Redesigning a Prosthesis for a Golfer with Transhumeral Amputation

by

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Abstract

The objective of this thesis was to determine the motions needed in a prosthesis that would enable a transhumeral amputee professional golfer, Michael Gibson, to play golf with similar dynamics to those of a two-armed golfer. Although he plays golf well using only one arm, his swings tend to have less power and are less consistent than his two-armed colleagues. Significant user testing was carried out using various prototypes with Gibson. Analysis was performed with Gibson's feedback, video comparisons of swings, and data from both motion capture and flight analysis software. Not only were differences in the dynamics of Gibson's swing and a two-armed golfer's swing studied, but the root causes of the differences were understood. It was determined that a prosthesis that enables wrist cock, forearm rotation, and slight elbow compliance would increase Gibson's golf performance.

Thesis Supervisor: Daniel D. Frey
Title: Associate Professor of Mechanical Engineering & Engineering Systems

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Most of all, I would like to thank my parents who have always been there to encourage and inspire me; my brother, for his companionship; and Andrew, for always making each day better than the last. You are the reason I'm the happiest and luckiest person on earth.

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Chapter 1. Introduction

Many amputees strive to return to the same quality of life as before their limb loss. However, because the market for upper-extremity prosthesis is so much smaller than the market for lower-extremity prosthesis, there are far fewer options of assistive devices for upper-extremity amputees. In golf, a sport that is enjoyed by over twenty million Americans, only two options exist for those with an above-elbow amputation. Therapeutic Recreation Systems Incorporated, a manufacturer of upper-extremity prostheses wanted to update and improve their existing transhumeral golf prosthesis design, the Golf Pro. The development process involved close user testing with Michael Gibson, a professional transhumeral golfer to understand better what factors in a prosthesis are important to amputee golfers and how to proceed in developing the prosthesis. Although Gibson is among the elite one-armed golfers and has perfected his swing as much as possible, being one-armed hinders his performance relative to other professional golfers. Therefore, finding the degrees of freedom that would allow him to utilize the same dynamics as a two-armed golfer became the priority for this research study. The results led to a prototype that allows Gibson to utilize the same dynamics of a two-armed golfer.

1.1 Bob Radocy

Bob Radocy lost his left hand in an auto accident in 1971. Frustrated by the limited performance, quantity, and diversity of prosthetic devices on the market, he went to graduate school to study engineering and biological science in the hopes of designing better prostheses. In 1979, Radocy formed Therapeutic Recreation Systems Incorporated, TRS, to develop prosthetic limbs for upper-extremity amputees. Twenty-five years later, TRS has become the leading innovator of body-powered prosthetic devices. Not only has Radocy created and improved prosthetic hands for daily use, he also has produced a variety of specific recreational prostheses for swimming, weight lifting, windsurfing, and archery, as well as for photography, playing the guitar, and other hobbies. For golfers, TRS makes two types of golf prosthesis for transradial, below-elbow, amputees, one of which can be adapted for transhumeral, above the elbow, amputees.

While these efforts met with some success, Radocy sought to improve performance even more. He contacted MIT Professor Daniel Frey to collaborate on an improved model. Radocy then contacted a professional gofer, Michael Gibson, who had bought the transhumeral version of the golf prosthesis, and inquired if Gibson was interested in testing a new prototype. Gibson agreed and was referred to Professor Frey as a resource for testing prototypes.

1.2 Michael Gibson

1.2.1 Initial Encounter with Prosthesis

Michael Gibson lost his left arm in a boating accident at the age of 17. As he was left handed, Gibson had to learn not only how to perform daily tasks with one arm, but also to make his right hand more dexterous. Gibson initially used a prosthesis to aid his recovery process, hoping that it would allow him to return to a two-handed life, but he found it to be cumbersome as well as restrictive to his range of motion. He wanted a prosthesis that could move like a natural arm. Unfortunately, at the time, this type of prostheses used weighty cables and attachments to operate. Disappointed with his limited options, he opted not to use a prosthetic limb at all.

1.2.2 Introduced to Golf

Nine years after Gibson's accident, Bill Condazis, Gibson's friend, decided to become a professional golfer. He invited Gibson to join him on trips to the golfing range and soon, had Gibson attached to the game. Gibson carefully studied swing mechanics of successful golfers and the physics behind achieving a controlled and powerful swing. From his studies, he experimented with methods to compensate for his missing arm. Two-armed golfers use their right arm mainly for control and their left arm for strength. However, they are not mutually exclusive. The left arm helps define the position of the right arm. Gibson's right arm was required to do both functions, which made him unable to perform as well as a two-armed golfer.

Gibson perfected his swing as much as he could with the help of Condazis and decided to join the PGA apprenticeship program. While in the program, Gibson began Golf Therapy, a program where he taught other disabled individuals how to play golf. Gibson loved teaching others and seeing golf empower his students; they were achieving goals that they never thought were possible. Since then, Gibson has continued to teach as a golf professional and is a nationally certified custom fitting instructor with Titleist. He is currently a full-time instructor at Harmon Golf in Rockland, Massachusetts.

1.2.3 Obtaining a Golf Prosthesis

Although it was extremely difficult to be distanced-challenged during his PGA apprenticeship, Gibson never considered using a prosthesis. It was not until he met U.S. Paralympics gold medal sprinters Dennis Oehler and Todd Schaffhauser that he became re-inspired to look into prostheses again. Oehler lost his leg in a car accident, but within four years, became the first amputee to run the 100 meter dash under 11 seconds. Schaffhauser had his leg amputated at the age of 15 due to bone cancer. Two years later, Schaffhauser set a world record in the 100 meter dash for above-knee amputees. The stories of their successes motivated Gibson to find out what prostheses could do for his golf career.

Acclimated to life without the aid of a prosthesis, Gibson desired one solely for golfing and looked for a prosthetist that would work with him. Next Step Orthotics and Prosthetics in Warwick, RI, was the only company to respond to Gibson. The company had fitted sockets, the interface that goes over a residual limb to connect the limb to the mounting point on a prosthesis, on many world-class athletes, and by chance, was the same prosthetic company that had fitted Oehler and Schaffhauser. A good fitting is essential to the comfort and function of the prosthesis. However, Next Step had never previously designed and fabricated a socket for an upper-extremity amputee. They agreed to help despite that and worked closely with Gibson to figure out how to overcome challenges related to upper-extremity sockets and formed a well-fitting, self-suspending socket that is comfortable and suits his needs as a golfer. The socket allows Gibson to move the full range of motion needed for golf and increases his proprioception of the club, the sense of relative positioning. In order to restrain the amount of rotation about the residual limb, a strap was attached to the socket that went around Gibson's chest. Next Step introduced Gibson to TRS's line of prostheses and soon he acquired a golf prosthesis, a Golf Pro, seen in Figure 1.1, to go with the socket.

Figure 1.1 Michael Gibson using his transhumeral golfing prosthesis, the Golf Pro

1.2.4 Using the Prosthesis Overview

Simply having a good fit does not ensure the success of a prosthesis. In rehabilitation, an amputee learns and masters basic tasks while strengthening and conditioning his or her residual limb muscles. This process is pivotal because it aids the amputee's transition into using a prosthesis on his or her own and could determine if the amputee will continue to use the prosthesis in the future[1]. Unfortunately, since Next Step had no upper-extremity rehabilitation program in place, Gibson had to adjust to his golf prosthesis on his own. The prosthesis often left Gibson tired and fatigued initially, but Oehler and Schaffhauser inspired him to continue.

As Gibson became accustomed to the prosthesis and his muscles developed, his game improved. He gained more control of the golf club and could focus on power, which led to discernable longer drives. However, after the initial phase of adoption, Gibson began noticing that the Golf Pro had too many degrees of freedom. The prosthesis would bend when he did not want it to, causing inaccurate and inconsistent swings. Gibson decided to backtrack and understand what incorrect dynamics the prosthesis was forcing him to do, and focus on these for adjustment.

Hitting the ball further is not helpful to Gibson if the prosthesis would not allow him to hit the golf ball where he wanted it to go. Additionally, the device was not accommodating enough for all aspects of golf. Gibson could not choke down, or grip further down, on the golf club with the prosthesis, so he would have to take the prosthesis on and off during a tournament. In the end, Gibson felt it was still easier to golf one-armed and stopped using the prosthesis.

1.2.5 Project Involvement

Disappointment with the Golf Pro made Gibson skeptical of prostheses yet again. Nevertheless, Gibson's natural curiosity about technology and desire for improved performance as an athlete compelled him to be part of this project. As someone who had experimented with prosthesis and had a natural interest in the project, Gibson believed he could provide valuable feedback about the design to ensure that the function of the device would meet the needs of transhumeral amputee golfers. Having been involved in teaching other disabled golfers, Gibson also sees how golf can really help others get back on track physically, mentally, emotionally, and socially. Gibson believes that more transhumeral amputees would play golf if an efficient and effective prosthesis came on the market.

Gibson's understanding of swing mechanics and technical approach to golf allowed him to break apart and analyze why a swing did or did not work. When given prototypes, he was quick to adjust to its new dynamics and work to determine how the prosthesis had changed his swing and if the change made his dynamics more like that of a two-handed golfer. The other instructors and fellow colleagues were intrigued by the project and often dropped by to give him pointers and things to consider. Being an instructor at Harmon, Gibson also had access to video analysis software, a motion capture vest, and other instruments that he uses to help teach and analyze swings.

2. Amputee Facts

In America, there are approximately 1.7 million people with limb-loss[2] and according to the Amputee Coalition of America, more than 185,000 new amputations are performed each year[3]. Including Mexico and Canada, the number climbs to an estimated 2.5 million total amputees in North American alone[4]. Dysvascular amputations account for 82% of limb-loss cases and are on the rise[5]. Diabetes, a dysvascular disease, makes up 51% of amputations performed annually, although only 3% of the United States population has diabetes[6]. Other causes of amputations include trauma, cancer, and congenital deficiencies.

2.1 Upper-Extremity Amputees

Out of the 1.7 million people with limb-loss in America, only 10% are upper-extremity amputees[7], and only a quarter of these have amputations beyond a finger[5]. Unlike lower-extremity amputations, trauma related accidents are the number one cause of upper-extremity amputations, making up more than 75% of the cases. These accidents are often the results of vehicle crashes, lacerations from tools or machinery, or frostbite[8].

Because there is more funding and resources for lower-extremity research, it may seem that the needs of leg amputees are favored in research and engineering initiatives. In reality, there is less funding for upper-extremity prostheses due to its small population. Prosthetic manufacturing companies do not expect a high enough return from developing upper-extremity prosthesis to invest in them[9]. Upper-extremity limb-loss patients have many physical, psychological, and social issues that they encounter and deserve to have more resources and attention allocated to their disability.

2.1.1 Physical Adjustments with Limb-Loss

An upper-extremity amputation means the loss of at least one hand's functionality. Hands are used to perform many daily tasks because of their ability to gather information and manipulate objects through sensory feedback. The human hand is able to provide a wealth of information about objects that people come in contact with everyday. Some of this information includes surface texture, compliance, weight, shape, size, orientation, and temperature. Grabbing and manipulating objects is possible because of the hands' impressive manual dexterity, ability to conform to a variety of object shapes, and aptitude to adjust grip force as necessary to handle different loads, which allows the hand to execute precise movements quickly. Higher level amputations affect joints, such as the wrists, elbows, and shoulders, which help position the hand and allow it to access a greater range of motion.

There are many physical activities that upper-extremity amputees cannot fully experience without a prosthesis, such as rock climbing, playing the violin, or archery. Other activities can be relearned with one hand, but are not as efficient as when done with two hands. Some of these activities include tying a tie, typing, and opening a soda bottle. A prosthesis can help the efficiency of such activities and gain back some of the functions of the arm and hand, but current available prosthesis are still a long way off from matching all the functions of an anatomical arm and hand. Due to the nature of upper-extremity amputations that result from trauma, the amputees, such as soldiers wounded on duty or someone in a motorcycle accident, tend to be more active, can be much younger, and feel the loss of their freedom more strongly.

Amputees with trauma-related injuries often end up with residual limbs that are not suitable for prostheses. The condition of the residual limb varies greatly depending on the type of trauma. The amputated limb could have been crushed, burned, torn, or severed from an accident. Surgery is often performed to save the patient's life and preserve the residual limb's shape and condition for a prosthesis is of secondary importance. Therefore, the residual limb may not be in a condition to tolerate being in a socket or taking the loads that a prosthesis would put on the limb. In contrast, those who lose a limb from vascular complications or cancer have the ability to find surgeons that will work with prosthetists, before their surgery, to optimize the shape and condition of their limb for a prostheses.

2.1.2 Psychological Adjustments with Limb-Loss

Having an upper-extremity amputation often affects the person's self-image, self-esteem, and self-confidence negatively. Amputees rely more on others to help them with even some of the simplest tasks that they used to be able to do with two hands and can become frustrated, lose self-reliance and self-confidence, and become depressed about their condition. 21% to 35% of the amputees following amputation become clinically depressed[10]. Additionally, upper-extremity limb-loss is more visually apparent than lower-extremity loss[10]. This can make amputees feel like outcasts, having a damaging effect on how they view their self-image and body-image. This makes it psychologically harder for them to approach and take part in social events.

Psychological effects can be much more severe for amputees that have been through traumatic loss of a limb. Not only is there emotional fatigue from the sudden change of situation, and perhaps even experiencing post traumatic stress disorder (PTSD), they also have to adjust to continuing life without the limb. Those with PTSD tend to avoid places and people that remind them of the preceding accident and are hypersensitive to daily experiences[11]. They often feel guilty that the accident was their fault and wonder "what if".[12] Even without considering prostheses, the process that a trauma patient under goes is emotionally draining.

Unlike those that have prepared for their limb-loss, trauma patients are often less acquainted with the types of prostheses that are on the market. They tend to have higher expectations of prostheses, having only been exposed to prostheses through movies, like Star Wars, and recent news about cutting edge prosthesis involving bionics. However, standard, affordable prosthesis usually do not meet their expectations. This unexpected revelation could cause the patient to lose confidence in all prostheses and prevent the success of the prosthesis that the patient ultimately obtains.

2.1.3 Social Adjustments with Limb-Loss

As mentioned in the previous section, upper-extremity amputations are visually apparent, and amputees consequently experience difficulty in readjusting into society. Most people have very little experience interacting with upper-extremity amputees and can react poorly when seeing them for the first time. At schools, children will tease and bully other children who have lost a limb. This discrimination reaches far beyond the school grounds, into the workplace and public areas, and is even observed in well-educated people[13]. Some openly stare at the amputees and physically avoid them, making the amputees "[feel] like lepers." [10] Others will ask insensitively intrusive questions about the amputee's loss and condition. Amputees are seen as less-able and they feel the need to demonstrate their competency[10]. These types of situations make it difficult for amputees to integrate into their surroundings at work, home, or school, and make them feel anxious in public situations. Sometimes, even their closest friends will avoid contact after an amputation[10].

Certain customs cannot be carried out with a missing upper-extremity limb[10]. In the western cultures, amputees that are missing a right hand cannot properly greet someone with a handshake or wave in the "normal," accepted manor. Amputees that are engaged or married and have their left hand missing cannot display their engagement ring or wedding band on the correct hand. When engaged in a conversation, amputees have limited body language and gestures to use for communication. These can all affect how a person is viewed and how they view themselves.

On a larger scale, social issues depend on culture as well. There are only a few countries where the appearance of a hook on the hand is socially acceptable. In other places, it is impossible for an amputee without a prosthesis to find work.

3. Prostheses

A prosthesis is an artificial device designed to be a functional, aesthetic, or a combination of functional and aesthetic replacement for a missing limb or body part. They are created and produced to assist amputees in regaining some normalcy after the amputation by allowing them to restore part of their movement and/or functions that they loss. Benefits of prosthesis include helping amputees keep their job, be more social and integrated with others, keep them active, raise their self-image, and be more independent. However, statistics show that most amputees do not use any sort of prostheses. Out of the more than one million American amputees in 1994, approximately only 20% were using prostheses. Over 85% that were using prosthesis were those wearing lower-extremity prosthesis[14].

3.1 Defining Prosthetic Success

The success of a prosthesis can be determined by many variables, but will not be successful unless the wearer has a level of satisfaction with the device. Two metrics for measuring the amputee's satisfaction with his or her prosthesis are prosthesis retention by the wearer and the percentage of time the prosthesis is used for applicable tasks. Retention is the bare minimum standard that the prosthesis should meet, meaning it meets of the basic needs of an amputee and performs at a quality that is tolerable. Wearers might not be completely satisfied with their prosthesis, but will keep wearing the prosthesis if the benefits out weigh the negative characteristics of the prosthesis, even if only by a small margin. Further determination of the success of the prosthesis can be done by looking at the percentage of time that the prosthesis is used for a relevant task. The higher the percentage, the more the prosthesis is used, and the more successful it is for the amputee.

It has been shown that a higher percentage of amputees who are fitted within the first 30 days of amputation are more likely to accept and retain their prosthesis than those who are fitted after 30 days[15]. A shorter time gap allows for a greater acceptance of the prosthesis because there is more of an emphasis of progress with bimanual functionality rather than the amputee focusing on what was lost[10].

3.2 Prosthetic Parts

An upper-extremity prosthetic limb, shown in Figure 3.1, consists of a socket, a liner and/or sock, and the main components of the prosthesis, which may include harnesses and straps as well as cosmetic covers, depending on the prosthesis.

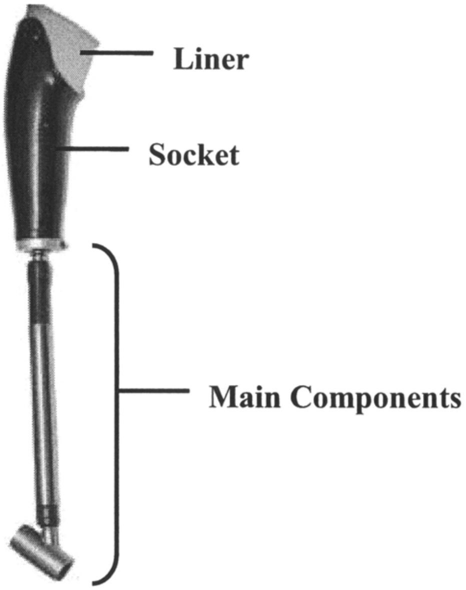


Figure 3.1 A transhumeral prosthesis with socket and liner

3.2.1 Socket

The prosthetic socket, shown in Figure 3.2, affects the comfort and functionality of the prosthesis.

Figure 3.2 An upper-extremity prosthetic socket

The socket attaches directly to the body and transmits forces from the residual limb to the prosthesis and also helps counteract the forces that are applied to the prosthesis. It is essential for an amputee to have a prosthetist develop a well-fitted socket. Unfortunately, many prosthetists lack experience in fitting upper-extremity sockets. The bone contour and lack of soft tissue makes it harder to fit a socket that is comfortable. Additionally, for lower-extremity fittings, prosthetists have the ability to use the hip and pelvis areas for support and bracing, but that sort of methodology cannot be transferred to upper-extremity sockets because it would limit the range of motion of the arm. Having a prosthetist that is willing to understand the amputee's needs fully and find the best socket structure for the amputee's residual limb helps to achieve the best functional and comfortable socket. Today, sockets are normally made from carbon fiber or plastic to provide a rigid support structure while being light.

3.2.2 Liners and Socks

The comfort of a prosthetic socket is affected by proper pressure distribution and the management of shear forces on the residual limb, which is achieved by a liner, shown in Figure 3.3.

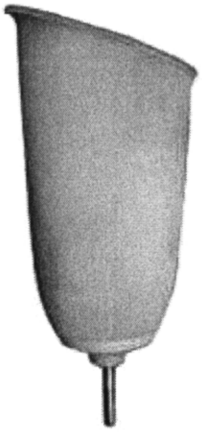


Figure 3.3 An upper-extremity prosthetic liner

A liner is worn between the residual limb and the socket to provide a cushion to absorb the shock and shear forces on the limb as well as to ensure a tight fit. Most liners are made of silicon and urethane polymers and are rolled on to the amputee's residual limb. The friction and compression holds the liner on.

