Wheelchair Tennis Adaptive Devices for Quad Tennis

Preliminary Report

Biomedical Engineering Design 200/300
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Abstract

The purpose of this design project is to design and fabricate a pair of assistive devices for the client to use while playing in a quadriplegic tennis league. The client requires these devices as a result of their condition, Becker Muscular Disorder, a progressive muscular disorder that results in the weakening of the legs, pelvis and arms over time. The two main goals of this project are to design and fabricate a tennis ball launching system and an optimized tennis racquet grip. Some important criteria for these designs are client safety, ease of use and accuracy. After evaluation of a range of brainstormed design 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 cords around the racket handle for an optimized grip. Moving forward, the team will research materials and further modifications for use in the designs and begin the fabrication and testing phases of the project.

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 one or both lower extremities and one or both of the upper 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 continually 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 racquet. As a result, a common method employed is the use of athletic tape to secure the racquet 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]

<u>Problem Statement</u>

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.

<u>Client Information</u>

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

Biology and Physiology Research

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]

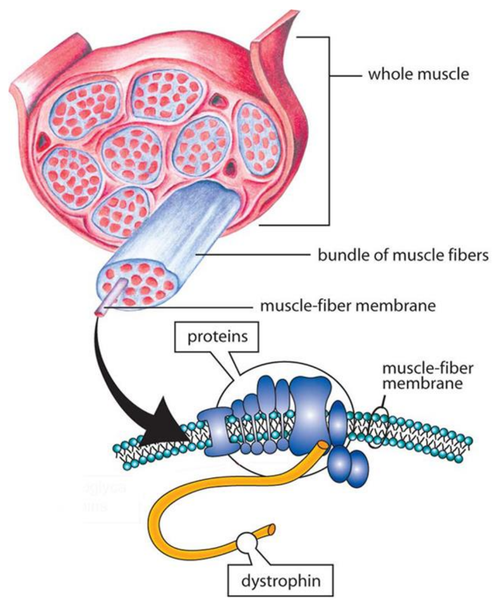


Figure 3: Dystrophin protein within the muscle-fiber membrane[9]

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 racquet, as long as any modifications do not alter the physical characteristics of the racket in order to enhance performance and the overall racquet length does 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 be able to 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 pinky and ring fingers 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.

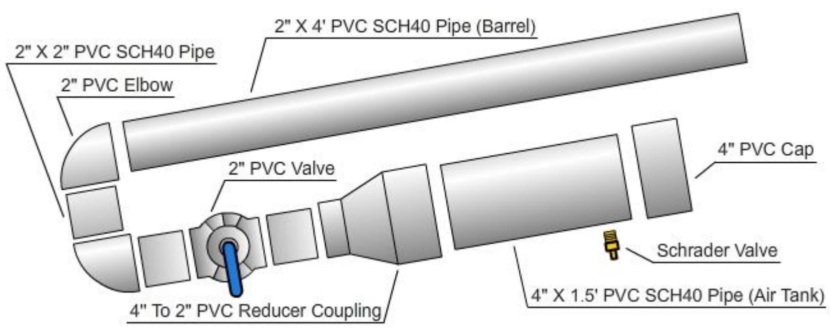


Figure 9: Pneumatic potato gun schematic[11]

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.

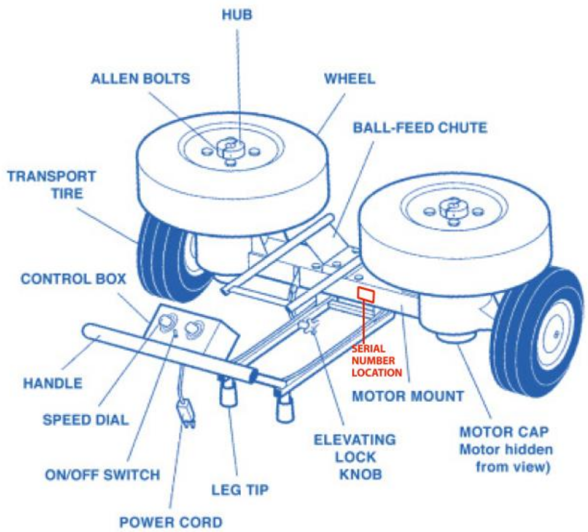


Figure 10: Soccer passing machine layout[12]

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.

