated, depress the push button and observe the LED light. If the LED turns on, this is indicative that the solenoid valve would be activated if used in the circuit.

Results:

Once the design was soldered into the PCB and connected to the 24V power source, we were not able to consistently activate the LED by compressing the push button. In some instances, the LED turned on when the button was pressed and some times it did not. Along with this, the LED would turn on and off on its own as well as when the push button was shaken. From this, we concluded the current design/fabrication was not suitable for use in the final product. As a result, we made the decision to replace the Arduino/FET circuit with a simple mechanical switch that connects the 24V power source directly to the Arduino. This temporary mechanical switch circuit works just as well, but may have a factor of safety slightly lower than that of the Arduino/FET circuit. The reason for this is that if a short circuit were to occur in the temporary circuit, it would occur at the button that the user is in contact with, rather than the FET, which the client does not touch.

Storage Tank Holding Platform

Testing Protocol:

The tank platform should be firmly attached to the wheelchair. The air tank is roughly 15.3 lbs (68.1 N) unfilled, and testing should determine the maximum amount of weight that can be placed on the plate until deformation to account for no deformation upon tank placement. Known weight amounts should be added to the aluminum plate until significant deformation is noticed.

Results:

Application of 75 lbs (333.6 N) of free weights were held by the plate without incident (figure 43).

Figure 43: Testing trial of 75 lbs on platform. No deformation was noted.

Upon consultation with the COE Student Shop to find more weight for testing, it was suggested to have a person stand on the plate to determine if it is able to hold the person's applied weight. Two test subjects of 145 lbs (645 N) and 166 lbs (738.4 N) were able to be fully held by the plate without deformation. A test subject weighing 208 lbs (925.2 N) was able to produce significant deformation of the plate upon application, and testing was discontinued before any permanent deformation could be placed on the platform by the test subject.

Launching Tube Holder

Testing Protocol:

The probability of placement of the ball into the launch tube was conducted using an exact binomial test. During this test, the test subject attempts to drop the ball into the launch tube over the course of 25 trials. A trial is considered a success if the ball landed in the launching tube. The baseline threshold is a 50% chance of completing the task.

Results:

The test subject was able to place the ball into the launch tube 11 out of the 25 trials, resulting in a success rate of 44% (figure 44). The calculated p-value for a 50% chance of properly placing the tennis ball in the launching tube was p = 0.7878. The results of testing ultimately indicate that the client does not have even a 50% of placing the tennis ball into the launch tube currently.

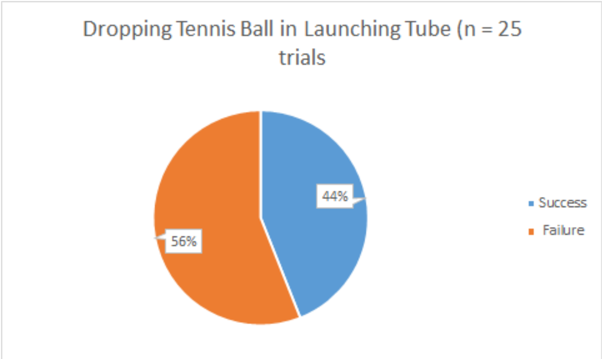


Figure 44: Depicts the results of the exact binomial test.

<u>Grip Support</u>

Testing Protocol:

The tension of the racket grip elastic bands is tested using hanging masses and calipers. Three different masses are hung from each elastic band and the displacement with each mass was measured. The grip is then tested by individuals who, after playing with the grip for 2-5 minutes are asked to rate it in 4 categories: functionality, ease of use, comfort, and aesthetics.

Results:

The weight of the entire product was measured to be 0.3 lbs. After plotting the force-displacement data of each of the bands, the slope of the best fit line was found. These values, indicating the stiffness of the elastic, were averaged to find a tension of 62.1N/m with a standard deviation of 8.01 N/m (figure 45).

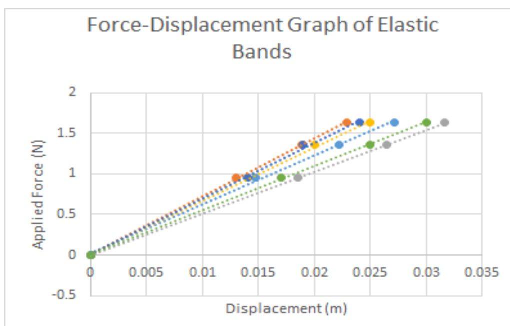


Figure 45: The linear force-displacement models of the 6 elastic bands on the racket grip. The slopes of these lines indicate the tension of the elastic.