To ensure the attachment of the liner to the socket, a locking pin or strap and harness can be used. A locking pin method utilizes a stainless steel pin at the distal end of the liner and attaches to the socket via a shuttle lock. A suction valve on the socket is normally used in conjunction with a locking pin liner. Air is forced out through a one way valve when the liner is inserted and forms a tight seal that holds the socket to the liner. Alternatively, a strap or harness may be worn that attaches to the socket to keep the prosthesis on the distal limb. Prosthetic socks, made of wool, cotton, or synthetic fibers, may be worn in conjunction with or in place of a liner to help compensate for day to day volume fluctuations in the residual limb caused by specific activities, weather, and other factors.

3.2.3 Main Components

The main components of a prosthesis are the working parts and will vary depending on the type and the function of the prosthesis. Components include the joints, terminal devices such as fingers and hands, and shafts that provide rigid connections. These components may be driven by a number of ways as explored in the prosthetic options section.

3.3 Prosthetic Options

Because every amputee is different, there is not a single prosthesis that meets everyone's needs. Each type of prosthesis has its share of strengths and limitations that would attract an amputee or prevent them from considering it. A person with an upper-limb loss is faced with six general options: not to utilize a prosthesis, to have a cosmetic or passive replacement, to have a body-powered prosthesis, to have an electrically-powered prosthesis, to have a hybrid prosthesis, or to have an activity-specific prosthesis. The type of prosthesis a person ends up with depends on the patient's physical condition after the amputation, the condition of the residual limb, his or her body type, activity level, hobbies, profession, family life, mechanical aptitude, cognitive level, and self-image. Additionally, an amputee may have more than one prosthesis for multiple functions.

3.3.1 No Prosthesis

Only half of upper-extremity amputees receive any prosthetic care at all due to lack of access; half of those that do receive a prosthetic limb stop using their prostheses within a year of receiving them[16]. Among the many reasons why a patient would find themselves not using a prosthetic limb are an amputee might never have sought care because of lack of finances, an unwillingness to go through the hassle of learning and using a prosthesis, or the patient feels physically limited and does not believe the prosthesis will help in his or her circumstance. Others just appreciate the comfort and simplicity of not having a prosthesis. Additionally, a major deterrent from continued use of a prosthesis is that many of the models do not meet the amputees' expectations or enhance their functionality. Those that abandon a prosthesis could have had problems with the prosthesis being uncomfortable, not performing as expected, being too complex, functioning poorly, looking displeasing, or requiring too much maintenance.

Amputees could also have complications that restrict physical strength or range of motion causing them to be unable to activate movement for the prosthesis. Alternatively, they might not have enough motivation to complete the entire acquisition and rehabilitation process for a prosthesis. A thorough examination and chat with a prosthetist early on could advert these problems mentioned.

Training and rehabilitation can be essential to amputees transitioning with their prostheses. Training helps the amputees understand the functionality of their prosthesis and allows them to become more comfortable with it. Rehabilitation helps the amputee gain strength in their residual limb and prepare for myoelectrics if needed. Many amputees said they needed more education on their prosthesis than what was given to them from their medical professionals[17]. Those that went to training learned to perform simple tasks such as stacking different size blocks, assembling sticks, and arranging dominoes, adapted better to situations encountered in their daily lives and continue to use their prosthesis more than those who did not receive training[15].

3.3.2 Cosmetic Prostheses

Upper-extremity amputations are very visible; therefore, many amputees want a prosthesis that resembles the limb they lost so that they feel less like outcasts in social situations. A cosmetic prosthesis, like that in Figure 3.4, helps fulfill this need.

Figure 3.4 An amputee with a cosmetic prosthesis[18]

With cosmetic prostheses, amputees can blend into crowds better, which improves their self-confidence, makes them more comfortable around others, and allow them to be more forward and independent. The prosthesis becomes a valuable part of the wearer's life. Cosmetic prostheses are normally made from flexible latex, rigid polyvinyl chloride (PVC) or silicone allowing them to be lightweight in comparison to other prosthetic options. Additionally they are low maintenance and are simple, needing no control cables or harnesses.

A cosmetic prosthesis is also called a passive prosthesis because it does not assist in the functionality of grasping. However, such devices have an important emotional and social function, and are often still used to balance, push, and carry items.

There is a wide range of cosmetic prostheses available today. Affordable options for most amputees are standard off-the-shelf cosmetic limbs that are approximately the same size and color of the person's natural limb, but lack finer details. At additional cost, a prosthetic limb with details down to exact replication of skin color and variation, hair, freckles and veins can be custom-made for the amputee.

3.3.3 Body-Powered Prostheses

Body-powered, or cable-operated, prostheses are the most common functional prostheses because they are simple, durable, reliable, fairly lightweight, and are able to be used in many environments, including under water, without being damaged. An example of a body-powered prosthesis can be seen in Figure 3.5.

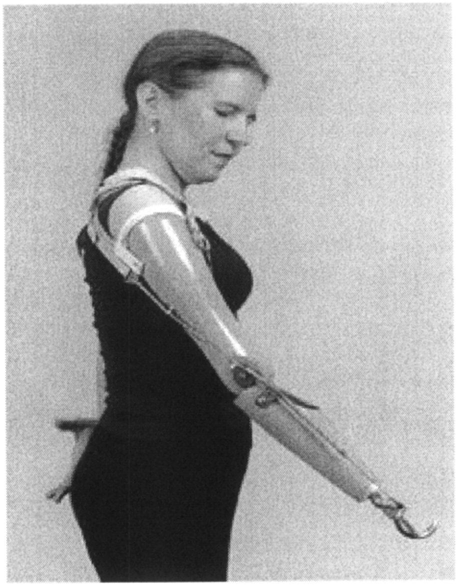


Figure 3.5 An amputee with a body-powered prosthesis[19]

These prostheses are powered and controlled via a harness by capturing gross body such as moving the shoulder, the upper arm, or the chest. The harness transmits the movement to an attached cable that moves a terminal device such as a hook or a hand and helps distribute the weight of the prosthesis. The wearer can feel the pressure from the harness to know what position the terminal device is in without looking at it. Each harness must be fitted to the amputee to optimize the function and increase comfort, much like a socket. Body-powered prosthesis can feel too restrictive, limiting the wearer's range of motion, and having the possibility of the harness causing nerve entrapment. For some, this type of prostheses is not an option because it is not pleasing to the eye and the patient must have sufficient residual limb length, musculature, and range of motion to begin with.

3.2.3 Electrically-Powered Prostheses

Amputees initially tend to show the greatest interest in electrically-powered prosthesis when choosing between the different types of prostheses on the market. This type of prostheses, seen in Figure 3.6, has a futuristic and high tech appearance and seems the closest to achieving the complex functionality of a hand being microprocessor-controlled.

Figure 3.6 An amputee wearing the DEKA "Luke" arm, an electrically-powered prosthesis[20]

Externally-powered prosthesis can also have a cosmetic covering to help with the aesthetic appeal of the unit. Benefits of this type of prostheses include that they do not require any cables or harnesses, they can achieve a tighter grip force, and they increase the range of motion of the limb over cable-harness systems. However, the components are very expensive and weigh a lot more than those of the body-powered prostheses. The additional weight causes amputees to expend more energy on the same action. Electrically-powered prostheses also require additional maintenance for upkeep because of the intricate components required. Therefore, electrically-powered prostheses might not satisfy the needs and wants of the patient as well as a simple and affordable prosthesis.

Electrically-powered prostheses run on batteries and use electric motors to move terminal devices or joints and require a control system. The two most common control systems used are myoelectric and switch control[21]. Myoelectric control utilizes surface electrodes to sense electric impulses produced by muscle contractions in the residual limb to activate motors. Switch controlled prostheses use small switches in the socket or harness to operate the motors. The switch is activated by a movement of a bony protuberance against it or a movement captured through a harness, like the body-powered prostheses.

Myoelectric limbs have an illusion of being effortless in recreating how a hand naturally moves. However, they currently are not as reliable as the body power prostheses, and cost several times more. This particular control system requires an amputee to undergo intensive pre-prosthetic training to condition their residual limb. They work on the strength and range of motion of the residual limb as well as improving the strength of their muscle contractions so the electrodes can pick up on the impulses. The amputee has to learn to achieve muscle independence so that both the elbow and the terminal device can open and close correctly and independently, otherwise the signals could cancel each other out. The prosthesis would be of little benefit if the amputee does not have the ability to properly control the device[22].

3.3.4 Hybrid Prostheses

Hybrid prostheses, shown in Figure 3.7, are more versatile than an electrically-powered prosthesis with a control scheme. Combining several types of prostheses provides increased functionality, especially for higher-level amputations such as transhumeral amputees.

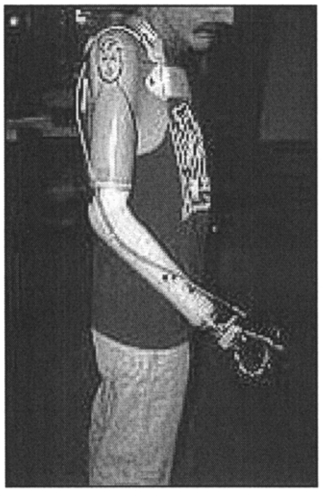


Figure 3.7 An amputee with a hybrid prosthesis[23]

Usually a body-powered elbow is combined with a myoelectrically-controlled terminal device such as a hook or a hand. Occasionally, the opposite is true, where an electrically-powered elbow is combined with a body-powered terminal device. These systems allow for the wearer to operate multiple joints simultaneously[16]. Other configurations require the wearer to control one joint at a time, such as flexing the elbow, locking it, and then using the terminal device. Hybrids are typically lighter than fully electrically-powered prostheses, but wearers must still have enough gross body movement to be able to operate this type of prostheses. Other strengths and limitations of body-powered and electrically-powered prostheses apply to hybrids as well.

3.3.5 Activity-Specific Prostheses

Lastly, there are specialized prostheses that are typically made for one specific activity in which any of the latter types of prostheses would be unsuitable due to their limitations in range of motion, function, and or durability. Some include playing the guitar, weight lifting, riding a bicycle, holding utensils, or holding tools for specific work related tasks. The prosthesis developed in this thesis belongs in this group.

4. Golf Overview

According to the PGA, over 26 million Americans play golf[24]. Golf is a game that is difficult to master, often frustrating, but can also be very satisfying and at times filled with "extreme ecstasies." [25] It is a game that not only challenges technique, but also grace and mental fortitude. Although golf is a non-contact sport and is normally played individually, it is a very social game and offers a time for many to enjoy the outdoors.

4.1 Purpose of the Swing

The most fundamental component of golf is the swing itself. Theodore P. Jorgensen, author of *The Physics of Golf*, claims that "[a]ny golfer, who wishes to improve his game, must work on himself. He is the one who makes his clubs go through the motions. The secret of golf is the swing." The goal of the swing is to generate and impart the necessary amount of energy for the ball to travel accurately and consistently[25]. Accuracy of the ball flight path depends on the clubface's trajectory. The clubface must be perpendicular, or squared, to the intended line of flight for the ball at impact, shown in Figure 4.1, to propel the ball straight towards the target.

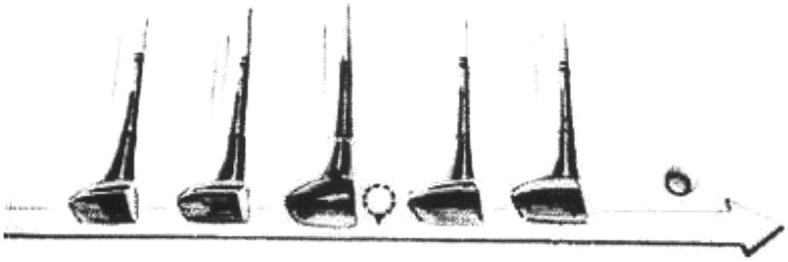


Figure 4.1 Squaring of the clubface at impact[26]

Consistency requires the golfer to understand what he or she does to achieve accuracy and power during the different phases of the swing and be able to repeat it.

4.2 Phases of the Swing

The swing consists of the address, backswing, top-of-the-backswing, downswing, impact, and follow-through. While physics does govern the understanding of how a golfer should approach golf, the details of how each phase is carried out differs amongst golfers. Jorgensen comments on this in *The Physics of Golf*:

> The theoretical understanding of the golf swing puts limits on what should be attempted in the doing but it does not specify exactly what should be done. If the theoretical understanding did establish exactly what should be done, we should all be swinging like automatons. The theoretical understanding indicates the *techniques* that should be used but, within the general area of the correct technique, we may each develop our own style of swing. . . . . The correct

> technique is essentially determined by the laws of physics and the limitations of the human body. Let us face the fact that our bodies are all different and for this reason alone the style of the stroke that each of us may develop will differ from the style of other golfers. [25]

4.2.1 The Address

The address is the first phase of golf. The golfer sets up for the swing and makes sure that his or her body is aligned with the target correctly. Figure 4.2 shows the address of Aaron Baddeley, a two-time PGA tour winner. Pictures of Baddeley are screen captures from videos obtained from the V1 Golf Academy's swing library.

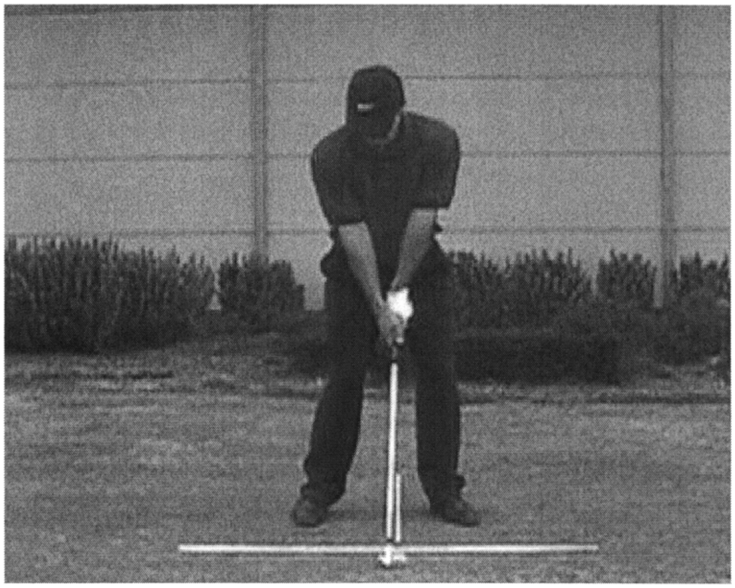


Figure 4.2 Aaron Baddeley at address[27]

Components of the address that affect the motion of the swing but differ amongst golfers include: the golfer's grip, stance, and alignment. The grip is defined as how the golfer's two hands interact with each other to hold the club. The stance is how the golfer positions himself or herself. This includes the amount of forward bend, or how much the golfer bends forward at the waist, how far apart the golfer spaces his or her feet, how the weight is distributed between the golfer's feet, how much the golfer bends his or her knees, and how the golfer's arms are positioned. Lastly, alignment is how the golfer positions himself or herself and the clubhead in relation to the target. All of these components of the address take place before the golfer begins the swing.

4.2.2 The Backswing and Top-of-the-Backswing

The purpose of the backswing is to position the club properly at the top of the swing so that during the downswing, the clubhead travels in a path that allows it to arrive inline of the ball at impact with the club face squared. According to Leslie King, who developed one of first methods for teaching golf based on studying swings, "If the club is out of position at the top, a correct downswing will be virtually impossible without some compensatory movement! ... Such compensatory movements are the beginnings of an unsound action." [28] The more compensation that is needed in the downswing, the less consistent the golfer will be[29]. Figure 4.3 shows the path of Aaron Baddeley's backswing.

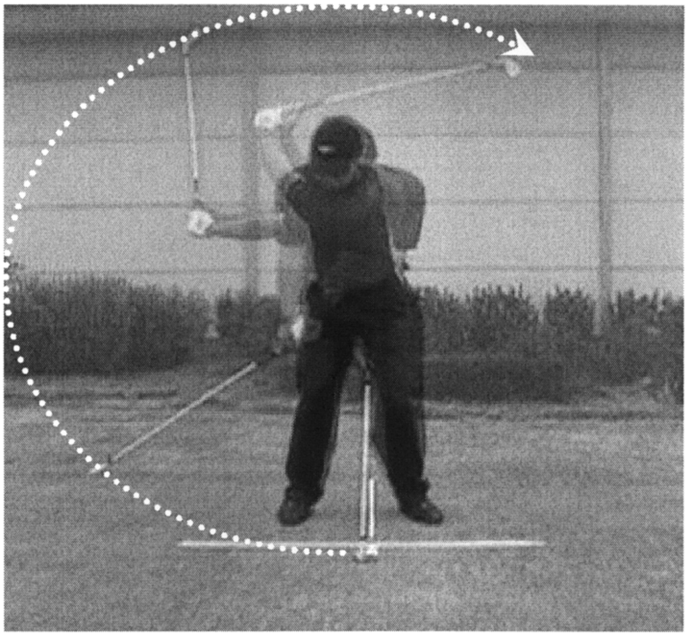


Figure 4.3 Baddeley's backswing[27]

Correctly positioning the club in the backswing also prepares the two-armed golfer to deliver a powerful swing in the downswing. Components that affect the positioning includes whether or not a golfer keeps his or her forward bend consistent, how his or her weight shifts, and the motions of his or her arms, including the hands, wrists, forearms, and elbows.

4.2.3 The Downswing

During the downswing, the golfer not only has to swing the club in a smooth arc so that the clubhead arrives inline of the ball at impact with the clubface squared, but also has to generate power in this timeframe. A downswing can be seen in Figure 4.4.