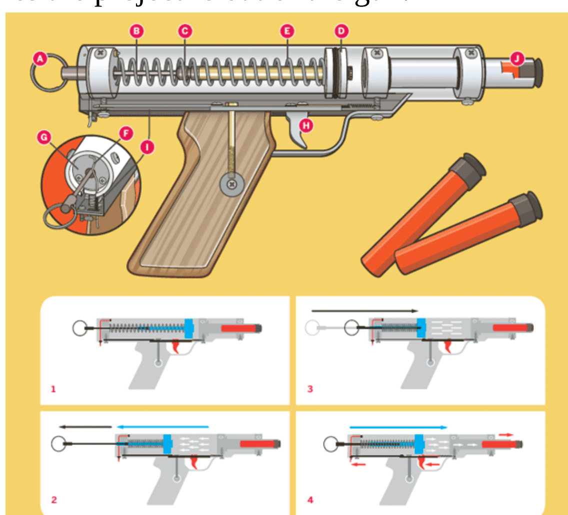


Figure 11: NERF gun infographic[13]

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

<u>*Compressed Air Cannon*</u>

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.

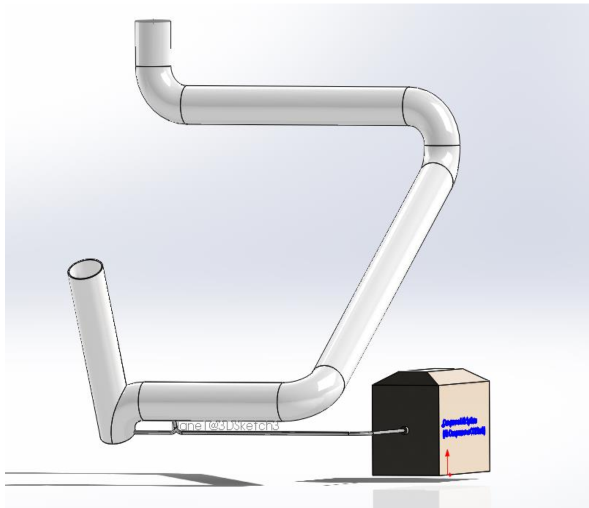


Figure 14: Compressed Air Cannon design model

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.

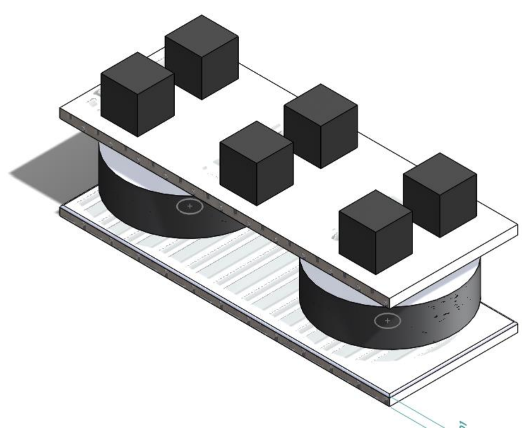


Figure 15: Caster Wheel Platform design model

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.

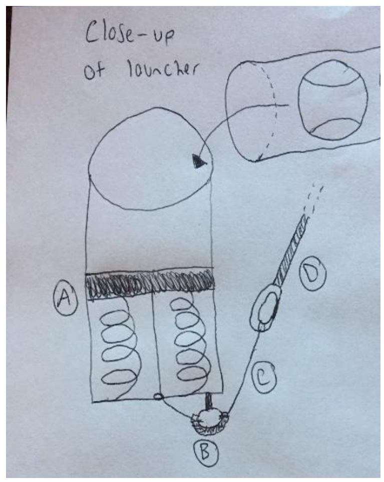


Figure 16: Loaded Spring Gun preliminary design model

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.

<u>*Design Matrix*</u>

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.