Ten individuals scored our design in four categories. The average scores of the survey conducted indicated the goal of designing a racket grip that improved function of maintaining a tight grip was achieved but the comfort was lacking (see table 3).

Category	**Average Score**
Functionality	5/5
Ease of Use	4/5
Aesthetics	4/5
Comfort	2.5/5

Table 3: Results of 10 individuals asked to rank the racket grip in the categories listed after playing with the racket.

Discussion

Serving System

Initial testing of the serving system proves that it is currently ineffective as a viable device, as it cannot even lift the tennis ball out of the launching tube. This difficulty is most likely attributed to the difference in the diameters of the tennis ball and launching tube. Since the tennis ball diameter does not fit snugly against the wall of the launching tube, air will follow the path of least resistance and flow around the ball as an immersed body rather than input work to lift the ball in the air. This can be corrected by modifying the geometry of the launching tube, but may introduce significant frictional effects on the tennis ball and greater difficulty in loading the mechanism. Additionally, more rigorous modeling of the work path of the ball could be introduced on a fluid dynamics basis to better account for these added effects.

The current iteration of testing also only utilizes pressures up to 90 PSI, but the storage tank can handle pressures much more than this. A better air compressor system could be utilized to better fill the storage tank and test for viability of its storage ability.

Finally, testing shows that the regulated outlet pressure is not constant but rather dependent upon the pressure within the storage tank at the time of the serve. This may affect consistency of serves, especially during use over a long period of time. One proposed method is to institute a secondary tank to better regulate pressure within the main storage tank for launching.

Solenoid Valve Circuitry

As stated before, the Arduino/FET circuit was replaced with a temporary mechanical switch/power source circuit in order to be able to provide the client with a functioning final product. Experimentation with the two different designs showed that the mechanical switch circuit in the PCB had a nearly 100% solenoid activation rate when the switch was compressed. This proved to be enough to replace the original Arduino/FET on a temporary basis.

Despite working better than the Arduino/FET circuit, the mechanical switch circuit is meant to be a temporary solution to this issue for two reasons. The first reason is that, while presenting little risk to the client overall, the mechanical switch has a slightly lower factor of safety than the Arduino/FET circuit. While this FOS is not quantifiable, it can be assumed based on the idea that if a 24V short circuit occurred in the mechanical switch while the user was pressing it, they may receive a shock. In the Arduino/FET circuit, a 24V short circuit would occur at the FET, which is connected to the Arduino. The push button is then connected to the Arduino, meaning that the point of contact of the client is two degrees removed from the 24V source.

The second reason for the temporary status of the mechanical switch is that the solenoid valve is open and releases air for as long as the button is pressed. This creates the potential for excess air release and an overall waste of the limited air tank capacity. A solution to this issue is working a timed release into the Arduino code. This potential code has been written and can be found in Appendix E. In summary, if the push button is pressed for less than five seconds, the solenoid valve will be activated and release compressed air for no more than one full second.

With more time, the Arduino/FET circuit most likely would have been completed. After evaluation, the team deduced that the problem with the circuit soldered into the PCB may have been the push button used, as it proved to be less reliable than the doorbell button purchased for the temporary circuit.

Storage Tank Holding Platform

According to testing, the storage tank holding platform is well over-designed for its designated function. While only intended to hold a little over 15.3 lbs (68.1 N), the platform sufficiently holds eight times this amount. The client is advised to use the platform for only its intended purpose, but clients will normally flaunt these rules in favor of accomplishing their own tasks. Thus, if the platform were to be used for a different purpose, there is a large margin of error before serious deformation or injury can occur.

Launching Tube Holder

The results of the exact binomial test indicate that the client has less than a 50% chance of effectively placing the tennis ball into the launch tube. Due to this low likelihood of success, it has become clear that the design team needs to make some modifications to the launch tube before the client can begin using it during play. One proposed idea to increase the likelihood of successful ball placement would be to attach a large funnel to the top, outer rim of the launch tube for better clearance of the ball into the opening.