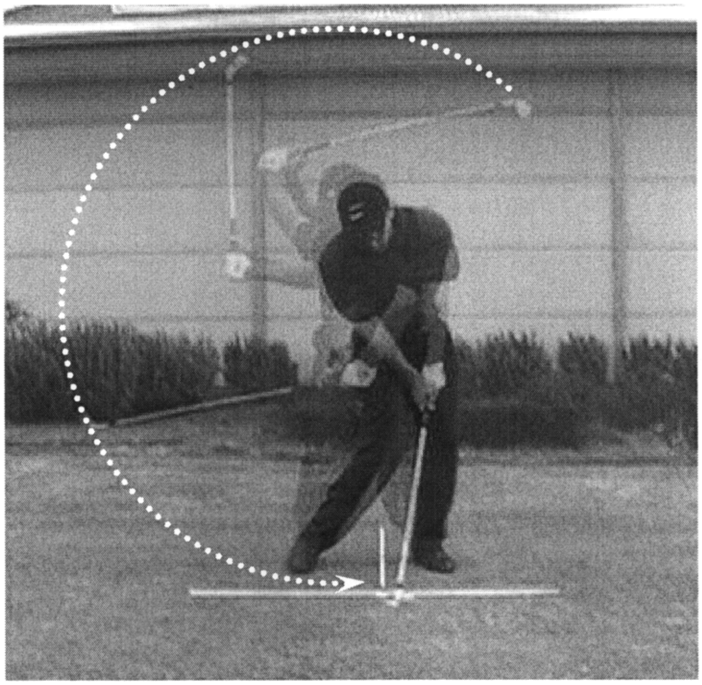


Figure 4.4 Baddeley's Downswing[27]

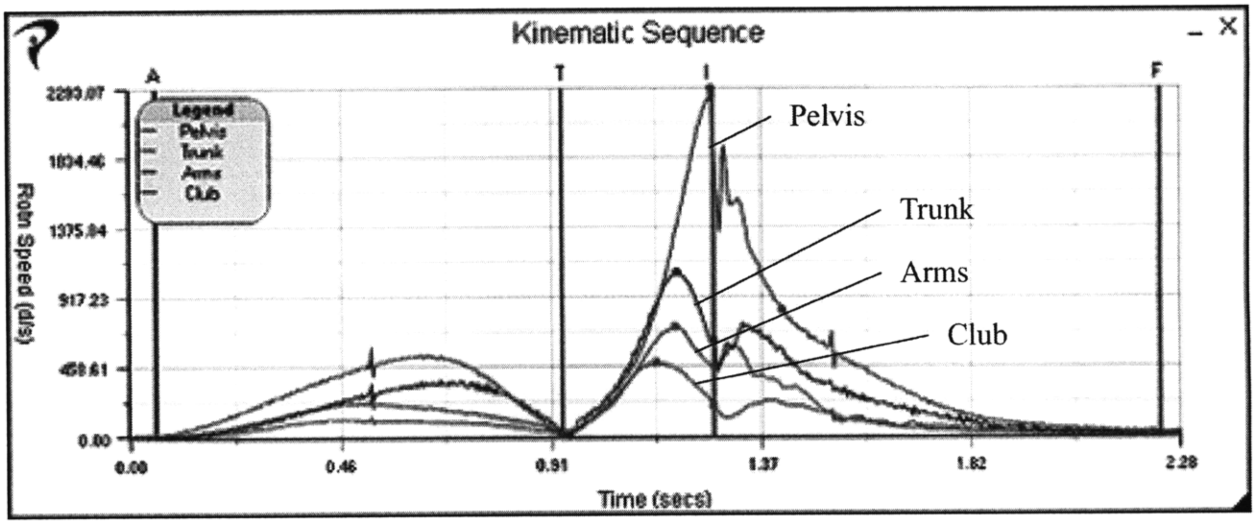
Jorgensen estimates that a professional golfer delivers energy at approximately two horsepower. Large muscles, when loaded, can generate about 1/8 horsepower per pound, which means that at minimum, 16 pounds of muscle need to supply the power for the golf swing. A more reasonable amount is 32 pounds of muscle to account for losses as the power is transferred to the clubhead. He observes that "[w]hen you look for 32 lbs. of muscle on the average human body, you do not find it in the arms or even in the shoulders. You have to go to the legs, the thighs, and the back before you begin to approach this amount of muscle."[25] Therefore, the downswing needs to be initiated with the lower body and not just with the arms in order to generate the amount of power needed in a swing. In addition, according to John Toepel, a veteran PGA Tour Player, "[t]he whole purpose of having the feet and legs move the body is to keep the arms relaxed and allow them to have maximum speed and consistency, returning the club through the ball for a true shot."[30]

4.2.3a The Kinematic Sequence

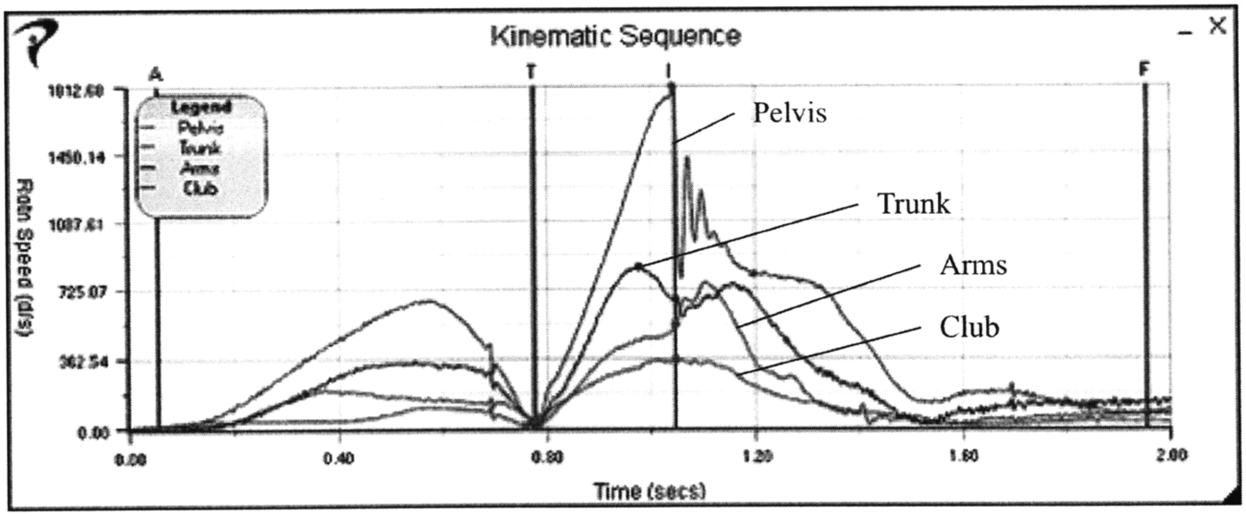
To transfer energy to the clubhead, segments of the body must accelerate and decelerate in the correct order with specific timing relative to one another to achieve maximum clubhead speed. This is analogous to how a whip works. The whip action is initiated by the hand accelerating, decelerating then stopping at the end of the stroke. As successive parts of the whip are stopped, the kinetic energy is transmitted further to smaller sections of the whip. Energy is conserved throughout this process so the mass at the end of the whip will move at a much higher speed than the initial hand motion[25].

The most efficient power transfer occurs when energy is generated in the hips, then is transferred to the thorax, then to the arms, and finally, transferred to the club. The desired outcome is a motion that causes each body segment to reach peak speed in the aforementioned order, and with each segment faster than the previous segment in a cascading effect. Proper execution of this kinematic sequence causes efficient transfer energy between body segments[31].

Figure 4.5 depicts two graphs comparing the kinematic sequence of a skilled golfer to that of an amateur golfer. The data for these two graphs were gathered by the Titleist Performance Institute.



(a)



(b)

Figure 4.5 The kinematic sequence of (a) a skilled golfer and (b) an amateur golfer[31]

The graphs show the rotation speed of the pelvis, the thorax, the arms, and the club throughout the swing. The four vertical lines mark the address, top of the backswing, impact, and follow-through.

The key area of interest for the kinematic sequence is the segment between the top-of-the-backswing and impact, otherwise known as the downswing. The more skilled golfer in Figure 4.5a shows a definite kinematic sequence, which allows the club to reach a maximum speed of about 2200 degrees per second at impact. Each subsequent body segment accelerates faster and peaks higher until the club shows up as a spike on the graph. The swells that show up after impact occur from the club imparting forces back onto the golfer during the follow-through before decelerating to a stop. The swing depicted in Figure 4.5b is an inefficient swing because the peaks do not occur cleanly and sequentially. The pelvis incorrectly maintains speed during the follow-through, and the thorax speed peaks in the follow-though instead of the downswing. The result is a clubhead speed of approximately 1000 degrees less than that of the skilled golfer.

4.2.3b The X-factor and the X-factor Stretch

Another way of gaining insight on power generated in the downswing is the X-factor. The X-factor is the relative rotation of the shoulders to the rotation of the hips at the top of the golf swing. According to Jeffrey Mann, in an in-depth study of the golf swing, the concept of the X-factor "can potentially increase [a golfer's] capacity to eventually rotate his upper torso at a faster speed a fraction of second later in the downswing by stretching his right abdominal wall muscles."[32] The more rotated the shoulders are compared to the hip, the faster they have to rotate to catch up to the hips at impact. This generates power by maximizing part of the kinematic sequence between the hips and shoulders. Therefore, a larger X-factor is believed to correspond to a higher club head speed at impact.

A study done by Phillip J. Cheetham of Skill Technologies, Inc., found that less skilled golfers, those with handicaps of 15 or higher, would on average have X-factor stretch of 44°while highly skilled golfers, including professionals that play scratch, or play with a handicap of zero or better, would have an average X-factor of 48°.

Cheetham also found that the maximum rotation of the shoulders to the hip rotation, the max X-factor, occurs early in the downswing. The X-factor stretch, the difference between the X-factor and the max X-factor, is a better measurement to gauge the effectiveness of a swing because there is a more drastic difference between the highly skilled and less skilled golfers[33]. Research done by Golf Biodynamics, Inc. on 75 tour professionals and 150 amateurs found that tour professionals have an average X-factor stretch of 17.4° and the amateurs would have an average of 5.9° [34].

Jim Mcleans, the developer of the X-factor measurement, demonstrates the X-factor stretch in Figure 4.6.

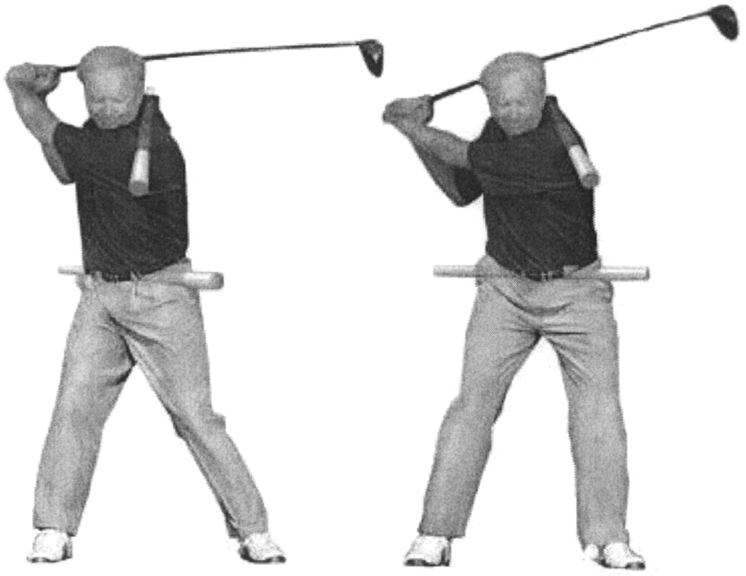


Figure 4.6 Jim Mcleans demonstrating the X-factor stretch[34]

The Mcleans on the left side shows the rotation of the shoulders and hips at the top of the backswing and the Mcleans on the right show the max rotation between the two during the early part of the downswing.

Although many golfers use the X-factor stretch to gauge their performance, there are golfers that do not believe the X-factor is an accurate method for measuring power in the swing. Using the X-factor, golfers learn to "accelerate the hips at the start of the downswing while keeping the shoulders back [so that] the lower body … easily outrace[s] the upper body during the downswing." [32] The golfers focus on keeping the ratio of hip to shoulder rotation large, often holding their arms back instead of letting them freely release. This has an adverse effect on clubhead speed.

4.2.4 The Impact

The impact is the moment the clubface makes contact with the ball. Baddeley's position at impact can be seen in Figure 4.7.

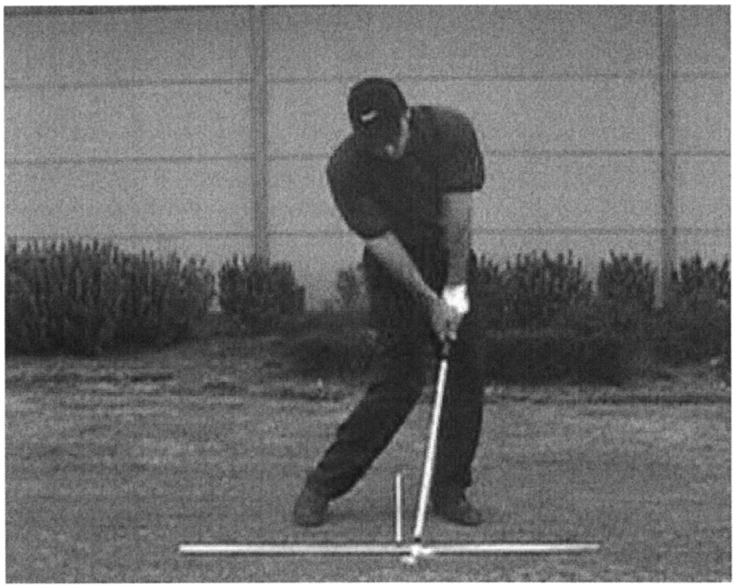
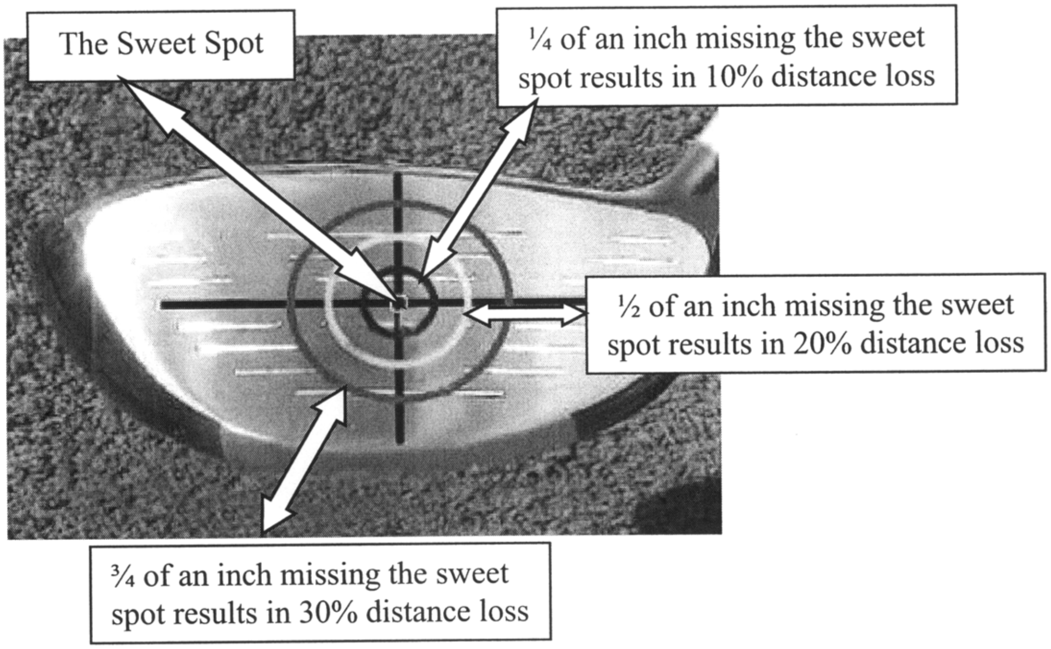


Figure 4.7 Baddeley at impact[27]

Not only does the ball flight path depend on the angle of the clubface at impact, it also depends where on the clubface the ball makes contact. Like baseball, there is a sweet spot where the golfer wants the clubface to contact the ball to maximize energy transfer. The sweet spot is located at the center of the clubface. When impact does not occur at the sweet spot, the club will want to twist, which results in a decreased flight distance.

Figure 4.8 relates the distance decreased in flight distance with how far off the sweet spot the ball is hit.



The Sweet Spot

¼ of an inch missing the sweet spot results in 10% distance loss

½ of an inch missing the sweet spot results in 20% distance loss

¾ of an inch missing the sweet spot results in 30% distance loss

Figure 4.8 Percentage of distance loss if ball is hit ¼”, ½”, or ¾”from the sweet spot[35]

In addition, the twist will cause the ball to fly off of the intended flight path.

4.2.5 The Follow-Through

The last phase of the golf swing is the follow-though, shown in Figure 4.9.

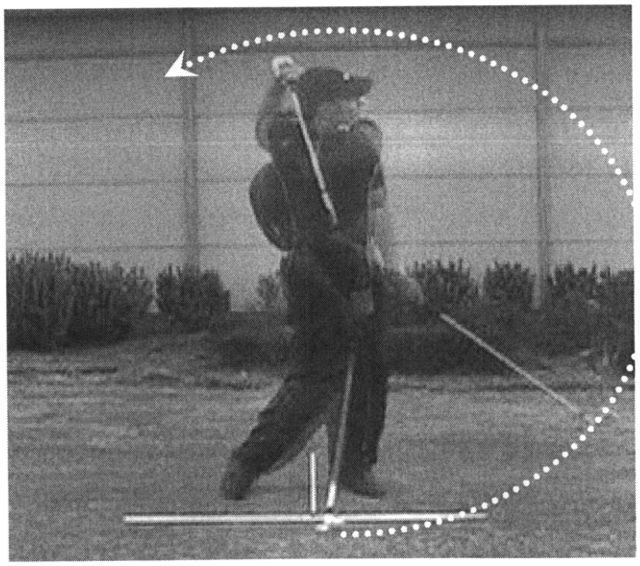


Figure 4. 9 Baddeley’s follow-through[27]

The follow-through is the natural finish to the swing. A good swing will end in a good follow-through with the arms extended through impact, while a faulty swing will have an imperfect follow-through where the golfer loses balance or finishes too early. Therefore the follow-through can be an indicator of mistakes in previous phases of the swing.

4.3 Methods of Swing Analysis

Analyzing the swing allows golfers to know what part of their golf technique is weak and needs improvement. The most basic way of analyzing the swing is to base it on how the swing felt and to see the ball's flight path. With just these two, a wealth of information about the swing can be obtained. The location where the ball makes contact with the clubface dramatically changes how the swing feels. When a ball hits the sweet spot, the swing feels effortless. According to Martin Hall, a golf instructor, "When you hit it off the heel, it'll feel like you just hit a brick and the ball will shoot dead left. If you hit it off the toe, you'll feel a soft impact, like you whacked an old apple." [36] By observing the ball's flight, golfers can determine what the clubface angle was at impact and how much power they generated and transferred to the ball. Golfers that understand the motions behind each phase of the swing can use both of these as feedback to diagnose and improve their swings.

To gain additional insight on what occurred during the swing and what they need to improve, many golfers use video and motion capture software. The video capture software allows the golfer to record his or her swing and then compare it side by side to that of a professional golfer's, or to another one of their swings. Some quantitative data can be gathered from drawing lines on the screen and obtaining angles. For a more in-depth analysis, motion capture software is used. This software can record the X-factor stretch, forward bend throughout the swing, speeds, the tilts and pitches of various body parts, and the kinematic sequence of the swing. One of the motion analysis software available, the iClub's Body Motion System, can even keep track of long-term performance, recent trends, and give coaching tips such as "Your forward address was more forward than usual. You may have addressed the ball while standing too far away".

There are also a multitude of other analysis programs that utilize other technologies to gain other insight to a golfer's swing. V1, a video capturing software developer, offers a balance board option to gain feedback on how the golfer shifts weight throughout the swing. Another product, FlightScope uses a 3D Doppler radar to show the flight path of the ball and capture various details, including its speed, launch angle, spins, and distance traveled.

4.4 The Mental Game

Aside from mastering golf technique, golfers also have to manage their mental game. Physically hitting a golf ball occupies less than one percent of the time in a round of golf. The rest of the time, golfers walk around to their ball and wait for others to play. According to Dr. John F. Murray, a sports-performance psychologist, instead of releasing stress through physical activity as in most other sports, "golfers are stewing in their juices. They have nowhere to go but think about what might happen. And you can't punch the wall because you're out there on the course." [37]

There is a lot of time to be distracted by thoughts, to lose concentration, to be bothered by past mistakes, or to worry about the next swing. According to Dr. Joseph Parent in *Zen Golf: Mastering the Mental Game*, “Performance anxiety, emotional reactions, and distractions interfere with the golfers’ abilities.” [38] Golfers need to learn to have clarity, commitment, composure, confidence, the ability to be focused and synchronized simultaneously, and to positively learn from mistakes to play at their best.

5. Playing Golfing as an Upper-Extremity Amputee

Persons missing one arm have the option to play golf unassisted, where only one arm can touch the club, or play assisted, where prosthetic devices or the other limb is used during the play.

5.1 Playing Golf Unassisted

Golf is a frustrating sport even for those with two arms. Although, physically, it is possible to execute as great a shot one-handed as it is two-handed, it is much more difficult to do so consistently. One-armed golfer is off-balanced to begin with and does not "have another hand 'counter-acting' the mistake that is being made to buffer the movement of the club head out-of-plane and/or becoming un-squared" like a two-armed golfer[39]. Traveling out-of-the plane refers to the clubhead traveling in a path that incorrectly positions it so it is not inline with the ball at impact.