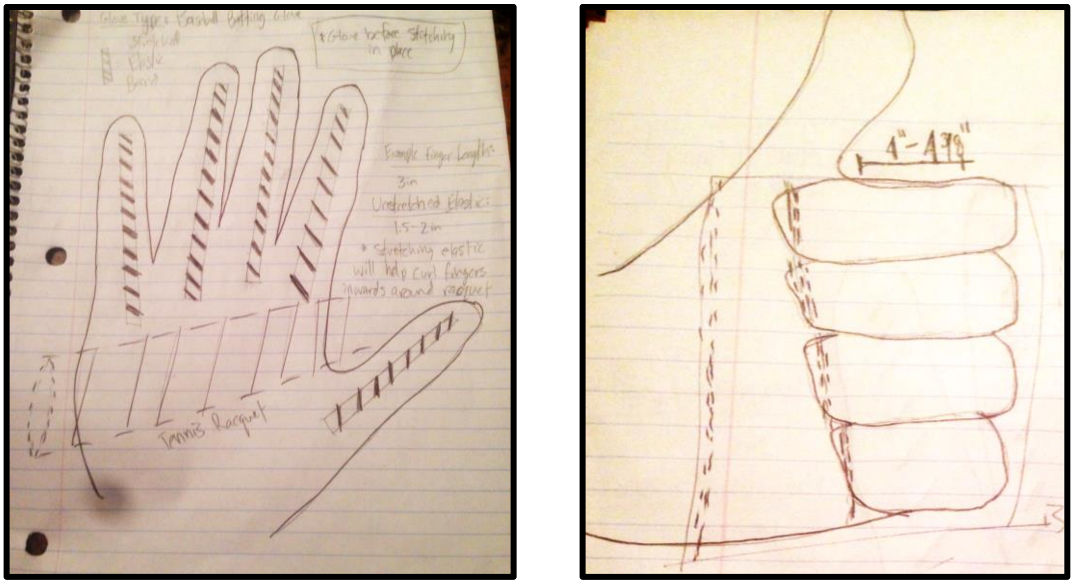
Proposed Final Design

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.

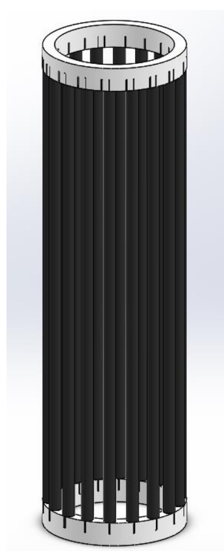


Figure 19: Racket Cords design model

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.

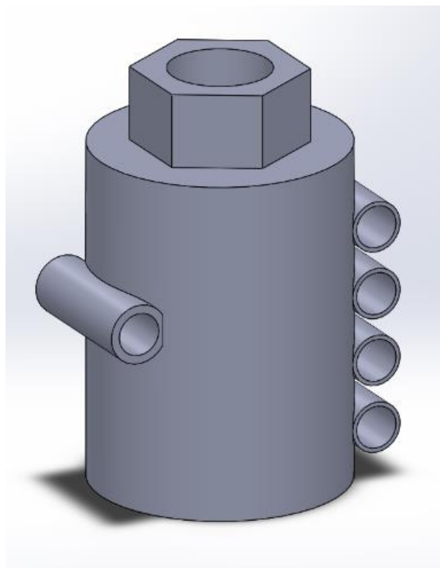
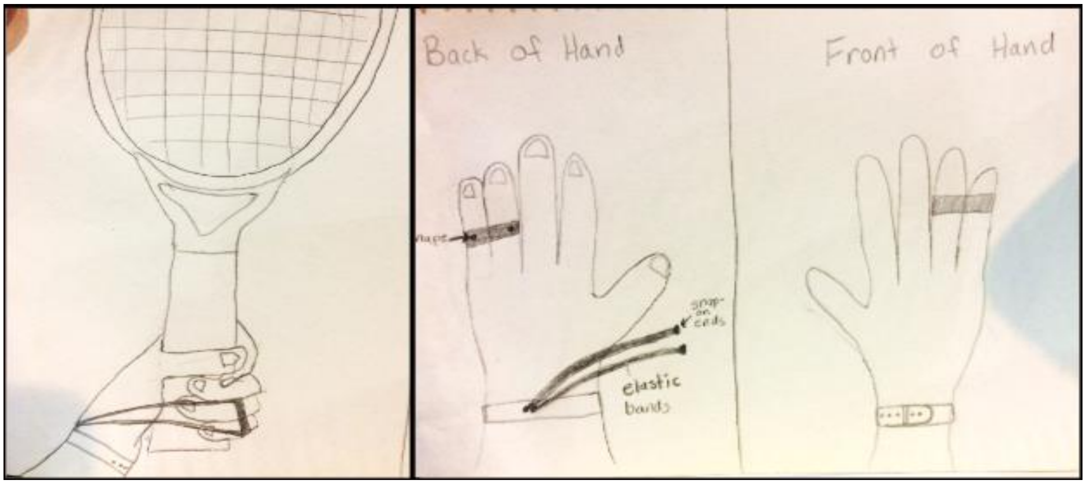