Additionally, it was noted that the air hose hits the ground when attached to the launching tube on the wheelchair. A redesign of the tube attachment system should account for this error by raising the launching tube and making the entire system more compact.

Grip Support

The testing of the grip support showed that the design is both functional and easy to use. In response to receiving a 2.5/5 for comfort the edges of the plastic clamps were rounded using a file. There was not time to re-test the design after this change was made, but since the main complaint by users was that the corners were digging into their wrists, this change should drastically improve the comfort of the design. The high score in functionality indicated to the team that the 62 N/m tension the elastic was initially tied at was appropriate for the function of the design. The tension is still easily adjustable, however, for personal comfort.

Another suggestion from the survey was that the weight of the clamps could be reduced. The mass of the objects is currently affecting the swing of the user. This change would require making the plastic clamps thinner, which may weaken their structural integrity. A different material could also be chosen, which may be able to reduce the weight.

Conclusion

The client, Dan Dorszynski, needed an enhanced grip device and an automated serving system in order to better perform in the quadriplegic wheelchair tennis league. This design team proposed designs to provide for and improve his current limited ability to serve the tennis ball and keep a firm grip on the tennis racket during play. After analyzing the strengths and weaknesses of each design via a design matrix, a pneumatic launcher design was selected for the serving system, and an elastic fiber design was selected for the grip support. The pneumatic launcher utilizes a 2.5 gallon compressed air tank, a solenoid valve controlled by appropriate circuitry components, and a launching tube to eject the tennis ball to the preferred height and location for serving. The grip support is an attachment to the client's tennis racket composed of vertical elastic fibers, which the client can slide his hand under to provide a more secure grip on the racket.

During testing of the pneumatic serving system, it was discovered that the current design doesn't adequately launch the ball. While air successfully flowed from the tank source through the line and into the launching cylinder as expected, the air diverted around the tennis ball upon entering the launching cylinder. A likely explanation for this problem is that the tennis ball does not have a snug enough fit against the inner wall of the launching cylinder, resulting in an ineffective seal.

One other concern with the launching cylinder is that it is too difficult to consistently load the ball into it due to the fact that the user must drop the ball into the cylinder. Testing revealed that the ball often deflects off the mouth of the launching cylinder instead of going into it. This loading inconsistency is caused by the fact that human error is involved in the loading process.

Excluding the aforementioned issues with the launching cylinder, the other components of the pneumatic serving system withstood testing well. The compressed air tank maintained pressure, the tank's holding platform did not deform, even when subjected to relatively large forces, and the solenoid valve was successfully controlled remotely using a button.

In regard to the grip support, testing and client feedback was mostly positive. During the testing phase, the only complaints that arose revolved around the comfort of the grip support. It was reported that the HDPE blocks were somewhat cumbersome as they interfered with normal wrist placement and added a small, but noticeable, amount of weight to the racket. The added weight slightly threw off the user's timing during play. In addition, there were some sharp edges that were irritating users; however, the actual functionality of the grip support was not called into question.

Acting on the results of the testing phase, the sharp edges were rounded out, and the final grip support design was given to the client for feedback. The client was pleased with the effectiveness of the grip support stating that he felt the grip made a significant, beneficial impact.

With respect to comfort, the client found the grip support to be quite comfortable on the whole. Unlike other users who claimed to be inhibited by the HDPE blocks, the client claimed that he was able to create added leverage to lift the tennis racket by pushing down on the HDPE block.

Looking toward the future, there are a number of improvements that could be made to the serving system to make it a more complete product. One of the major changes that needs to be made is to the launching cylinder. As mentioned previously, air is diverting around the ball as it enters the launching cylinder. There are a multitude of potential fixes for this issue, but one solution would be to create a hollowed out cylindrical mold with an outer diameter of approximately 3” and an inner diameter of approximately 2.6”. This mold could then be inserted inside of the launching cylinder to create a snug fit between the tennis ball and the walls of the mold. This snug fit should solve the problem of air going around the ball since there won’t be enough room for the air between the mold and the ball.