Alan Gentry, the founder of the North American One Armed Golfers Association, recalls the difference in results after losing an arm in an industrial accident in which his jacket sleeve became attached to a rotating auger of a drill rig. He wrote:

> When I had two arms and played scratch, and I made a swing mistake, I hit the ball in the rough or slightly missed a green in regulation. The same swing mistake as a one-armed player may result in missing a target by over 50 yards. This type of mistake for a two-armed player, on a championship caliber course, might make it challenging to save your par. The same mistake for a one-armed player will usually cost him/her at least two shots. [39]

What differentiates great golfers and average golfers is consistency and it is much harder for one-armed golfers to be consistent. Each error compounds much more drastically for a one-armed golfer. As Gentry notes, "[one-armed golfers] are much better than their score tallies up at the end of the day in the 19th hole." [39] This also causes the mental game to be that are much harder for one-armed golfers. Errors are that much more damaging to their score, so on the course, they have to learn not to let swing faults throw them off their game on the course.

An average golfer with a handicap index of 16.1 will score approximately 100 on an 18 hole course, according to the National Golf Foundation, an industry research-and-consulting service[40]. Professional golfers, with a handicap index of less than 1.4, normally score in the 70's, but are capable of achieving low 60's [41]. The best one-armed golfers that play unassisted, are capable of a score in the mid 70's, but will generally play in the upper 70's to mid 80's, with handicaps ranging from high single digits to high teens. These numbers cited for one-armed golfers incorporate both transradial and transhumeral golfers[39]. Although the golf handicap system was meant to provide an equal playing field for golfers to base their scores upon, the system, like the score, does not accurately capture the skill level of one-armed golfers. "[The handicap system] is not really reflective of the talent level, because we play a 2-handed game, on a 2-handed course, with 2-handed rules and a handicap scoring system designed for 2-handed play, and we play 1-handed." [39]

Golfing one-armed causes a lot of physical stress because the impact is taken up by only one arm thereby not as distributed as golfing with two arms. Many of these golfers face tendonitis early in their golfing careers.

5.2 Assistive Options for Transhumeral Golfers

Prostheses aim to help amputees overcome limitations from their disabilities so that the amputees can improve their level of functionality physically, socially, emotionally, and mentally. However current transhumeral golf prostheses are currently not able to help skilled amputee golfers perform better than when the amputees golf one-armed. Therefore most transhumeral golfers, like Gibson, tend to golf without an assistive device. In contrast, transradial golfers tend to use prosthesis when golfing because they tend to score better wearing a prosthesis than when playing without one[42].

Two companies, TRS and Troppman Prosthetics, offer golfing prostheses for transhumeral amputees. Both designs are adaptations of their transradial versions. TRS is associated with the Golf Pro line and Troppman Prosthetics is associated with the Troppman Grip. Although only the Golf Pro was tested in this thesis, the two companies' prostheses are very similar. Comparable benefits and issues likely exist between the Golf Pro and the Troppman Grip.

5.2.1 The TRS Golf Pro

The Golf Pro, as shown in Figure 5.1, consists of a flexible coupling, an interface that connects the Golf Pro to the socket, and a grip component.

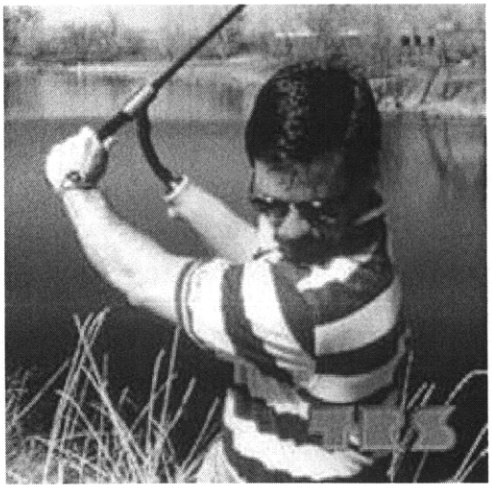
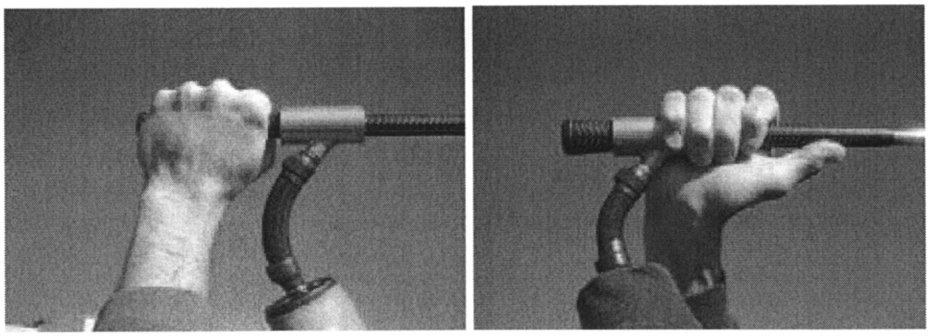


Figure 5.1 Golf Pro being used by an amputee[43]

The Golf Pro was initially designed for golfers missing their non-leading arm. For right-handed golfers this would be their right arm and for a left-handed golfer their left arm. TRS now also offers a version for golfers missing their leading arm. The difference between the two is the length of the flexible coupling due to the positioning, either in front of or behind the sound hand, of the prosthesis on the golf club grip, as seen in Figure 5.2.



(a) (b)

Figure 5.2 The Golf Pro being used as (a) the trailing arm and (b) as the leading arm for a right handed golfer[43]

5.2.1a The Flexible Coupling

The flexible coupling gives the Golf Pro its length and acts as the wrist joint. The transradial versions of the Golf Pro use a high strength, steel braid reinforced hydraulic hose type material for the coupling. It was aimed to provide amputee golfers with a full range of movement and freedom while being simple to manufacture.

Gibson's Golf Pro, shown in Figure 5.3, is approximately eight inches longer than the transradial versions of the Golf Pro to compensate and include both his elbow and wrist.

Figure 5.3 Gibson's Golf Pro

Redesigning the arm for transhumeral amputees, TRS changed the flexible coupling material to polyurethane to allow for the coupling to store and release energy due to the material's spring-like properties. However, TRS never analyzed how different configurations store and release energy during the swing. Energy storage is generated when the Golf Pro bends at the top of the swing and energy is released during the downswing when the tube springs back into its original state. Currently TRS is working with students from several schools to study how configuration and materials can be optimized for energy release and performance for their golfing line. By improving the amount of power the amputee could transfer to the ball, the further the amputee can hit the ball.

5.2.1b The Socket Interface

The flexible coupling has a ½"-20 threaded post, shown in Figure 5.4, which allows the prosthesis to be fastened to the socket.

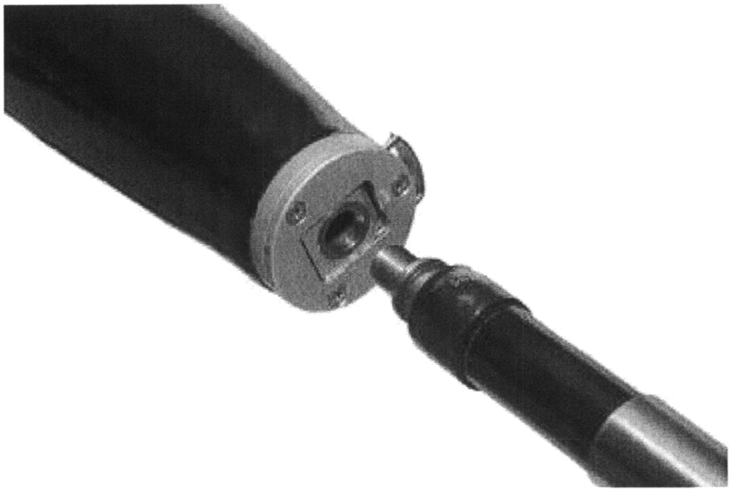


Figure 5.4 The socket interface of the Golf Pro

Being the standard attachment interface for upper-extremity prostheses, the ½"-20 post allows for the Golf Pro to fit onto any socket directly, or with an adaptor that could be screwed into the post and then attached to the socket. The design intention was for the post not to be screwed in completely, allowing the prosthesis to rotate in the socket, mimicking forearm rotation.

Using this particular arrangement is unsafe because there is the possibility that the prosthesis could completely unscrew and fall out of the socket. Also the length of the prosthesis will change depending upon where the threaded post it is when the swing is initiated.

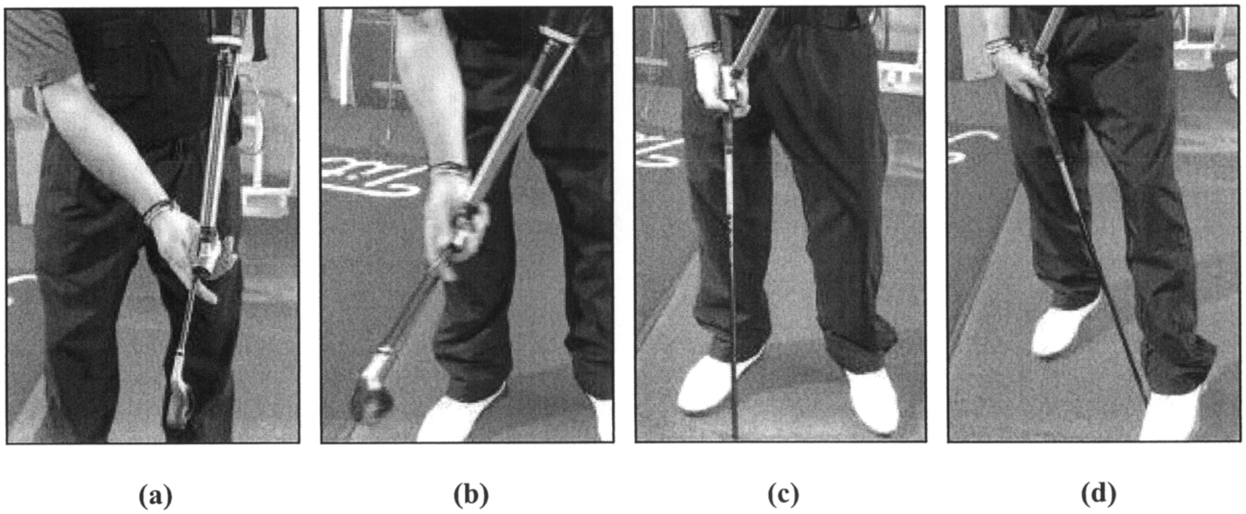
Feedback from users differs on whether or not forearm rotation is needed; some amputees prefer some rotation, while others did not want the arm to rotate at all. The current interface allows for unrestricted rotation. It is unknown whether or not limiting the rotation is better than unrestricted rotation.

5.2.1c The Grip Component

The grip component on the Golf Pro which holds the golf club, shown in Figure 5.5, is made of a C-shaped channel with two internal plastic sizing rings.

Figure 5.5 The grip component of the Golf Pro

Hand positioning varies with different golf grip, which affects the game's feel, control, and comfort. Grips come in many sizes, styles, material, textures, and amounts of cushioning. The sizing rings are custom made and tailored to the wearer's golf clubs to account for the different grips and their tapers. To grasp the club, the device slips over the shaft near the head of the club then jams in place on the grip when pulled up upon. Figure 5.6 details this process.



(a) **(b)** **(c)** **(d)**

Figure 5.6 The process of inserting a club into the Golf Pro (a) Slipping the component over a the part of the shaft with small diameter (b) Sliding the component up the club shaft (c) Sliding the component up the grip of the club (d) Tightening the club in the component by pulling up while stepping on the clubhead

5.2.2 The Troppman Grip

The Troppman device was also initially designed to replace the non-leading arm. Like the Golf Pro, it can be custom made to accommodate for other situations. The prosthesis has a similar flexible coupling and utilizes a modular component that goes over the ½-20" post to provide a quick disconnection point and prevent forearm rotation at the interface.

The major difference between the Troppman Grip and the Golf Pro is the grip. The Troppman Grip, shown in Figure 5.7, is a molded plastic cradle that supports the golf club. It has no way of securing the golf club without a "sound" hand to go around the grip.

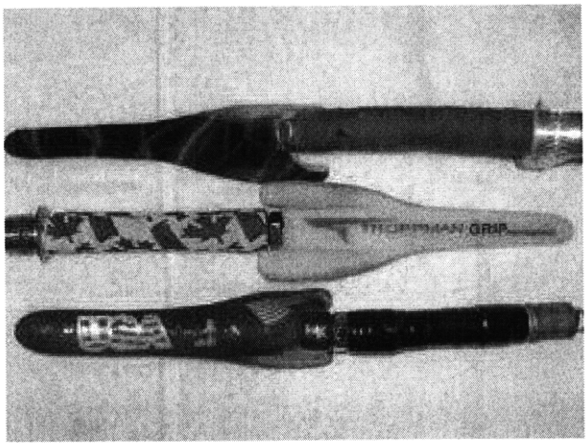


Figure 5.7 The Troppman Grip[44]

TRS makes a similar grip to the Troppman Grip, called the Amputee Golf Grip, seen in Figure 5.8.

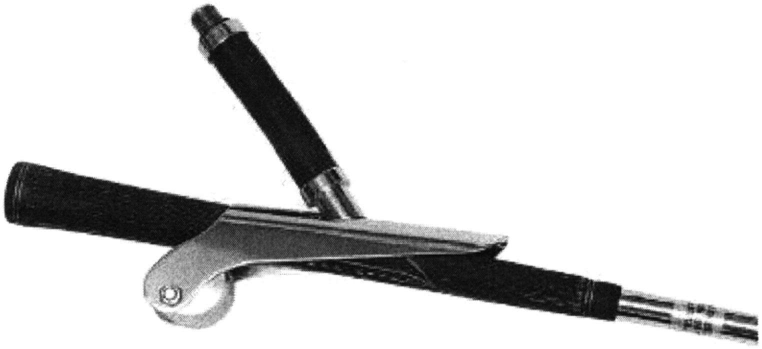


Figure 5.8 The TRS Amputee Golf Grip

The Amputee Golf Grip has an aluminum cradle, with a cam to help with placement and prevent slippage. Like the Troppman Grip, another hand is needed to secure the golf club in place. TRS only manufactures transradial golf prostheses with the Amputee Golf Grip.

6. Gibson's Golf Experience

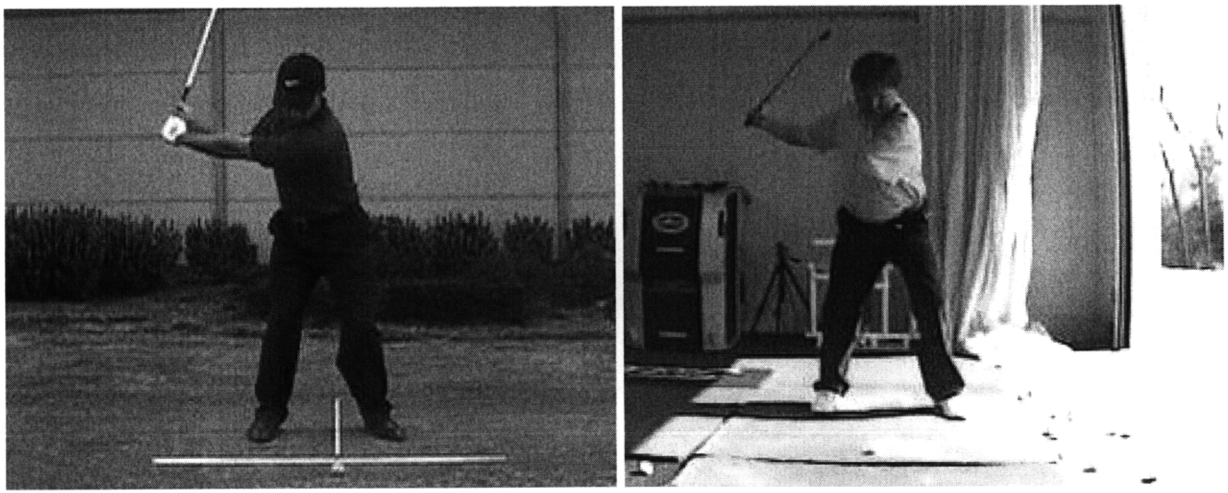
Being a transhumeral amputee, Gibson is more unbalanced and has less control than transradial golfers. With a handicap index of 8.1, he typically scores around 80, which ranks him among one of the best one-armed golfers in the nation.

6.1 Details of Playing with One-Arm

Gibson would like to improve his score so that it is in the 70's. However, with only one arm, he cannot fully focus on both control and power. If he focuses more on one, the other worsens. Gibson has managed to find a good balance between focusing on power and control, but it means that there is not much room for improving his performance when playing one-armed.

6.1.1 The Backswing

Two-armed golfers are able to constrain their upper body movement and the positioning of their right by using the left arm. Without this constraint, a disconnect exists between the right and left sides of the body preventing proper club positioning. Gibson's one-armed backswing is shown in Figure 6.1, compared to a professional two-armed golfer.



(a) (b)

Figure 6.1 Mid-backswing for (a) Baddeley[27] and (b) Gibson one-armed

Aaron Baddeley must rotate his left shoulder forward and across his body during the downswing to reach the desired club position at the top of the swing. Keeping his left arm straight, Baddeley constrains his right shoulder and arm movement. His shoulders will act as a unit and both shoulders will rotate the same amount, connecting the left and right sides of the body. Gibson, conversely, is not forced to rotate his left shoulder forward because he does not have to pull up his left arm. Instead, he consciously rotates his shoulders, knowing that it is needed to generate power in the downswing. However, without constraint, his shoulders do not act as a unit and the right shoulder will rotate more than the left shoulder in the backswing, opening up his chest more than Baddeley does his. This causes the arc of the clubhead during the backswing to be more flat, or parallel to the ground, than Baddeley's arc. Figure 6.2 shows the difference in between Baddeley's arc and Gibson's arc.

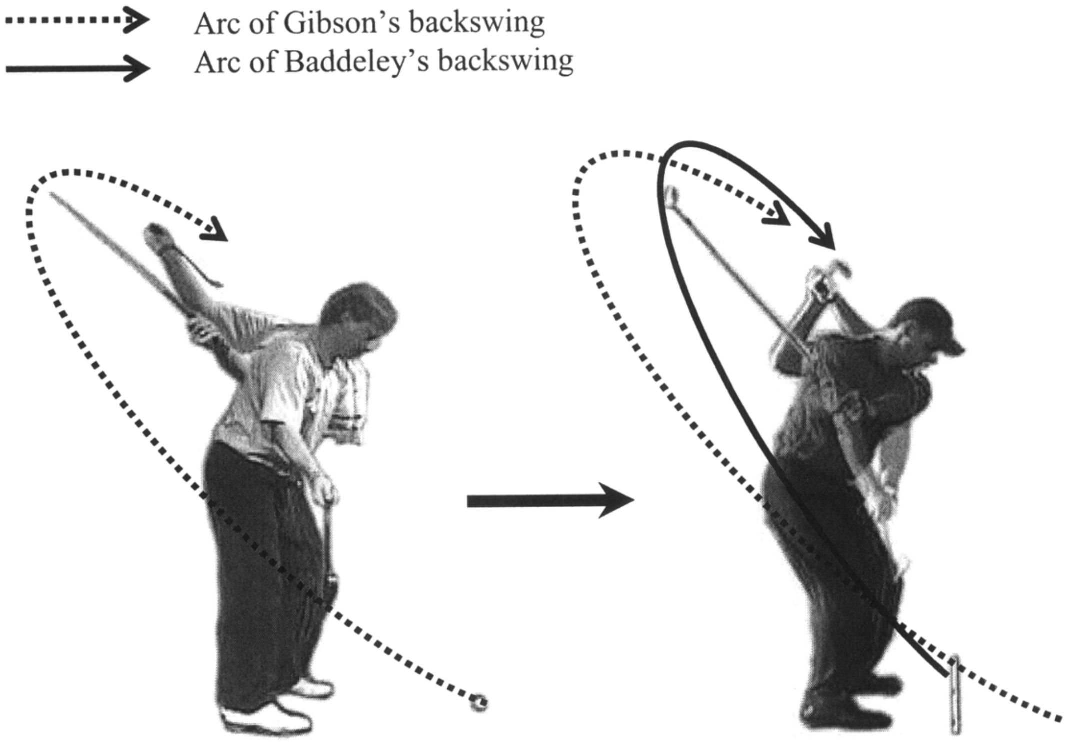


Figure 6.2 Comparison between the backswing of Gibson playing one-armed and Baddeley's backswing[27]

6.1.2 The Top-of-the-Backswing

The result of Gibson not being able to constrain his left arm is that he is extremely open and rotated at the top-of-the-backswing, seen in Figure 6.3.