Figure 20: 3D Mold preliminary design model

Spiderman Wrist Mounted Strap

The last design features a thin wrist strap connected by elastic to a band around the pinkie and ring fingers (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.

Proposed Final Design

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

Conclusion

The client, Dan Dorszynski, needs an enhanced grip device and an automated serving system in order to better perform in the quadriplegic wheelchair tennis league. This design team has proposed designs that will provide for and improve his current limited ability to serve the tennis ball and keep a firm grip on the tennis racket during play. The proposed serving system design currently involves utilizing a compressed air source to push the tennis ball to the preferred height and location for serving, and the grip support is an attachment to the client's tennis racket composed of elastic fibers to firmly keep the client's hand on the racket. These preliminary final designs will be modified with input from the client and advisor, further research into the design specifics, and adjustments to account for any unforeseeable pitfalls in the designs.

In regards to design, both the serving system and grip support will be better remodeled to account for the complex geometries of the wheelchair and tennis racket. In addition, the question of easy attachment/detachment was not fully addressed in these preliminary designs and should be answered in modifications to the structure of the designs, especially with regards to the serving system. Now that a final design has been chosen for each device, the math and physics of the devices will need to be fully investigated, which may lead to further adjustments and modifications to the current designs. In regards to the serving system, the optimal velocities, pressures, areas, and other dimensions for the compressed air system should be solved, the circuitry to automate the serve should be investigated, and the dynamics of the tennis ball's flight should be ascertained. As for the grip support, the proper elasticity and stretch of the elastic fibers to maintain a comfortable grip should be computed, and the dimensions of the grip base should be optimized to promote comfort and support.

As for materials, research should be done to determine the optimal materials to handle the specific loads and functions carried by each design. The source of the compressed air for the serving system will be debated between an attachable tank or a functional air compressor. The best tubing for the tennis ball carrier system and hose for the air should also be determined. As for the grip support, more research will have to be done to find the optimal elastic fiber material and the right material for the clamp supports.

When the fabrication stage is reached, a proper fabrication protocol should be created for each part so that, if applicable, the client can easily reproduce parts that become damaged on the design. Of important concern for fabrication is the protocol for the tube and hose system for the serving system and for the base of the grip support. For the grip support base, an item for consideration is whether to have it 3D printed or hand-fabricated using tools from the machine shop on UW Madison's engineering campus.

Finally, the testing of the fabricated designs will determine the designs' viability for the needs of the client. The testing criteria for the serving system include a consistent activation of the serving system using the design's circuitry, a consistent serving height and location upon activation of the circuitry, and proper serving function for the duration of the match or the number of typical serves per match. The grip support's testing criteria include the ability to maintain a firm grip upon application of the force typical to a tennis hit, a similar range of motion with the grip compared to without, and the ability to hit the tennis ball in a similar or better manner as compared to no grip support. Experiments should be implemented that can provide accurate and relevant results that can support the designs' functions to carry out these criteria.

As these preliminary final designs are further modified, fabricated, and tested, the implications of them should not be forgotten. The goal of these designs is to improve the client's ability on the tennis court, and any detriment to this ability is highly discouraged upon submission of the project's prototypes. The serving system and grip support will be used by the client repeatedly for practice and play and should thus meet the client's expectations.

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Appendix A.

Wheelchair Tennis Adaptive Devices for Quad Tennis
Product Design Specifications
Current Version: October 18, 2016

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 Launching 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 launching 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 launching 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 launching 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 launching 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