Another change that should be made to the serving system concerns the circuitry aspect of the launcher. The solenoid and launch button are currently connected in such a fashion that when the button is pushed to release air, air will be released for as long as the button is held down. Naturally, this leads to an inconsistent amount of air being released each time the button is pushed. Not only does this inconsistency cause too much variance in the height and location of the serve, it also wastes a limited supply of compressed air. The solution to this problem involves reconfiguring the circuitry with the help of an Arduino so that a predetermined amount of air is consistently released every time the launch button is pressed (see Appendix D for outline of potential code).

Outside of these two larger changes, there are also a few more minor modifications that should be implemented in the future. The first of these is to construct a cover to protect the solenoid valve, air pressure gauge, and circuitry protruding from the air tank. While a gentle hit from a tennis ball shouldn’t damage any of the serving system’s components, a simple plastic case would better protect them from the environment as well as any accidental collisions.

The second minor change that needs to be made involves the launching cylinder. Since the loading process is currently far too inconsistent, some sort of assistive device is needed to guide the ball into the launching cylinder dependably. While there are a myriad of devices that could accomplish this task, one that immediately comes to mind is using a second cylinder, a loading cylinder, which the client could place the ball into. The loading cylinder would be within arm’s reach of the client, so that there would be no need to drop the ball. Once placed in the loading cylinder, the ball would roll down and into the launching cylinder by having the end of the loading cylinder lead directly into the mouth of the launching cylinder.

The final modification that should be made to the current design is to use smaller turnbuckles. The turnbuckles that are being used right now are slightly too large and don’t allow for proper triangulation of the launching cylinder and cause the launching tube to be positioned lower than initially envisioned. This translates to too much freedom of motion for the launching cylinder and causes the bottom of the air hose to graze the ground. Using smaller turnbuckles would allow for proper triangulation to take place, locking the cylinder in place until adjusted by hand, and for a less hindered design setup.

While all of the above changes assume that the current design is carried forward into the future, there is also one other route that could have been taken. This route uses a linear solenoid rather than compressed air. For this design, current would be run through a linear solenoid, causing the linear solenoid to push out a solid metal cylinder very quickly. A tennis ball could conceivably be placed on top of where the cylinder is set to push out from, so that when a button is pushed, current runs through the solenoid and launches the ball. The trajectory of the ball could be altered by adjusting how quickly the solenoid's cylinder pushes out or by adjusting how far the cylinder pushes out.

Switching over to the grip support, there are not any drastic changes that need to be made to the current elastic fiber attachment design to produce a complete product. Instead, optimization is the overarching goal for future work on the grip support. For example, utilizing less material for the HDPE blocks would reduce the weight of the design. This would be a straightforward fix to the issue of some user's timing being thrown off when swinging the racket. Another way to improve the current design would be to create grooves on the inside of the HDPE blocks. Not only would this reduce the amount of material used, but it would also create a space for the knots in the elastic bands to be held in place, keeping them out of sight and giving a more appealing aesthetic to the grip support.

Another optimization idea that would be more involved would be to replace the HDPE blocks with thin, adjustable metal bands. The main improvement is that the total weight of the grip support would dramatically decrease if metal bands were used since less material would be required. One way to accomplish this would be to use a locking system akin to that of a wristband, as depicted in figure 47 below. The elastic bands could then be stretched out underneath the metal bands and secured by tightening the metal bands' locking system.

Figure 47: Adjustable Stainless Steel Wristband[22]

Bearing all the preceding information in mind, this design team's goal of manufacturing an automated serving system and an enhanced grip device in order to increase the client's level of play were both met to a certain extent. Despite the fact that the serving system is not a fully functional, match ready device as initially envisioned, much of the groundwork has been laid out for that to be the case in the near future. In the case of the grip support, the elastic fiber attachment is completely match ready and has already received the client's approval, which was this design's team goal for the semester. Regardless of how the final prototypes turned out for each of the designs, both the serving system and the grip support offered valuable insight into the engineering design process and show great promise for improvement in the future.

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Appendix A: Product Design Specifications

Function: The design project client, Dan Dorszynski, has Becker Muscular Dystrophy (BMD), which is a slowly progressive muscular disorder caused by a mutation in the dystrophin gene. The client plays in a quadriplegic tennis league, in which the player must have a permanent disability that results in a substantial loss of function in both lower extremities and one or both upper extremities. The players are allowed assistive equipment, along with the wheelchair, to facilitate play of the game. The type of equipment varies per individual and their respective conditions, but the client requires an optimized tennis racket grip, tennis ball serving system and an arm support mechanism to aid with raising the racket for a high shot. This equipment must be attached to the client's wheelchair in order to prevent interfering with the game play. The client has requested that we design these wheelchair attachments in order to assist his game play and eventually, that of other individuals in the quadriplegic tennis league.