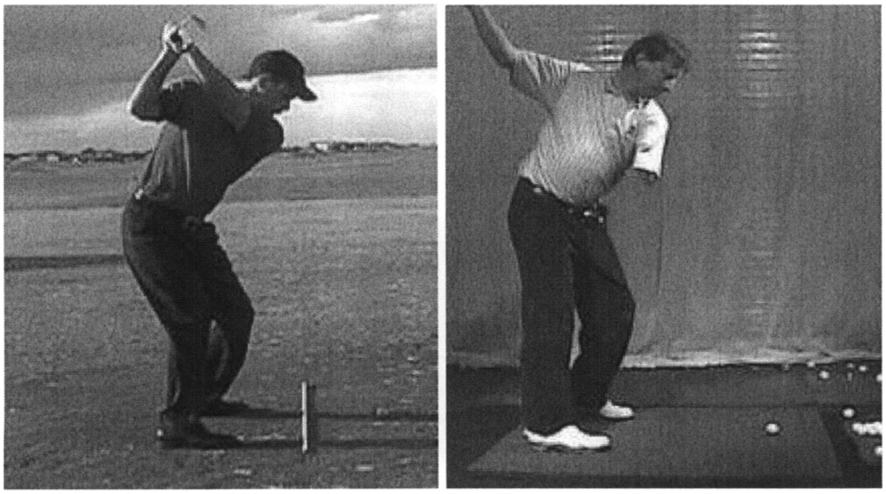

(a) (b)

Figure 6.3 The top-of-the-backswing for (a) Baddeley[27] and (b) Gibson one-armed

Gibson's club is lifted a lot further up and away from his body than Baddeley's because of the openness in his right shoulder and how little his elbow bends in the backswing. There is an approximately 90° difference between the obtuse angle that Gibson's elbow makes and Baddeley's acute angle from this view point.

6.1.3 The Downswing

Like his backswing, the arc the clubhead travels in Gibson's downswing is too flat and causes an over-the-top swing. This normally initiates a slice, which is a type of swing fault that causes the golf ball's path to curve significantly, landing to the right of the target. Figure 6.4 illustrates various types of golf shots from a right-handed player's point of view.

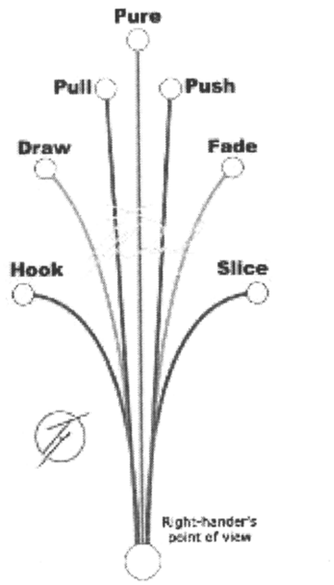


Figure 6.4 Shots from a right hand golfer's point of view[45]

Gibson needs to compensate in the downswing for the misalignment caused by the openness of his right arm at the top-of-the-backswing to prevent the slice[28]. Attempts to prevent the arm from opening as far as it does would result in inconsistencies. When playing one-armed, Gibson opens his right arm until movement is restricted by the shoulder blade. Although this is much further open than what a two-armed golfer would do, it allows his swings to be somewhat repeatable because he has a fixed reference point to guide his arm. Trying to position his right arm consistently where Baddeley's is at the top of the swing is impossible because Gibson has no reference point there.

Instead of trying to constrain the position of his right arm, Gibson instead compensates for its openness by flipping the clubface during the downswing so that the clubface is closed at impact. This changes the results of the swing from a slice to a compressed pull, shown previously in Figure 6.4. A pull is a straight hit towards the left of the intended target. Although this is a much improved hit over a slice because the ball lands closer to the intended target, it could still be better.

6.1.3a The Kinematic Sequence

Gibson's one-armed swing dynamics results in the following kinematic sequence, seen in Figure 6.5.

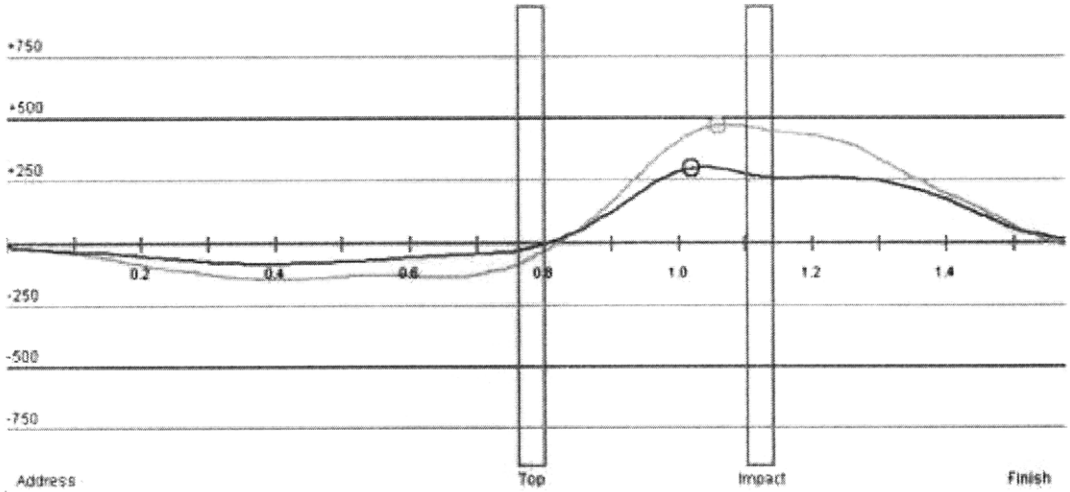


Figure 6.5 Gibson's one-armed kinematic sequence recorded with iClub's Body Motion System

Although the arm and clubhead speeds were not recorded, the resulting kinematic sequence with just the hips and shoulders is still informative. The upper line in the downswing portion tracks the speed of the shoulder rotation. The other line tracks the speed of the hip rotation during the swing. There is not a clear peak in either shoulder or hip rotation, much like the amateur's swing in Figure 6.5 in Section 4.2.3a, which implies that Gibson's one-armed swing is inefficient at generating and transferring energy. The maximum flight distance Gibson can achieve one-armed with an eight iron is about 115 yards, which is about 40 yards less than what a two-armed professional golfer can achieve.

This kinematic sequence can be explained by the fact that Gibson is missing a large amount of mass on his left side due to the lack on an arm. His center of mass is no longer on the center line of his body, but instead is shifted to the right. Therefore, as he rotates in the swing, Gibson has to shift and rotate his hips much more throughout the downswing than two-armed golfers for a balanced swing. The lack of a left arm also means that Gibson's right arm does not follow correctly in the downswing. Gibson feels that his arm is disconnected from the rest of his body. A larger hip turn throughout the downswing helps connect his arm and pull it forward. This is why the hips do not have a clear peak in the kinematic sequence.

6.1.3b The X-factor and X-factor Stretch

Even though Gibson has to force his hips to rotate through every swing, his X-factor is in the 40's, similar to that of less skilled golfers[33]. Additionally, his X-factor stretch is usually 0° when golfing one-armed. This is because in the downswing, Gibson immediately rotates his right shoulder forward, along with his hips knowing that his right shoulder already starts too far back and needs to make up the distance. He has to power some of his swing with his arm.

6.1.4 The Impact

Figure 6.6 compares Gibson's impact stance to that of Aaron Baddeley's stance at impact.

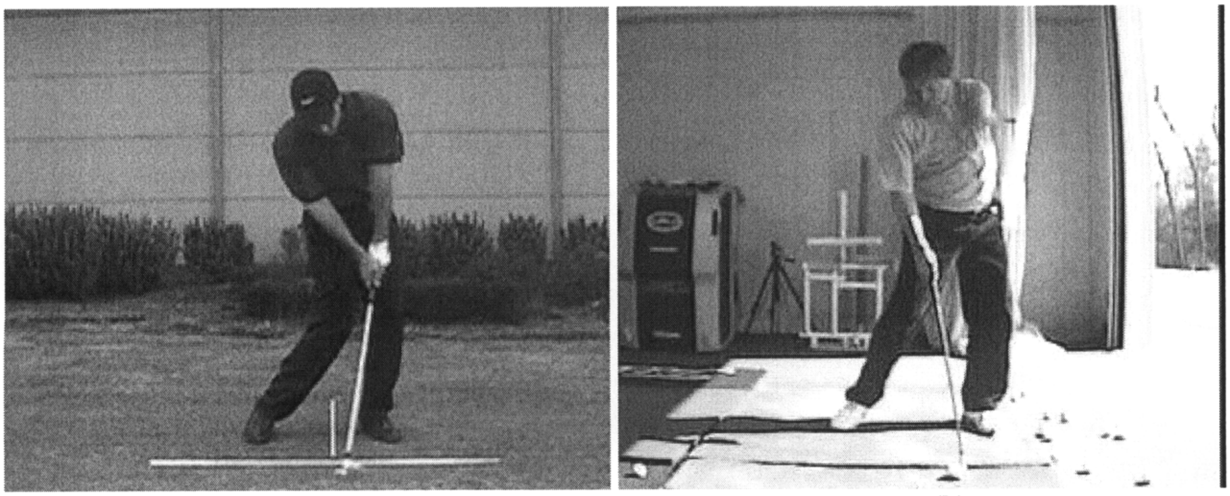

(a) (b)

Figure 6.6 Impact stance for (a) Baddeley[27] and (b) Gibson one-armed

Gibson is able to hit the ball and obtain a stance that is fairly similar to that of Baddeley's. The major difference between Gibson's impact and Baddeley's is that Baddeley's wrists are in front of the clubhead at impact whereas Gibson's wrists are behind the club. Having the wrists in front of the clubhead "allows a golfer to apply a solid compressive force to the ball at impact." [46]

A closer look at Baddeley's wrists reveals that the left wrist is flat while the right wrist is bent. At impact, his left shoulder, his left arm, and the shaft of the club nearly form a vertical straight line. The club shaft lags just slightly behind the arm to hit the ball as the clubhead is moving downward. This ensures a solidly compressed hit that has much better results than a ball that is scooped up, which is what Gibson does.

Gibson, only using his right arm, does not have a bend in his right wrist. The club shaft is inline with the right shoulder instead of the left shoulder like Baddeley's. Although Gibson does not have a left arm, his body and club positioning, in Figure 6.6 implies that his non-existent left wrist would have an inward bend. Jeffrey Mann writes that "[a]ny inward bending (scooping) of the left wrist is a major fault that causes weak shots, plus/minus an inconsistent ball flight due to variable clubface closure through the impact zone." [46] Gibson's stance is similar to that of Baddeley's but because of his wrist position, the results of his swing are much weaker than Baddeley's.

6.1.5 The Follow-Through

Gibson and Baddeley's follow-throughs are shown in Figure 6.7.

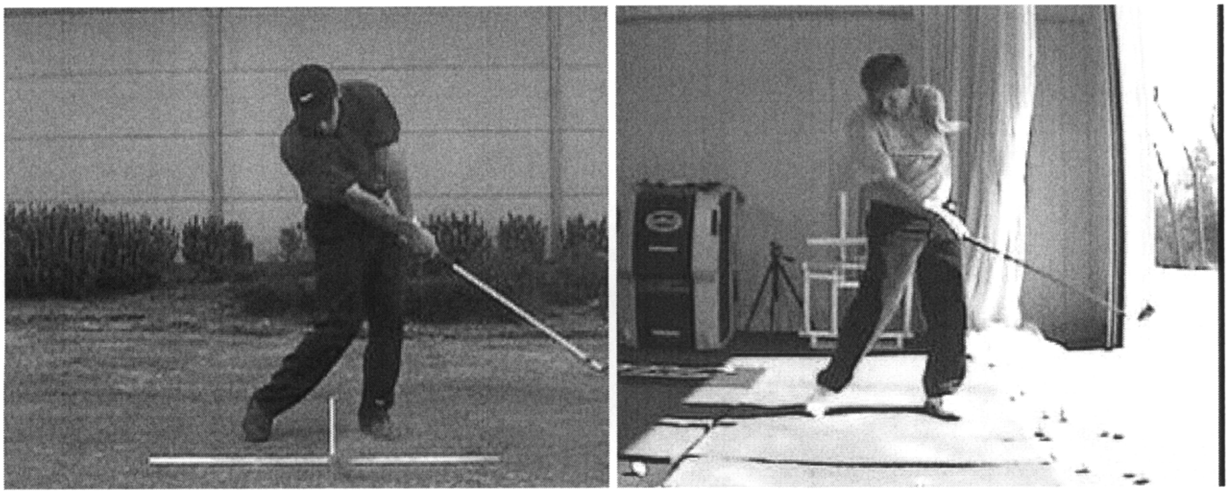

(a) (b)

Figure 6.7 Follow-through for (a) Baddeley[27] and (b) Gibson one-armed

Gibson has a shortened follow-though revealed by the bend in his right elbow, which causes him to pull up. Baddeley, having drove the clubhead though the line of impact squarely, is still fully extended with both of his elbows locked straight.

6.2 Experience with the Golf Pro

Initially, the Golf Pro provided a constraint that seemed beneficial to Gibson's swing. However, after becoming accustomed to the prosthesis, Gibson found that the dynamics of the swing with the Golf Pro did not improve his golf performance to the level he desired; however, he has never fully analyzed why until this project.

6.2.1 The Backswing

During the backswing, the Golf Pro allows Gibson to better control how far his right arm opens up. Because of the coupling's flexibility, Gibson's right arm is still slightly open throughout the backswing, seen in Figure 6.8, but was improved from when Gibson played one-armed without a constraint.

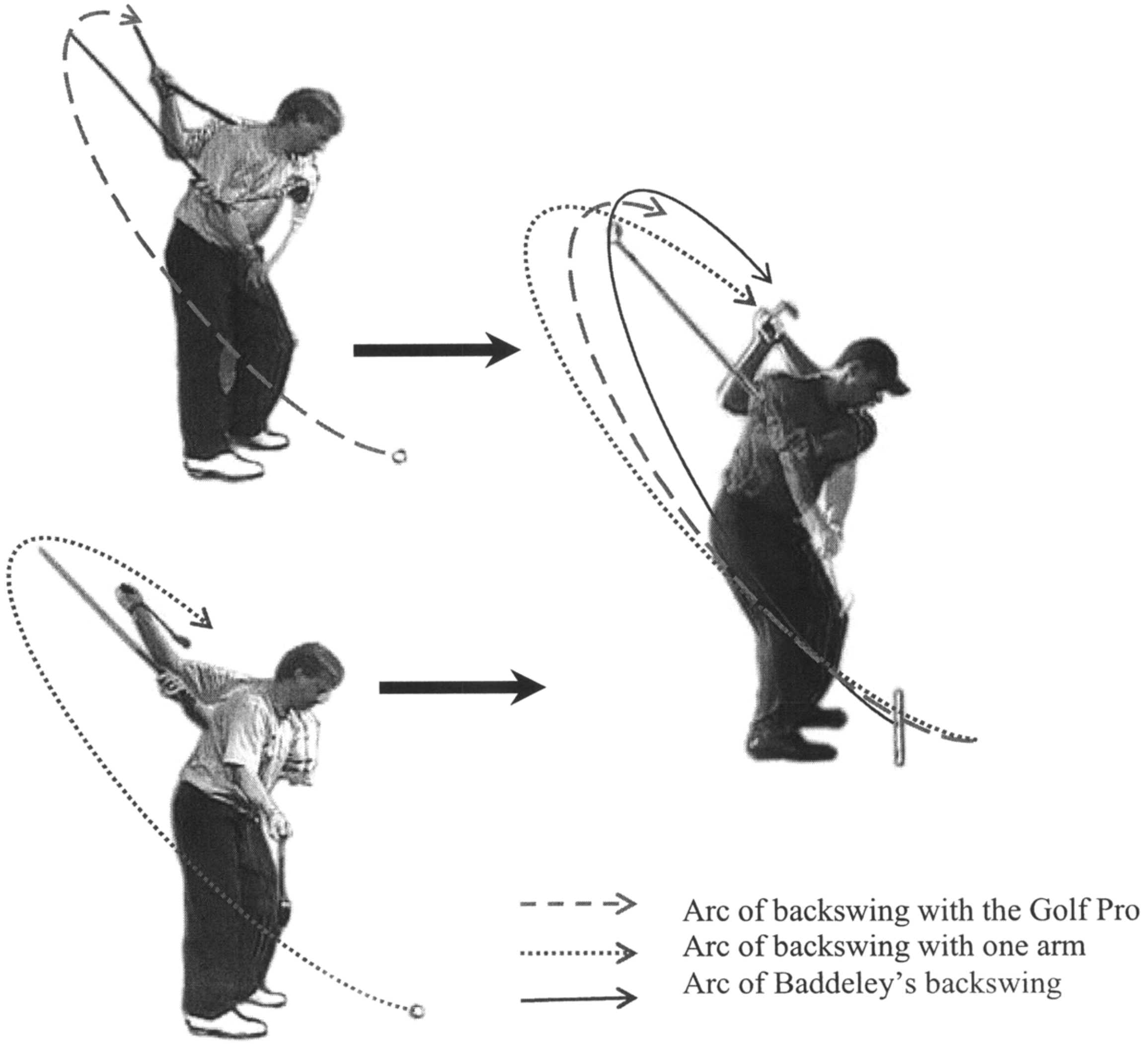


Figure 6.8 Comparison between Gibson's one-armed golf backswing, Gibson's backswing with the Golf Pro and Baddeley's backswing[27]

6.2.2 The Top-of-the-Backswing

Looking in the mirror, Gibson could see how similar the top of his backswing was to that of a two-armed golfer's. Figure 6.9 shows what Gibson saw in the mirror. This gave him the impression that the prosthesis would improve his game.