Client Requirements: *The client's specifications are as follows*
1: Tennis Racket Grip
2: Tennis Ball Serving system

Physical and Operational Characteristics:

1. *Performance Requirements:*
    1. The client is looking for an optimized tennis racket grip that helps them maintain a firm grip on the racket without sacrificing wrist mobility or endurance. This grip must be able to withstand typical sports conditions, such as sweat, strain and, heat without limiting the client's wrist movement, as that is the source of power behind a shot.
    2. As a result of their condition, it is difficult for the client to toss a tennis ball in the air for a serve. The tennis ball serving system must be mounted to the wheelchair and able to launch the ball to an optimal height and location for the client to hit. This optimal height is around 42 inches and location is about 36 inches from the wheelchair.

2. *Safety:*
    1. The grip device should not injure or irritate the client during play. This means that the grip should not cut into his wrist or rub his hand raw after continuous movement. The grip should also not cause further limitation to the client's abilities.
    2. The serving system should not cause injury to the client's hand, arm, or other parts of the body during the serve. If mounted to the wheelchair, the serving system should not cause the wheelchair to tip. If electrically powered, the system

should be noted as such and preventions should be made to prevent accidental electrocution. Any mechanism to propel the tennis ball should be carefully evaluated to limit its potential for injury to the client during the serve or gameplay.

3. *Accuracy and Reliability:*
    1. The tennis racket grip should be able to withstand the forces received during a normal session of tennis without altering in any way. A tennis match can last up to 3 hours and the weather may vary from cold and rainy to extreme heat. The grip should not deform for any reason or cause discomfort to the client.
    2. The service device needs to be able to maintain a constant height and direction throughout duration of play. The height of the device needs be at knee level for the client, which is 42 inches off the ground. It also needs to be 36 inches away from the wheelchair so the client has room to swing. These distances should be consistent every time the ball is served. The serving device should also be reliable in weather conditions, such as wind, that may alter the path of the ball.

4. *Life in Service:*

    All: Both components of the design must be able to function at optimum performance for a minimum of three hours of continuous use. However, the design should operate for durations longer than this time requirement to meet the client's practice needs. Ideally, all three elements of the design should function with minimal maintenance throughout the client's time playing quadriplegic tennis.

5. *Shelf Life:*

    All: Each of the adaptive devices will be stored in the client's van or in his house. If left in the client's van for extended periods of time, the devices could be subjected to extremely hot temperatures in the summer (as high as 160°F due to heat being trapped inside). In the winter, temperatures could drop to as low as -20° to 30°F, so the devices must be able to withstand both the heat and cold. They could also be stored in very humid conditions during the summer, so they should be able to withstand that as well. Additionally, the devices may move around in the back of the client's van, so they should be able to withstand minor collisions with each other as well as the interior of his van.
    1) The grip should be made durable, so that it has a functional shelf life of 5-10 years or more.
    2) The serving system should be made durable, so that it has a functional shelf life of 5-10 years or more.

6. *Operating Environment:*

1. The tennis racket grip will be subject to the heat, sweat and pressure of the client's hand while playing. The average human body temperature is 97.7 to 99.5 degrees Fahrenheit. The average male hand grip strength is 105-113 pounds. Human sweat has acidic characteristics, with a pH range of 4.5 to 7, and is composed of mostly water and salt. The grip must not be significantly affected by these environmental factors.
2. The tennis ball serving system will be attached to the wheelchair, and therefore, subject to the same operating conditions, such as exterior heat. The launch system should not be affected by normal outdoors temperature, ranging from 100 degrees Fahrenheit in the summer to the minimum indoors temperature of 55 degrees mandated by the International Tennis Federation. The launch system should be water resistant to a degree, but not necessarily waterproof since the client would not be playing outdoors in the rain.

7. *Ergonomics:*
    1. The grip should accommodate the natural position of the client's hand during serving and play. The grip should not limit wrist range of motion or inhibit regular tennis serving motions. The grip should provide adequate support to the client's hand to prevent slipping during the tennis serving motion.
    2. The serving system should be easily prepared with minimal input from the client. The system should be automated to serve the ball to a height of 42 inches from the ground and a distance of 36 inches from the wheelchair without a great extent of force on the client's part. The height of the serve would be ideally adjustable within a range of around 6 inches to account for fluctuations in the client's serving motion.

8. *Size:*
    1. The grip needs to be able to fit on the handle of a racket so that the overall grip size is between 4 ¼ to 4 ⅝ inches. The client has played with a variety of grip sizes and does not have a preference of one over the other.
    2. The serving device should be around 10cm in diameter. It will need to be able to fit a tennis ball (67mm), but it should be a compact as possible so as not to get in the way while playing. The device may also have a component to activate the serve, which would need to be the appropriate size for the client's foot or right hand to reach it comfortably.

9. *Weight:*
    1. The racket grip should be relatively lightweight so that it does not restrict the client's range of motion or serving movement.

2. Although the allowable weight of the serving system is more flexible than the maximum weight for the other design components, it should not impede the client's ability to move effectively. Furthermore, it is critical that the serving system does not cause the wheelchair to become unbalanced. In order to account for this, a counterweight will most likely be utilized as well.

10. *Materials:*
    1. The tennis grip should be made of a lightweight material that will not infringe upon the client's ability to move his wrist or fingers. It should also have some resistance to heat and cold such that it does not burn the client's hand in hot temperatures or freeze it in cooler temperatures. Possible materials for the grip include rubber or silicon.
    2. The serving system will be made of a lightweight or medium weight material that can withstand a moderate amount of internal pressure (necessary to launch the ball). It too should have some kind of resistance to transmitting heat so that the client does not accidentally burn themselves by touching it on a hot day. Possible materials for the serving system include PVC pipe, an air compressor, or a spring.

11. *Aesthetics, Appearance, and Finish:*

    All: A rule the USTA has in the quadriplegic tennis league limits the number of exposed logos a player may have on their person/wheelchair. As a result of this, all devices shall be devoid of logos, so as not to infringe on this rule.
    1. The grip should have a smooth finish, so that it does not irritate or bother the client's wrist/hand in any way. The color of the grip will most likely be black to match the grip color on the client's racket. The shape of the grip will be molded to fit with the shape of the client's hand/fingers.
    2. The service serving system will have a fairly smooth exterior texture and will be cylindrical in shape. The color of the serving system could be a variety of hues, but black seems most likely as it would blend in with the wheelchair.

12. *Product Characteristics:*
    1. **Quantity:**
        i. As of now, only one of each device tailored for the client is necessary, with a possibility of expanding the use of this device to multiple users. A future application would be expanding the range of device measurements to accommodate a larger audience and modifying the designs for faster production to reach this larger audience.
    2. **Target Product Cost:**

i. Total target product cost is $500, but this amount is flexible both in general and as distributed between the two.
    1. The upper target cost for the grip is $100-200.
    2. The upper target cost for the serving system is $200-300.

13. *Miscellaneous:*
    1. **Standard and Specification:** The designed devices must meet USTA standards for play. The client specified that some devices may not have been thought of yet so they may make a new regulation if the new equipment is brand new to the adaptive community.
    2. **Patient-Related Concerns:** The client is most concerned with the devices aiding his tennis abilities. During hot weather, he gets very overheated so none of the devices can add to his body temperature. They should not constrict sweat in any way. They are also concerned about their movements being limited by the devices. The arm support cannot take away any degree of freedom of their movement and the grip cannot take away his wrist movement.
    3. **Competition:**
        i. The most common method of grip in quadriplegic tennis right now is using medical tape to secure the player's hand to the racket. Using tape limits the movement of the wrist which essential to the client's style of play. It also makes the hand sticky and becomes uncomfortable in high temperatures. There are also other less common methods including rubber bands.
        ii. Currently, the most common method for adaptive serving helps to have an assistant toss the ball for the player. This method requires practice with the assistant and can be inconsistent. There are also serving machines that are used for practice but these tend to send the ball in an arc from its position at the net rather than just up in the air.
    4. **Customer:** Dan Dorszynski, Private Client