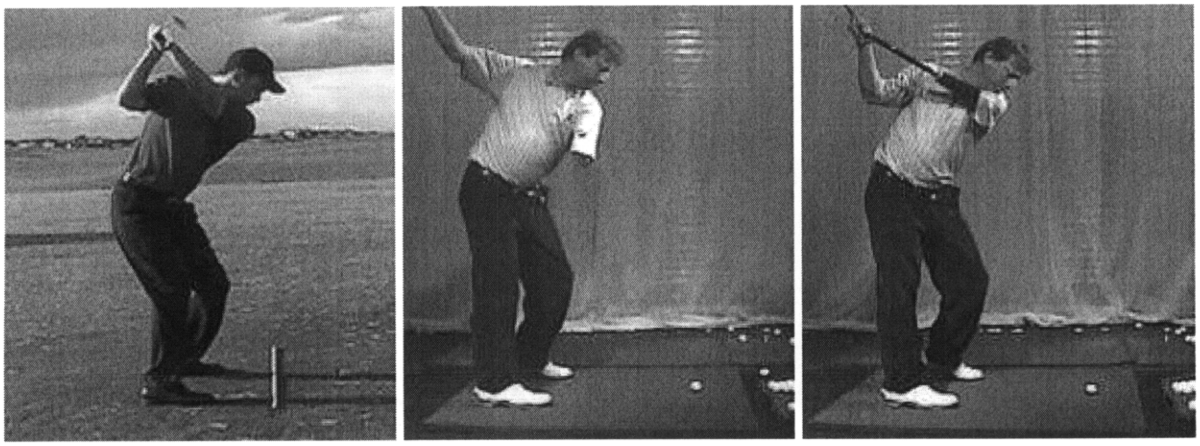
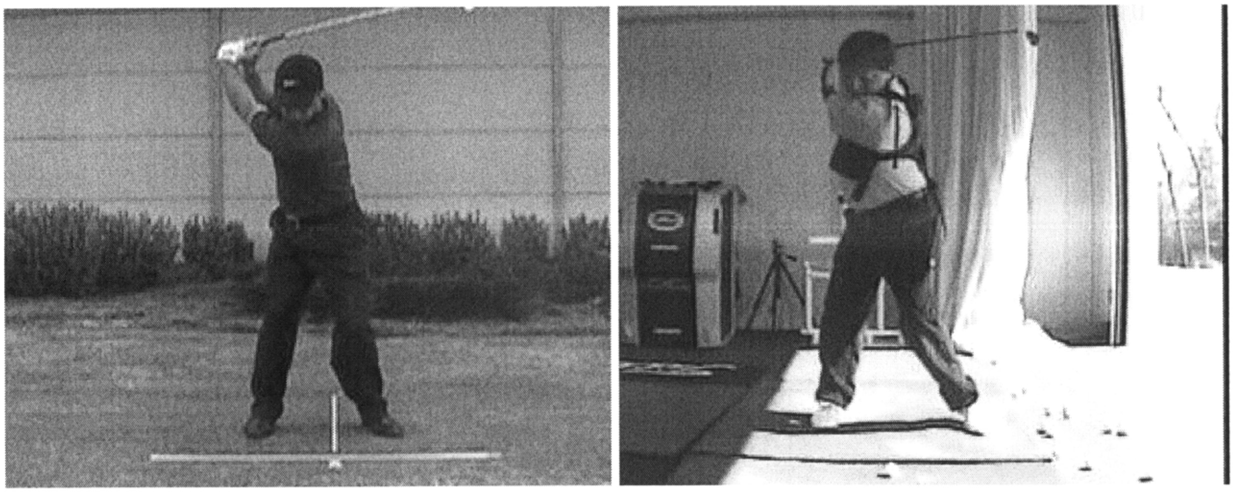


Figure 6.9 Down-the-line view of the top-of-the-backswing for (a) Baddeley[27] (b) Gibson one-armed and (c) Gibson with the Golf Pro

Gibson's elbow is now bent at an acute angle like Baddeley's. Looking at Gibson's top-of-the-backswing from front on in Figure 6.10, it can be seen that Gibson, with the Golf Pro, rotates his shoulders more than Baddeley does his. Because this did not cause Gibson to be off balanced, it did not cause an issue.



(a) (b)

Figure 6.10 Front-on view of the top-of-the-backswing for (a) Baddeley[27] and (b) Gibson with the Golf Pro

6.2.3 The Downswing and Impact

By limiting the amount Gibson's right arm opens in the backswing, the Golf Pro significantly reduces the over-the-top swing fault in the downswing, a problem that was troubling him when he was playing one-armed. However, a new, more troublesome issue appeared in the downswing.

Through the momentum gained in the downswing, skilled two-armed golfers will fully uncock their left wrist to be at a neutral position at impact. The wrist cock is depicted in Figure 6.11.

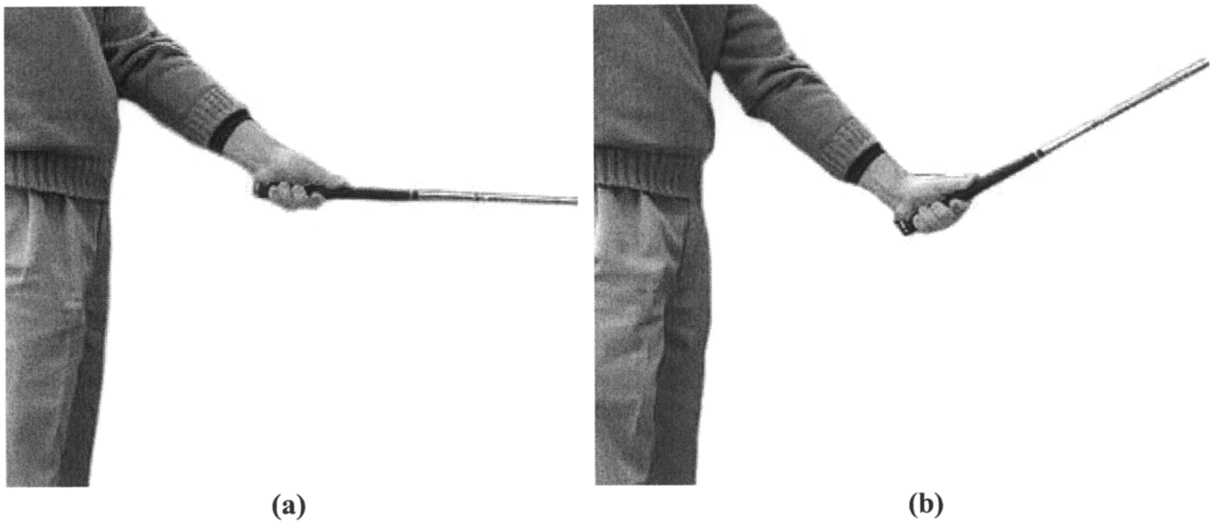


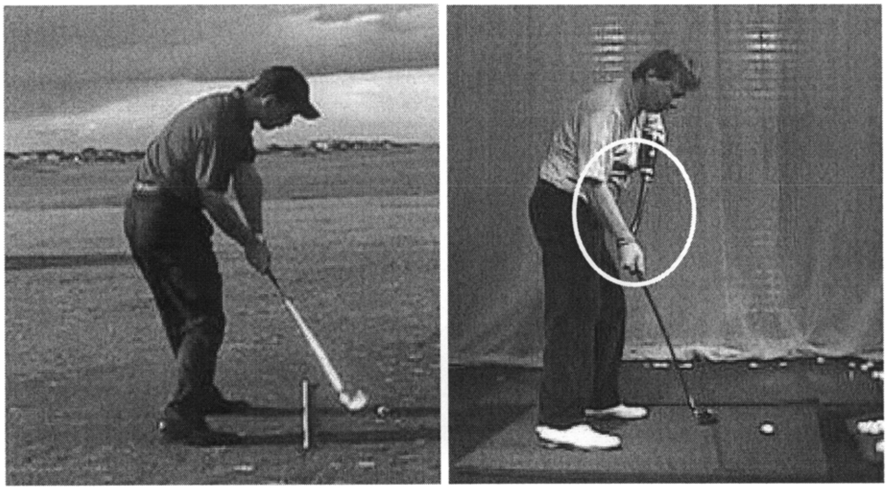
Figure 6.11 (a) Wrist in neutral position and (b) Wrist cocked up[47]

The neutral position is when the top of the forearm is inline with the top of the index finger. An upward wrist cock, where the thumb becomes closer to the forearm, is also known as the radial deviation of the wrist, and a downward wrist cock, where the pinky becomes closer to the forearm, is known as the ulnar deviation of the wrist[47]. Uncocking of the wrist not only makes sure that the clubface contacts the ball correctly, but also adds power to the stroke.

The Golf Pro's neutral position is a slightly cocked anatomical wrist, shown in Figure 6.12.

Figure 6.12 Golf Pro's neutral position compared to the anatomical wrist neutral position[47]

Because of this, Gibson has to use his right hand to force the coupling to bend down to hit the ball at the center of the clubface, as seen in Figure 6.13.



(a) (b)

Figure 6.13 (a) Baddeley in the downswing with a straight left arm[27] (b) Gibson with the Golf Pro in the downswing bending the coupling

The problem occurs from the flexible coupling having enough resistance to prevent Gibson from bending the coupling to a fully uncocked position of an anatomical wrist. This causes Gibson to top the ball. Topping means that the golfer hits only the top half of the ball, resulting in no lift.

Gibson's solution was to use the forearm rotation in the prosthesis setup to lower the clubhead so that he could hit the ball higher on the clubface. This rotation and how it affects the clubface is seen in Figure 6.14.

Figure 6.14 (a) Using the Golf Pro and squaring the clubface, the clubhead is off the ground at impact (b) Using the Golf Pro and closing the clubface, the clubhead is on the ground at impact

By impact, Gibson's forearms are over rotated, seen in Figure 6.15.

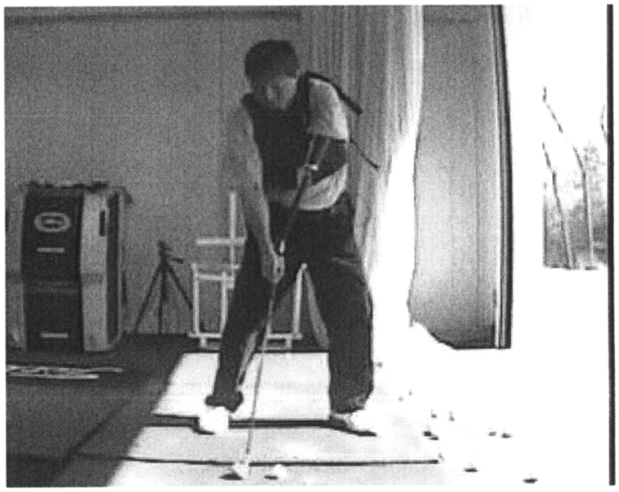


Figure 6.15 Gibson with the Golf Pro at impact with his forearms over rotated

If the clubface had been setup squared to the line of flight, at impact, the clubface would have been closed, not allowing the ball to fly directly towards the target. To avoid this, Gibson started with the clubface slightly open at address so that at impact, it would be squared.

Still, for the solution to work, Gibson's wrists have to end up closer to the right leg and cannot come as forward as he would like to make a nearly vertical line though his left shoulder, arm, and club shaft. This is a weak impact stance.

Another issue with the Golf Pro is that it is capable of bending in the swing plane. At impact, as the clubhead imparts force on the ball, the ball will impart a force back onto the clubhead. The Golf Pro deflects slightly, bending in a direction opposite of the swing and thus causes a loss of energy transfer because the bend absorbs the energy. At an extreme case, it is like hitting the golf ball with cooked spaghetti instead of a wooden board.

6.2.3a The Kinematic Sequence

The kinematic sequence of Gibson's swing with the Golf Pro is shown in Figure 6.16.

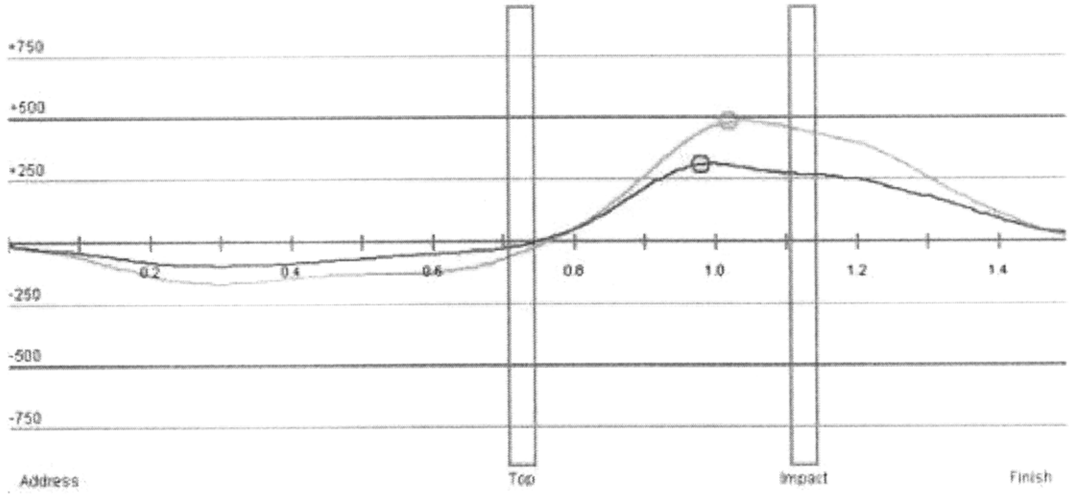


Figure 6.16 Gibson's kinematic sequence with the Golf Pro recorded with iClub's Body Motion System

This kinematic sequence is very similar to his one-armed swing. There is not a clear peak in either shoulder or hip rotation, which means the clubhead speed is not optimized.

6.2.3b The X-factor Stretch

By allowing a greater rotation at the shoulders, the Golf Pro increases Gibson's X-factor stretch by 1°. However, with the Golf Pro, Gibson allows his hips to outpace his shoulders. Gibson believed that the Golf Pro would constrain his swing, which it could in tension, but not in rotation. Therefore, this X-factor stretch is not an accurate measurement of power generation and transfer.

6.2.4 Other Aspects of the Golf Pro

The grip component of the Golf Pro was designed to fit only one size golf club at a certain location on the club grip. Having no adjustability, Gibson could not choke up on a golf club with the Golf Pro, which becomes problematic on a course. Gibson is thus forced to strap the prosthesis on and off every time he needs to choke up on the club. Additionally, only being able to use one size grip was undesirable for Gibson as an instructor. He often grabs different clubs that are around to demonstrate swings for his students. These clubs are not the ones he uses when playing in tournaments, and have different types and sizes of grips.

Other issues relate to the difficulties encountered when using the grip component. It is inconvenient to have to shift where one holds the golf club to slide the component on and off. The process of inserting and removing a club is inconvenient. With no mechanical lock on the grip, how tightly the golf club is held depends upon how hard the golfer jams the club in the component. If not pulled hard enough, the golf club has the potential to rotate about in the grip, and worse, slide out. Additionally, if the ball is hit on the toe of the club, the club will spin in the grip component. To avoid this problem, Gibson tends to pull with more force than necessary so the golf club is securely in place. However, this makes it very difficult to remove the golf club and wears down the inserts. Gibson has broken at least one of his golf club grips trying to remove it from the grip component and says that tightening down the inserts by himself "was a pain." Even when Gibson pulls hard, the club is still able to wiggle because the inserts are not cut to size perfectly, shown in Figure 6.17.

Figure 6.17 Space between the sizing ring and golf club grip

The larger insert holds tightly around the club, but the smaller insert is slightly too big, causing the club to move around in the component.

6.3 Experience with the Modified Golf Pro

Gibson believed the Golf Pro was not improving his performance because of the coupling's flexibility. Even before the start of this project, in an attempt to make the prosthesis stiffer, Gibson had his friend insert a ten inch titanium tube over the coupling. The modified Golf Pro with the titanium tube is shown in Figure 6.18.

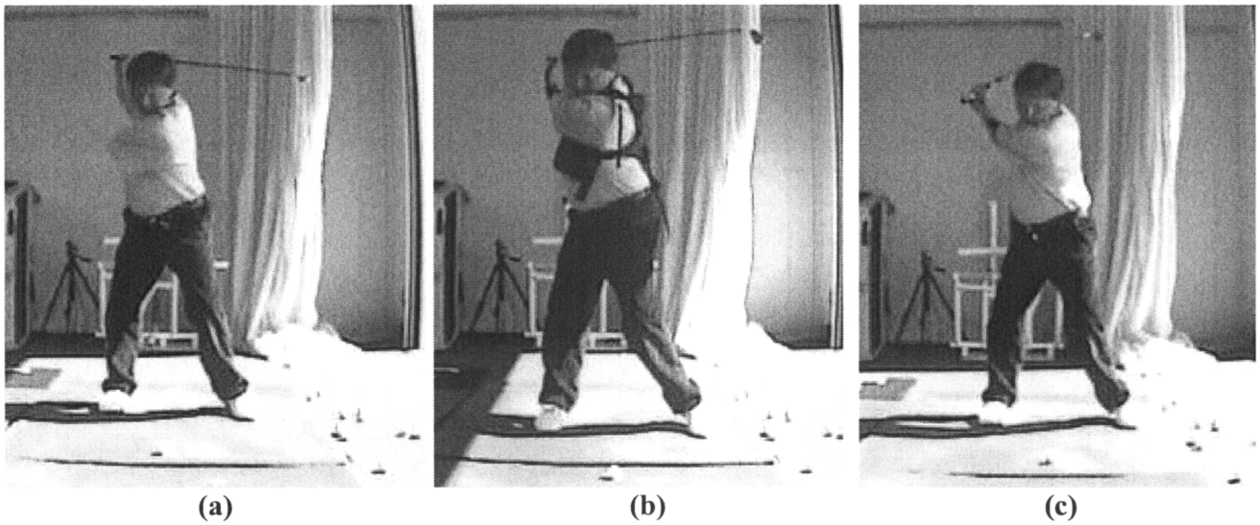
Figure 6.18 Modified Golf Pro with a titanium tube over the flexible coupling

As seen, the titanium tube spans about ten inches and does not cover the entire length of the flexible coupling to allow certain locations to bend. The titanium can either slide over the wrist section, allowing the elbow to bend, or slide over the elbow section to allow the wrist to bend. The impact feels less solid when the titanium is slid over the wrist because the coupling can bend in the plane of the swing more than when the titanium tube is slid over the wrist. Therefore, because the goal of this project is to find the best prosthesis, only this modified version is discussed in this section.

The titanium tube really helped Gibson's swing in some parts, such as the kinematic sequence, but the prosthesis had its share of issues that caused Gibson to stop using his Golf Pro.

6.3.1 The Backswing and Downswing

With the titanium tube cover, the Golf Pro bends less, constraining Gibson's backswing even more than the original Golf Pro, and allows Gibson to have the same amount of shoulder rotation as Baddeley's, as seen in Figure 6.19.



(a) **(b)** **(c)**

Figure 6.19 Gibson's top-of-the-backswing (a) one-armed (b) with the original Golf Pro and (c) the modified Golf Pro

The modified Golf Pro allows him to constrain his backswing and properly allow hip and shoulder rotation. So although his X-Factor stretch reverted back to 0°, the kinematic sequence of the swing, shown in Figure 6.20, reveals that a prosthesis with stiffer components is better for Gibson's swing.

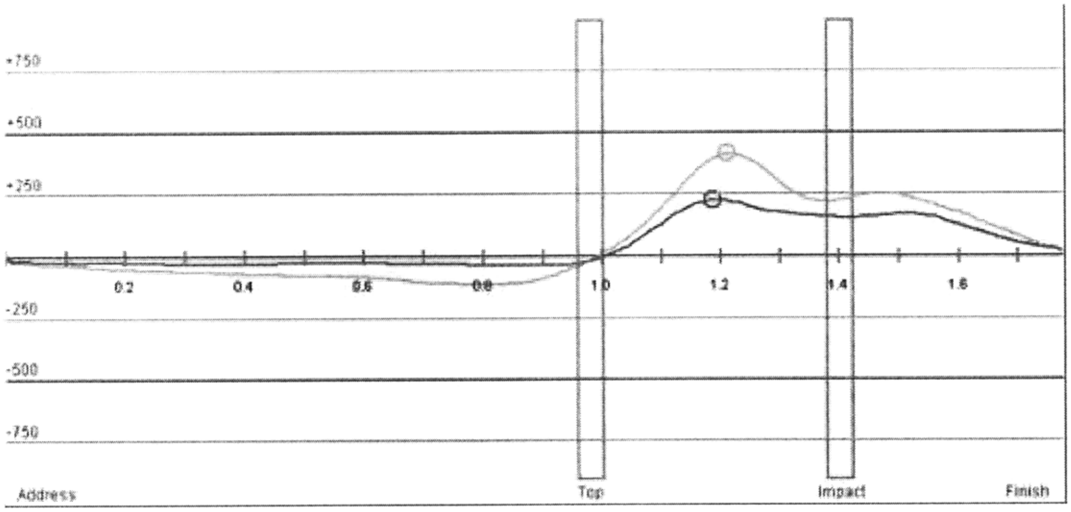


Figure 6.20 Gibson's kinematic swing with the modified Golf Pro recorded with iClub's Body Motion System

The kinematic sequence of a swing with the modified Golf Pro has two distinct peaks with one, the shoulder rotation subsequently higher than the other, the hip rotation. This is characteristic of a swing that will efficiently generate power and transfer it to the ball.