Appendix B: Budget Report and Materials Expenses Spreadsheet

Accounting									
Description	**Supplier**	**Part/Model #**	**Link to Part**	**Quantity**	**Date**	**Price**	**Tax/Shipping**	**Total**	
Solenoid Valve	Amazon	8262H020-24	Amazon	1	10/31/2016	$ 46.27	$ 3.25	$ 49.52	
Compressed Air Tank	Amazon	91028	Amazon	1	10/31/2016	$ 72.00	$ 3.25	$ 75.25	
Elastic	Amazon	1/2" x 1 yard	Amazon	2	11/7/2016	$ 10.34	$ 0.60	$ 10.94	
HDPE Sheet	Amazon	D4976-245	Amazon	1	11/7/2016	$ 22.35	$ 0.59	$ 22.94	
Push Button	Amazon	52mm Yellow	Amazon	1	11/7/2016	$ 7.82	$ 0.60	$ 8.42	
Arduino	Digikey	1050-1024-ND	Digikey	1	11/7/2016	$ 21.49	$ 6.75	$ 28.24	
Circuit Board	Digikey	1528-1195-ND	Digikey	1	11/7/2016	$ 4.50	$ 6.74	$ 11.24	
Box for Circuitry	Mouser	546-1591BS-BK	Mouser	1	11/7/2016	$ 3.63	$ 4.99	$ 8.62	
Polyurethane Hose	Home Depot	12-25E-HOM	Home Depot	1	11/8/2016	$ 19.98	$ 0.43	$ 20.41	
Air Regulator w/ Gauge	Home Depot	HDA70900AV	Home Depot	1	11/8/2016	$ 21.89	$ 0.43	$ 22.32	
Safety Valve	Home Depot	21707HOM	Home Depot	1	11/8/2016	$ 6.98	$ 0.43	$ 7.41	
Male safety coupler	Home Depot	HA2002	Home Depot	1	11/8/2016	$ 4.98	$ 0.43	$ 5.41	
Swivel Plug	Home Depot	12233HOM	Home Depot	1	11/8/2016	$ 2.47	$ 0.43	$ 2.90	
Tank Drain	Home Depot	21559HOM	Home Depot	1	11/8/2016	$ 3.39	$ 0.43	$ 3.82	
Hose Repair Kit	Home Depot	HDA40700AV	Home Depot	2	11/8/2016	$ 7.78	$ 0.43	$ 8.21	
Air Gauge	Home Depot	24811HOM	Home Depot	1	11/8/2016	$ 8.49	$ 0.43	$ 8.92	
FNPT Reducer	Home Depot	21535HOM	Home Depot	1	11/8/2016	$ 2.29	$ 0.43	$ 2.72	
Steel Nipple	Home Depot	561-040HN	Home Depot	1	11/8/2016	$ 0.92	$ 0.43	$ 1.35	
Iron Plug	Home Depot	511-801HN	Home Depot	1	11/8/2016	$ 0.71	$ 0.42	$ 1.13	
Air Compressor Kit	Home Depot	41225HOM	Home Depot	1	11/8/2016	$ 12.98	$ 0.42	$ 13.40	
PVC Cap Slip	Home Depot	C4817HD3	Home Depot	1	11/8/2016	$ 4.28	$ 0.42	$ 4.70	
Aluminum Plate	Midwest Steel Supply	6061ASHT250	Midwest Steel	1	11/15/2016	$ 16.03	$ 10.90	$ 26.93	
PVC Pipe	True Value	PVC073000600RS	True Value	1	11/13/2016	$ 9.69	$ 0.53	$ 10.22	
Enclosure Box	Amazon	1591ESBK-HAMMOND	Amazon	1	11/20/2016	$ 7.81	$ -	$ 7.81	
Box for Circuitry	Mouser	546-1591BS-BK	Mouser	1	11/7/2016	$ (3.63)	$ -	$ (3.63)	RETURN
Extension Spring	Amazon	E05000555000S	Amazon	1	11/28/2016	$ 1.26	$ 0.07	$ 1.33	
Tank Fill Valve	Blain's Farm and Fleet	809034	Farm and Fleet	1	11/28/2016	$ 4.99	$ 0.27	$ 5.26	
Turnbuckles	Home Depot	807016	Home Depot	2	11/27/2016	$ 3.70	$ 0.20	$ 3.90	
U Bolts	Home Depot	806886	Home Depot	2	11/27/2016	$ 3.00	$ 0.17	$ 3.17	
90 degree elbow	Amazon	6130	Amazon	1	12/1/2016	$ 5.91	$ 0.33	$ 6.24	
							TOTAL	$ 379.10	