6.3.2 The Impact

The titanium cover helped stiffen the coupling, improving the kinematic sequence of the swing. However, the coupling would still bend and resist bending in the same way as without the titanium tube. Therefore, it still had issues with topping the ball and Gibson still had to compensate for this by flipping the clubface closed.

6.3.3 The Follow-Through

Gibson's follow-though with the titanium tube is shown in Figure 6.21.

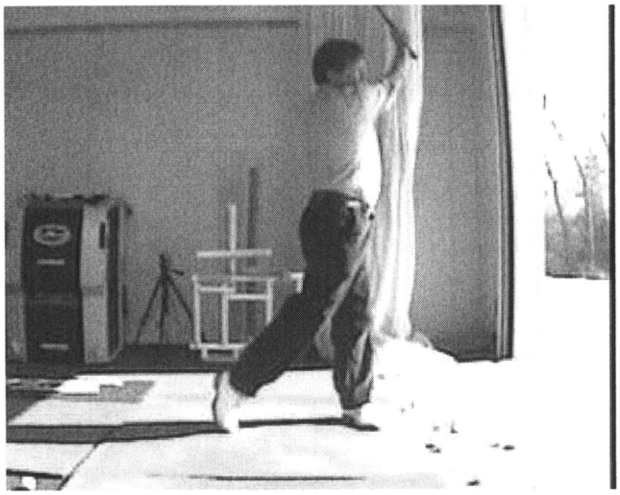


Figure 6.21 Gibson's finish with the modified Golf Pro

Gibson is unable to bend the prosthesis as much as he needs for it to decelerate the swing to a stop properly. It causes him to stop abruptly with too much energy left, which results in pain as the brunt of the force is absorbed by his residual limb. A proper follow-through should result in something more like Figure 6.22.

Figure 6.22 Baddeley's finish[27]

Baddeley's whole body is rotated with the elbows bent. This gives him the max travel distance to reduce the speed of the club instead of the abrupt finish that Gibson experiences when he uses the modified Golf Pro.

7. Design Objectives

Two-armed golfers achieve more accurate and powerful swings than one-armed golfers. Therefore, the project goals were to understand the needed degrees of freedom, where they should be located, and how they should be constrained in a prosthesis to enable Gibson to golf with dynamics like that of a two-armed golfer's. The prosthesis should constrain the swing properly to improve his golf performance, allow Gibson to use the same techniques as a two-armed golfer to improve his swing, and permit direct compare Gibson to other two-armed golfers. Enough degrees of freedom need to be incorporated so that Gibson can accommodate for the various scenarios he will face on the course. Nevertheless, the prosthesis should not have too many degrees of freedom or degrees of freedom that are not properly constrained. Otherwise, with one arm, Gibson will not be able to control the prosthesis, causing accuracy, consistency, and power issues.

In addition to understanding the correct motions needed, the project aspires to allow Gibson to continue to enjoy golf just as well as when playing one-armed, if not more. The prosthesis should be effortless to use and controlling it should easily become second nature so that Gibson does not have to focus on the prosthesis, but instead just focus on playing the game.

The project does not aim to give Gibson an unfair advantage over two-armed golfers by designing a prosthesis that has capabilities beyond an anatomical arm. The prosthesis should put Gibson on an equal playing field with two-armed golfers because of its ability to provide an extra constraint that two-armed golfers have, but Gibson lacks. It should not incorporate extra energy storage or additional constraints that would make his swing more powerful and accurate than what can be achieved by a skilled two-armed golfer. Otherwise the arm could cause controversy as to whether or not it is fair for Gibson to use in a tournament with two-armed golfers. Part of the enjoyment of golf is the camaraderie, so this prosthesis should allow Gibson to have more opportunities to play with other golfers and fit in.

8. My Journey

The nature of this project was extremely challenging because I have both of my arms, had not played golf before, and had little prior knowledge of prostheses. A deep understanding and mastery of all three of these seemed necessary to develop a prosthesis that would allow a one-armed professional golfer to play more proficiently. Initially, I was overwhelmed by the broadness of each of these subject areas and was often unsure if I was gathering the right information and proceeding in the best direction. Yet, that is the nature of product development. One has to gather a breadth of information quickly about subjects and then be able to ascertain what is most important and deciding the best way to continue.

Simply using motion capture software is not sufficient to deduce the motions that a prostheses needs to enable Gibson to swing with the dynamics of a two-armed golfer. The software allows for direct comparison between Gibson's one-armed swing and a two-armed professional golfer's swing. However, just knowing the positions of the body segments over time is not enough information. The movements of each body segment captured are not fully independent of each other so the root causes of the motions were needed. It was necessary to uncover and understand how the movements were achieved so the correct dynamics can later be built into the prosthesis. For example, during the swing from the vantage point of a spectator that is viewing the golfer from a frontal view, a golfer will rotate his forearm 90° between the time of impact to the fullest extension point in the follow-through. This was caused not just by forearm rotation, but also a combination of torso and shoulder rotation. Understanding how each of these factors contributes to the rotation of the forearm helps dictate the movements that are needed in the forearm portion of the prosthesis.

Humans move by consciously thinking about generalized motions, such as "grab that cup" or "walk," but specific path and movement of each joint is subconsciously carried out. When walking, a person does not think about how high to lift his or her foot of the ground, how the angle of the knee changes over time, which muscles are actuated, or the timing needed to accomplish a step. To achieve a golf swing, the golfer does not dictate how each joint moves. Instead, he or she learns key positions of the arms and clubs that are necessary to swing though and the movement is carried out subconsciously by the mind. This allows for a natural, powerful swing, but it makes it difficult to understand the dependencies of each action easily.

The greater purpose of this project was to help develop a fully functional and refined prosthesis for Gibson and other amputee golfers. The prosthesis needed to be functional, intuitive to use, comfortable and possible to manufacture. Therefore, beyond just determining the dynamics needed for Gibson to golf as a two-armed golfer, considerations of how these dynamics would manifest themselves in a prosthesis design were examined.

8.1 Initial Briefing

A phone conference was initially held between Bob Radocy, Michael Gibson, Daniel Frey, and myself. The purpose of the call was to connect with all of the stakeholders, find out more about TRS's golf prosthesis design, gather user feedback about the Golf Pro, and to gain greater insight into the direction of the project. Online searches had yielded very little information about the Golf Pro besides its features and recommended users. There were no records detailing how well the Golf Pro worked, what users felt about its strengths and weaknesses, or what features users thought could be improved. This information was needed to provide a direction for the research.

8.1.1 TRS's Motivations and Recommendations

TRS strives to produce quality products for its client base and wanted to pursue a more thoroughly engineered design to deliver better performance for transhumeral golfers. TRS felt that the initial transhumeral Golf Pro worked well, and incorporated concepts that seemed beneficial to the golfers, however, they never performed studies with transhumeral golfers to quantify how well the design worked. They knew that more in-depth research and analysis would further improve the function of the Golf Pro in future designs. Radocy was looking to improve the performance of the Golf Pro, without adding complexities to the manufacturing process. He preferred the continued use of an elastomeric material as the flexible coupling because of its potential to help amputee golfers with its spring-like properties. Continuing the use of the polymer would also be advantageous for TRS because the company already has the capabilities set in place to manufacture it. However, TRS knew that the current cylindrical shape of the coupling was not ideal for golf and wanted the project to explore other shapes that would allow localized bending in the appropriate directions to optimize the energy storage and release capabilities of the prosthesis. Manufacturing many types of prostheses for various activities, Radocy was also interested in designing concepts that could be applied to golf prostheses used by other transhumeral and transradial amputees, not just by Gibson, and even potentially applying the concepts to other sport prostheses.

8.1.2 Gibson's Motivations and Recommendations

Being the user of the Golf Pro, Gibson was looking for improvements upon the prosthesis' functionality, usability, and comfort so that he could increase his golf performance. The flexibility of the coupling in the original Golf Pro had hindered his performance, so he had a friend insert a titanium tube over the coupling to limit its flexibility. Although this did allow Gibson to hit balls further, it did not resolve issues with controllability and also made his swing more uncomfortable. This, in addition to irritation caused by the chest strap used to prevent the socket from rotating about his residual limb, was a distraction to Gibson as he was playing golf. Lastly, Gibson desired more adjustability in the grip component to add compatibility for all golf clubs and to allow him to change where he grips his club for certain shots.

8.2 Seeking Expertise

After the phone call, individuals with expertise in golfing and prosthesis production were sought and consulted with to gain background knowledge. Face-to-face meetings allowed guided conversations in areas that were more pertinent to the research and questions were addressed immediately to allow for instant clarification on issues that were unclear. These meetings also allowed for hands-on interaction with products, such as other prostheses, sockets, and golf clubs, to understand their functionality better and how users interact with them.

8.2.1 Meeting with MIT's Golf Coach

The complexity of golf is testified to by the sheer number of books published about golf technique and the number of golfers seeking professional trainers to improve their game. Realizing that it was possible to read book after book about golf and still not fully understand the essence of the game, I contacted Bruce Chalas, the head coach of the MIT golf team. At MIT's indoor golf range, Chalas demonstrated the basics of golf, detailed techniques that might be of use to me, and allowed me swing and hit golf balls. From him, I learned the importance of each part of the swing and that a good swing should feel natural and well-balanced.

8.2.2 Initial Meeting with Gibson

The one question that Chalas could not answer was what it would be like to golf one-armed. Because the swing is sensitive to small deviations, it seemed impossible for someone who only had one arm, with more degrees of freedom to control, to golf anywhere near as consistently and accurately as a two-armed golfer. I found it extremely difficult to understand how Gibson could possibly play golf well with just one arm, preventing me from being able to proceed with the project. Accordingly, I contacted Gibson to set up a meeting with him at Harmon Golf.

There, I was surprised by how well Gibson related to my situation and how easily he could explain how he played golf one-armed. When he first began playing, Gibson read a lot about golf and had two-armed friends teach him techniques. Most of the advice stemmed from an understanding of two-armed dynamics, so Gibson had to spend a lot of time at the driving range trying a variety of the tips and seeing which ones were actually compatible with his dynamics. Instead of focusing on the fact that he was missing a limb, he started thinking of the swing from a more technical point of view. He knew that he needed to square the clubface to the intended line of flight at impact and looked at it as a constraints problem. He had a different set of initial conditions than most golfers, but there was still some set of dynamics that would allow him to obtain the desired outcome. Working with this mindset, he continued to improve his swing.

Looking at Gibson's swing as a physics problem that dealt with geometries and constraints, I saw how it would be possible for Gibson to have found a set of dynamics that he could control. Granted that this set of dynamics was not exactly like that of a two-armed golfer's, it still allowed Gibson to golf fairly accurately and consistently. Being able to relate to Gibson, we then started to talk about how having two arms would allow him to achieve better performance.

This is when I learned that Gibson had stopped using the Golf Pro and had reverted to playing one-armed. From the initial phone conversation, I knew that there were problems with the Golf Pro that Gibson wanted addressed, but had not realized that they had made him stop using the prosthesis entirely. He had high hopes for the Golf Pro and had sincerely tried working through the issues that he encountered. Gibson attributed most of the issues to the flexibility of the coupling. However, Gibson's modifications to try and fix the flexibility of the coupling did not fully solve the issues and new issues arose. It was not until further analysis that we were able to detail exactly how the Golf Pro negatively affected Gibson's swing.

8.2.3 Meeting with Prosthetist

Looking for more information on prosthesis, I visited Luke Richards, a prosthetist at the Boston VA hospital. I wanted a better understanding of prostheses, why someone would choose one prosthesis over another, what considerations should go into a golfing prosthesis, if amputee veterans were interested in learning golf, and if he had any suggestions that would help Gibson prevent rotation of the socket without the use of a strap.

Although many of the veterans were being fitted with microprocessor-controlled prostheses, these specific prostheses tend to be heavy and not fast enough for golfing purposes. Therefore, Richards recommended a purely mechanical arm, and because the prosthesis was for an upper-extremity amputee, it was critical for it to be as lightweight as possible. We discussed using a suction liner with silicone bead valves to stop the rotation of Gibson's socket, but unfortunately, the liner was only manufactured for lower-extremity limbs and did not work with Gibson's socket.

8.3 Initial Approach

After meeting with Chalas, Gibson, and Richards, I felt like I had enough background to begin the process of designing a prototype. Because the main issue with the Golf Pro was its flexibility, I decided the first step should be to build a rigid prototype and compare it to the Golf Pro. I wanted to design a model that could be directly compared to the Golf Pro, so the design needed forearm rotation, an elbow joint, and a wrist joint.

8.3.2 Identifying Constraints

The two main two constraints that needed to be accounted for in this prototype were the size of the prototype and the robustness of its components. Limiting the size was important to prevent the prosthesis from impeding motion or burdening the wearer with unnecessary weight. The components needed to be robust to ensure that impact forces from the club hitting the ball would not cause them to fail.

Not having a good sense of the impact force, I was concerned that my prototype would not be durable enough. Hence, I tried to analytically determine the stresses that would occur in the components of the prototype at impact. This process was complex, took a fair amount of time, and I ended up getting results that seemed physically impossible. Incorrect assumptions drastically affected the results of the calculations. This and the fact that I ended up spending a lot of time designing mechanisms that I knew could not be used in the actual prototype caused me much frustration, so I decided to change my approach. It would have been much easier to determine if the prototype would withstand the impact forces of golf just by performing bench level experiments.

8.4 Bench Level Test 1: Confirming Double Pendulum Model

Previously, in order to get a feeling of what sort of stresses would be in each component, arbitrary mechanisms were designed without knowledge of the actual motions that were needed in the prototype. Changing my tactic, I decided to begin by focusing on determining the motions that are needed in a prosthesis, find mechanisms for the prosthesis that would allow it to provide those motions, and then test the mechanisms to see if they are robust enough, rather than using calculations.

With additional research, I found Isogolf's website which explained the biomechanics involved in the swing and how to model the downswing as a double pendulum. The upper segment of the double pendulum consists of the entire left arm, which pivots at the wrist and connects to the lower segment consisting of the club. Figure 8.1 shows the double pendulum model depicted over Aaron Baddeley.

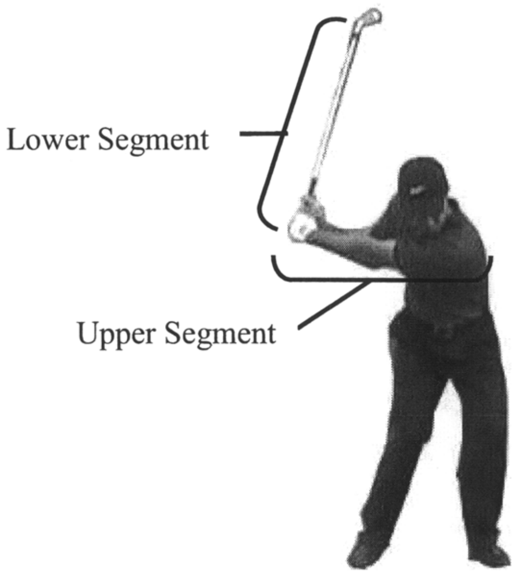


Figure 8.1 The double pendulum model for the downswing[27]

This model was first discussed by Rod White in the American Journal of Physics. According to White, "the wrist-cock angle is the most significant efficiency-determining parameter under the golfer's control." [48] From this, it was deduced that the prototype needed to incorporate a wrist joint that allows it to pivot. Because the model was only valid for the downswing, it was still questionable if an elbow joint or forearm rotation was needed.

To answer these questions, a simple wooden prototype was built. Although I was not an expert on golf, I wanted to test what combination of movements would result in the most natural feeling swing and then apply what I learn to a prototype for Gibson.

8.4.1 The Design

The design, shown in Figure 8.2, had an unrestricted elbow joint and wrist joint.

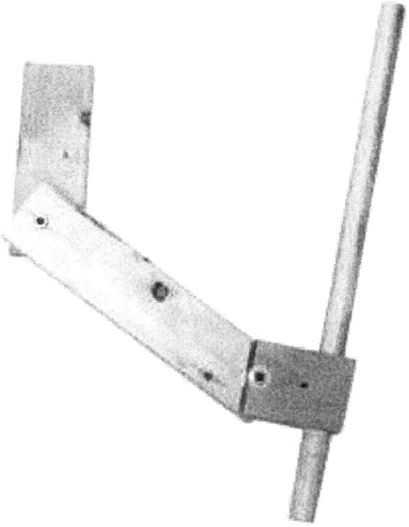


Figure 8.2 Bench level test 1: wooden prototype

The upper and lower arms were comprised of two wooden ¾" x 2 ½" slats that were loosely pinned together. The upper slat was 6.5" long and the lower one was 10" long. A 1 ½" x 2 ½" x 3" wood block, acting as a clenched hand, was pinned to the lower slat to form a wrist joint that could cock up and down. A hole was drilled out of the hand piece to fit a 7/8" inch diameter PVC tube that represented a golf club. The pieces were roughly dimensioned to my anatomical arm and there was no mechanism for forearm rotation. The device would attach to the inside of my left arm with an elastic bandage wrap, as seen in Figure 8.3.

Figure 8.3 Bench level test 1 attached to tester with an elastic bandage wrap

Shown in Figure 8.4, another elastic bandage wrap could be used to wrap the upper and lower slats at the elbow joint to prevent it from bending.

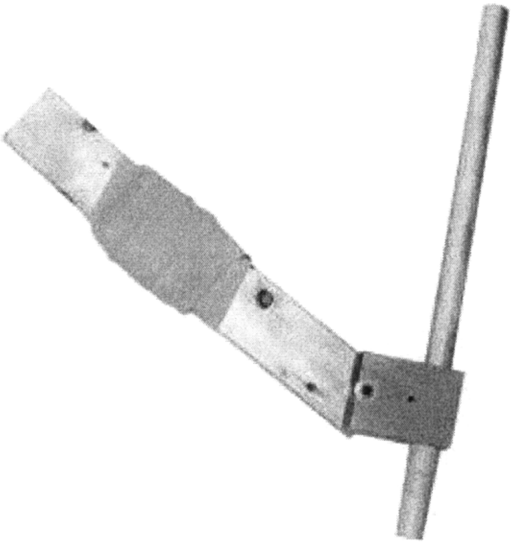


Figure 8.4 Elastic bandage wrapped around elbow joint

8.4.2 Conclusions from Testing

Without the elbow wrapped, there was no way to position the club correctly at the top-of-the backswing. At this position, a two-armed player's right hand pulls the straight left arm as far around the body as possible. Muscles in the left arm, not the right hand, keep the elbow from bending. However, with an unrestricted joint, such as the one in the wooden prototype, one of two situations occurs. Either the right arm pulls the left arm away from the body to keep it straight, or the right arm tries to pull the left arm around the right side of the head and the left arm bends and does not constrain the position correctly. Neither pose, shown in Figure 8.5, was ideal.