Appendix C: *EES Code for Serving System*

```
"Launching System EES"

$UnitSystem SI K Pa J mass deg

"Constant"

F$ = 'air'
m_ball = 58.5 [g] * convert(g,kg)
H_0 = 42 [cm] * convert(cm,m)
D_0 = 36 [cm] * convert(cm,m)
theta_launch = arctan(D_0/H_0)
tube_L = 10[in] * convert(in,m)
tube_D = 3 [in] * convert(in,m)
ball_D = 2.5 [in] * convert(in,m)
P_atm = Po#
T_atm = converttemp(F,K,75 [F])

1/2 * m_ball * V_0^2 = m_ball * g# * (H_0-tube_L*sin(theta_launch))

A_tube = pi * (ball_D/2)^2
F_ball = (P_inlet - P_atm)*A_tube - m_ball * g# * cos(theta_launch)
F_ball = m_ball*a_ball

F_ball * tube_L = 1/2 * m_ball * V_0^2 + m_ball * g# * tube_L * sin(theta_launch)
```

Unit Settings: SI K Pa J mass deg

a_{ball} = 16.22 [m/s^2]	A_{tube} = 0.003167 [m^2]
$ball_D$ = 0.0635 [m]	D_0 = 0.36 [m]
F$ = 'Air'	F_{ball} = 0.9487 [N]
H_0 = 0.42 [m]	m_{ball} = 0.0585 [kg]
P_{atm} = 101325 [Pa]	P_{inlet} = 101762 [Pa] {14.76 [PSI]}
θ_{launch} = 40.6 [deg]	$tube_D$ = 0.0762 [m]
$tube_L$ = 0.254 [m]	T_{atm} = 297 [K]
V_0 = 2.235 [m/s]	

No unit problems were detected.

Calculation time = 125 ms

Appendix D: Current Circuit Code

```
//This code is currently used in the Arduino, allow for the solenoid valve to be activated as long
//as the push button is pressed
// Constants won't change. They're used here to
// set pin numbers:
const int buttonPin = 2;     // the number of the pushbutton pin
const int solPin =  13;      // the number of the Solenoid Valve
// variables will change:
int buttonState = 0;         // variable for reading the pushbutton status
void setup() {
 // initialize the Solenoid pin as an output:
 pinMode(solPin, OUTPUT);
 // initialize the pushbutton pin as an input:
 pinMode(buttonPin, INPUT);
}
void loop() {
 // read the state of the pushbutton value:
 buttonState = digitalRead(buttonPin);
 // check if the pushbutton is pressed.
 // if it is, the buttonState is HIGH:
 if (buttonState == HIGH) {
   // turn Solenoid on:
   digitalWrite(solPin, HIGH);
 } else {
   // turn Solenoid off:
   digitalWrite(solPin, LOW);
 }
}
```

Appendix E: Proposed Updated Circuit Code

```
//Compressed air output limiting code
//This code activates the solenoid valve for a duration of 1000ms when the push button is pressed
//for less than 5000ms
int solPin = 13; // choose the pin for the Solenoid Valve
int inPin = 7;   // choose the input pin (for a pushbutton)
int val = 0;     // variable for reading the pin status
int t=5000;      // variable for amount of time button pressed
void setup() {
 pinMode(solPin, OUTPUT);  // declare LED as output
 pinMode(inPin, INPUT);      // declare pushbutton as input
 pinMode(t, INPUT);             // declare time as input
}
void loop(int duration t1=1000){      //set loop time limit to 1000ms
 val = digitalRead(inPin);      // read input value
 t = digitalRead(t);                 // read time value
 if ((val == LOW) && (t == LOW)) {          // check if the input is LOW & button pressed for
<5000ms
        digitalWrite(solPin, HIGH);  // turn Solenoid Valve ON
 } else {
        digitalWrite(solPin, LOW);  // turn Solenoid Valve OFF
 }
}
```