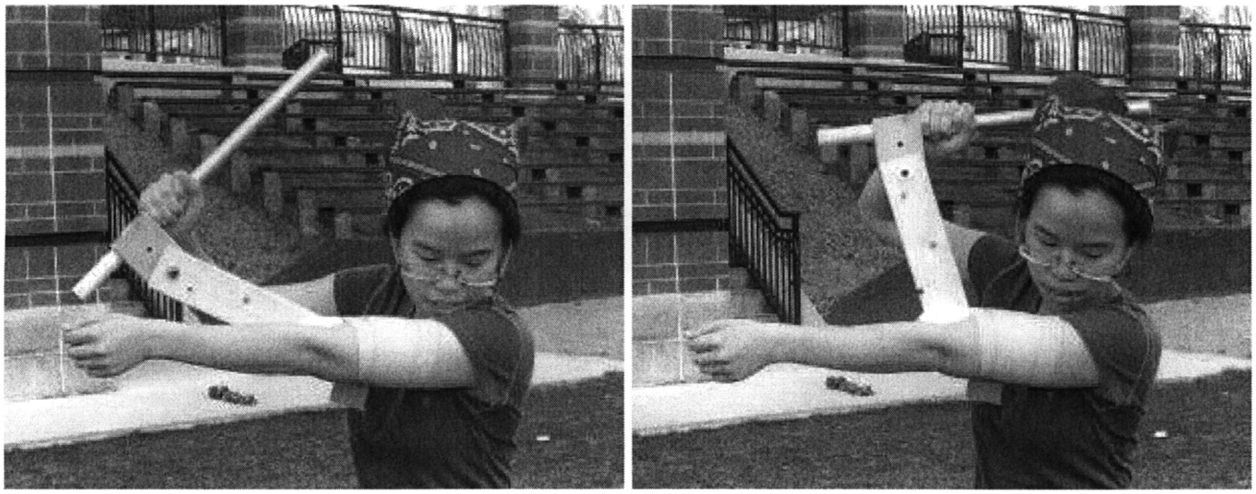


Figure 8.5 (a) Right arm pulling the prototype straight and (b) Right arm pulling the prototype around the head and the prototype bending at the elbow joint

Another observation was that with the elbow free to pivot during the downswing, the elbow would rotate beyond a straight 180° position. This not only caused energy loss, but also caused the follow-though to feel awkward. Normally during the follow-though, the golfer bends his elbow and the distance between the hand and the shoulders shortens. With the elbow beyond 180°, the arm must pivot back through its maximum extension before bending like an anatomical elbow.

Testing with the elbow locked, the backswing and downswing motion were constrained well and seemed to be what Gibson had described as needed. The shortcoming was that the swings ended very abruptly. From this, it was presumed that the elbow mechanism needed to keep the arm straight through the back and downswing, but bend in the follow-through.

During these tests, the top slat was exerting a lot of pressure on the upper arm trying to force it to rotate during the follow-through. I started to rotate my whole body to alleviate the pressure, but this was incorrect form. It seemed like forearm rotation was also necessary.

8.5 Bench Level Test 2: Mechanism Design and Robustness Testing

The intension of the next prototype was to incorporate the findings from the previous test with the wooden prototype and see if certain mechanisms could withstand the impact forces. The goal was to take this prototype to a driving range, examine how the motions felt, see if it was possible to hit a ball, and test if the chosen mechanisms would break.

8.5.1 The Design

The overall design of this prototype is seen in Figure 8.6.

Figure 8.6 Bench level test 2

The prototype was attached to my arm by an armband that I had sewn and riveted together. The upper box extrusion was 6.5" in length, long enough that I could attach it comfortably to the inside of my left arm and have the elbow joint at the same level as my anatomical elbow. The lower box extrusion was 8" long, and was the length of my anatomical lower arm. Specifically, the measurement taken was from the inner part of the arm when the elbow was bent 90°. This prototype still had no mechanism for forearm rotation.

8.5.1a The Elbow

The elbow mechanism needed to allow the upper and lower arm segments of the prosthesis to remain straight throughout the backswing and downswing, but be able to bend during the follow-through. The first option reviewed was commercially available detent hinges. These hinges have built in soft stops to allow the hinge to remain open or closed at certain angles. Because a human elbow can bend about 145°, the specific detent hinge for the prototype had to have detents at 35° and 180° [49]. However, none of the detent hinges available were within the size constraint nor had detents at the correct angles. Making a bistable switch seemed like the best option for the elbow joint.

There were many considerations to take into account when designing the bistable elbow for this application, such as what the spring constant of the springs should be, the initial length of the springs, and how the springs should be positioned relative to the pivot. Needing a quick way to understand how each parameter would affect the bending kinematics of the elbow, a test setup was made.

The test setup consisted of two 1" x 1" box extrusions, both having a gird of holes drilled in them. The two box extrusions were connected together by a piano hinge. Different configurations of the bistable switch could be achieved by using screws to attach a pair springs in different arrangements to the box extrusions. See Figure 8.7 for the set up.

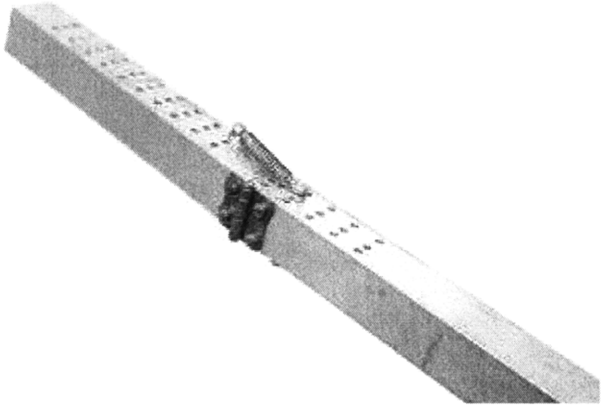


Figure 8.7 Setup for testing the bistable elbow joint

Detailed dimensioned drawing of the test setup can be found in Appendix A.

Although I was skeptical that a piano hinge could handle the impact forces of a golf swing, many aspects of it were perfect for the application. The hinge would help constrain the joint from rotating past 180° and it was available in a size small enough to fit onto the 1" x 1" box extrusions without protrusions past the sides of the box extrusion, thus preventing it from scraping and poking the golfer. I decided to try the piano hinge for this prototype and test its robustness at the driving range.

8.5.1b The Wrist

A quarter inch shaft served as the pin joint in the wrist. The wrist joint is illustrated in Figure 8.8.

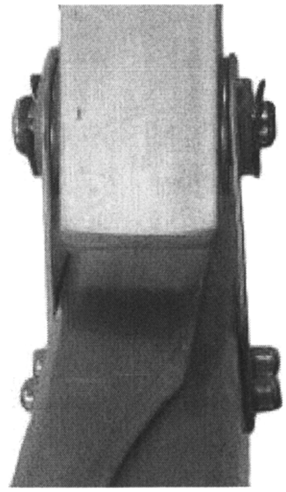


Figure 8.8 Front-on view of the wrist joint

The shaft ran through a nylon bearing on each side of the lower box extrusion and was fastened on each end by e-clips. Between each nylon bearing and e-clip was a 1"x 2"x 1/8" aluminum metal strip that was also riveted to the grip mechanism.

8.5.1c The Grip

Not much prior thought had been put into grip mechanisms until this prototype. Many vice-grip-like mechanisms, cams, and clamps were researched, but they all seemed overly complicated for an early stage prototype. Strapping a golf club into a tubular channel seemed like the best option. However, this configuration was not ideal because it would not account for alterations in tapers or differently sized golf grips. Additionally, it would not properly constrain the club without sizing rings.

In the end, two 1"x1" angle brackets were used for the grip mechanism, seen in Figure 8.9.

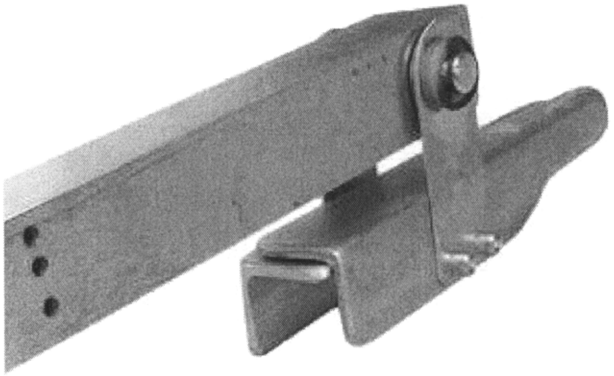
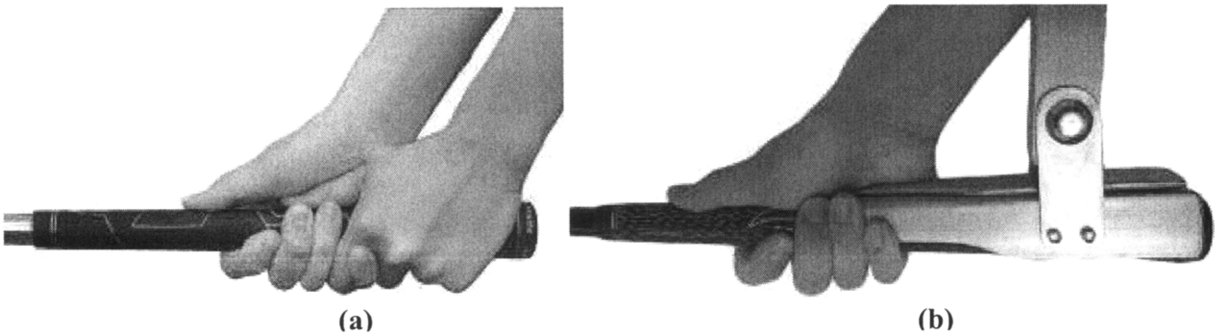


Figure 8.9 Grip mechanism made of two angle brackets

The angle brackets are configured in an upside down u-channel to allow for easy insertion and removal of any golf club. Hose clamps were used to secure the golf grip in the channel. To accommodate for both variations in tapers and sizes of golf clubs, the top edge of each angle bracket was cut down at an angle. This setup would also allows for the user to choke up on a golf grip. The grip component was machined so that the minimum inner width of the back of the component would be 0.84" while the width at the front would be 0.59". This allows for gripping down to reasonably small diameters. The length of the grip component was designed to incorporate both the length of a fist and the thumb because the most common handgrip is the interlocking grip, depicted in Figure 8.10.



(a) (b)

Figure 8.10 (a) The interlocking golf grip and (b) the grip with the grip component

In the interlocking grip, the little finger on the trailing hand is intertwined with the index finger on the lead hand and the palm of the trailing hand cups the thumb of the leading hand.

See Appendix A for detailed dimensioned drawings of the grip component.

8.5.2 Conclusions from Testing

Swinging the prototype outside in a park, I found that the 1 ¼" springs in parallel were not stiff enough. During the backswing and downswing, the elbow did not remain straight. After changing to stiffer springs the elbow would still flex. I decided not to change anything until Gibson tried the configuration, but if necessary, more springs could be added.

The trip to the driving range proved it was possible to use this prototype to hit golf balls, but because the armband was slightly loose, it was hard to gather additional information. Overall the motions provided by the prototype felt correct, and the next step was to allow Gibson to test them.

8.6 Prototype I: Initial Prototype for Gibson

There was a variety of feedback that I wished to gather from this first prototype for Gibson. This included how the overall device felt, if the swing felt natural, how much of Gibson's swing dynamics were changed, if the changes seemed positive, and what design flaws he noticed. More specifically, feedback about the bistable elbow and forearm was necessary.

8.6.1 The Design

The design of this prototype was very similar to the second bench level design except that the dimensions of the overall device had to change to fit Gibson's body measurements and the attachment interface had to be compatible with his socket. The prototype is shown below in Figure 8.11.

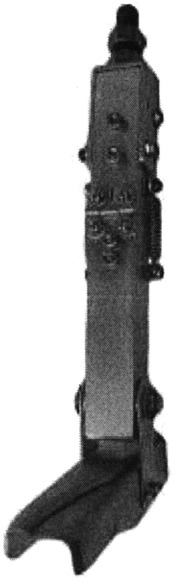


Figure 8.11 Prototype I

8.6.1a The Attachment Interface

For the purposes of this project, there was no need for Gibson to obtain a new socket, especially because Next Step had spent so much time designing his current one for him. Because the socket would only accept a ½”-20 post, a 2” long ½”-20 bolt was used as the attachment mechanism. To connect the bolt to the prosthesis, a cap was constructed by cutting a 1 ¼" x 2 ½" rectangular aluminum extrusion. A nut fixed the bolt in place against the cap, while two screws fastened the cap to the upper box extrusion. The attachment components are depicted in Figure 8.12.

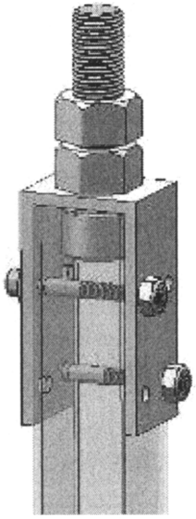


Figure 8.12 The attachment interface with the socket

The bolt was 2” long to allow for two nuts to be on the bolt while still having enough exposed threads for the socket to attach onto. The purpose of the second nut was to allow testing of forearm rotation. Tightening the nut against the socket, as is in Figure 8.13, would fix the prosthesis in a certain orientation and prevent rotation.

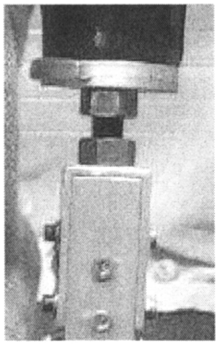


Figure 8.13 Second nut tightened against the socket

The bolt and nuts made the attachment mechanism the heaviest part of the prototype.

8.6.1b The Dimensions

After getting the dimensions of Gibson's right arm and comparing it to the dimensions of his residual limb with the socket on, it was discovered that his socket extended an inch beyond where his anatomical elbow should be located. Although it was desired for the elbow joint of the prosthesis to be close to where his anatomical elbow would be, room had to be allocated for both the attachment mechanism and the springs for the bistable switch. As illustrated in Figure 8.14, the elbow mechanism in actuality was about five inches below where Gibson's anatomical elbow would be.

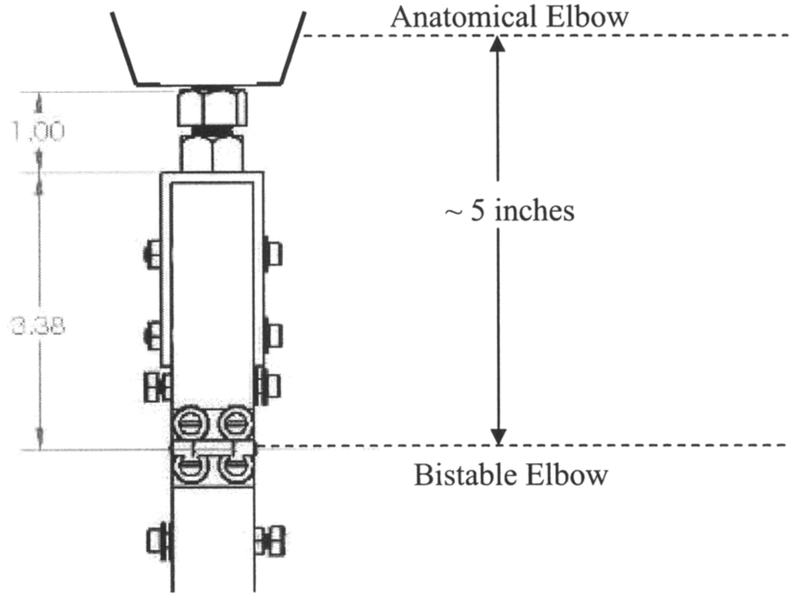


Figure 8.14 The bistable elbow in relation to where Gibson's anatomical elbow would have been

This caused the lower box extrusion to be much shorter than expected, as seen in Figure 8.15.

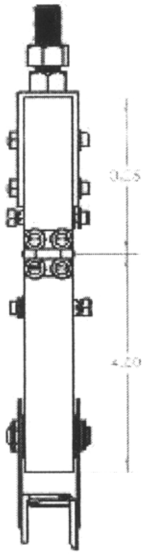


Figure 8.15 Dimensions of prototype I

See Appendix A for fully dimensioned drawings of prototype I.

The overall length of the prosthesis was designed to be about two inches shorter than Gibson's anatomical arm because the left hand grabs the golf grip about two inches higher on the grip than the right hand.

8.6.2 Initial Testing with Gibson

A voice recorder and a video camera were taken to Harmon Golf to capture videos of Gibson's swing and to record how Gibson described what was happening. This was also useful for acquiring golf terminology because I had never played golf before and was unfamiliar with the language used. Initially, the prototype was not explained to Gibson except for how it would attach. This was done to see how efficient the use of the prosthesis was for a new user.

8.6.2a Determining the Necessity of Forearm Rotation

I had Gibson start out the test by using the prototype with a miniature club to get comfortable with the motions of the prosthesis, as well as to make sure that I could gain some feedback before he began hitting balls in the event that the prosthesis broke upon impact. Looking at himself in the mirror, the first thing Gibson noticed was his impact stance. It caught his attention that he could make a line from his left shoulder, through the prototype, and along the club shaft. He had never been able to achieve that position before.

As Gibson was swinging with the miniature club, Tom Cavicchi, the director of Harmon golf who had been a PGA Golf Professional for over 30 years, was in the room and pointed out how the prototype should rotate. Figure 8.16 shows Cavicchi working along side Gibson and demonstrating how Gibson's arm should be positioned at address.

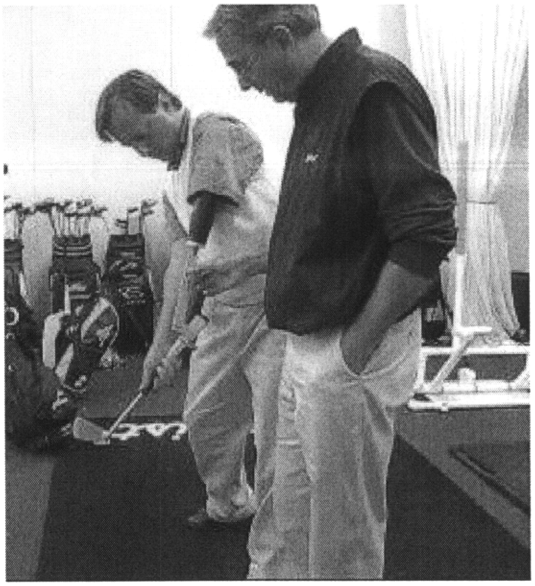


Figure 8.16 Forearm squared at address

The insides of the forearm were "squared" and faced away from Gibson's body at address. During the follow-though, Gibson's forearm had to rotate open 90°, seen in Figure 8.17.

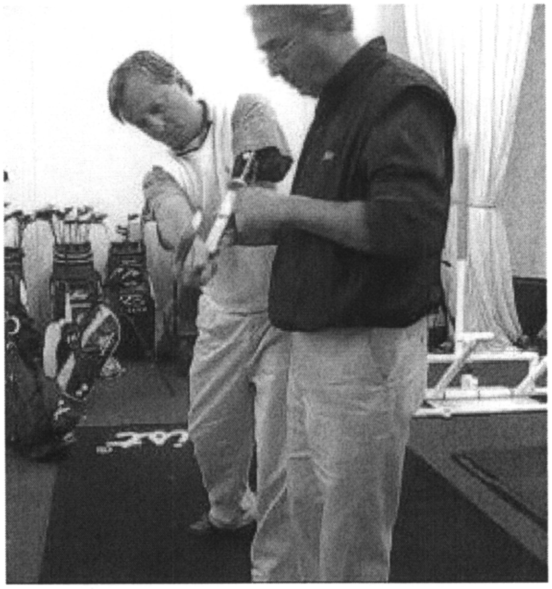


Figure 8.17 Forearm rotation of 90° in follow-through

After observing the follow-through, the second nut on the attachment interface was tightened to prevent the prosthesis from rotating about the ½"-20 bolt. Swinging again, Gibson was still able to rotate his forearm open 90°. Hence, it was determined that the shoulder and socket provided enough rotation for Gibson and that he did not need additional forearm rotation in a prosthesis.

8.6.2b Figuring Out New Dynamics

As soon as Gibson moved on to trying the swing with a full sized club, Cavicchi immediately noticed that Gibson was still using his one-armed techniques with the prototype. Gibson was engaging his right arm muscles to power the swing and was rotating about his right side, trying to scoop up the ball. Just as having both arms does not instantly result in a good golf swing, Gibson's dynamics did not automatically transform his twenty-plus years experience swinging with one arm. This showed that Gibson still had to train to develop his swing and that the device was not automatically providing him with a better swing and giving him an unfair advantage.

Cavicchi directed Gibson to stop using his right arm and to rotate his body by engaging his core muscles. Following Cavicchi's advice, Gibson began pivoting about his left side instead of his right, which caused his weight to shift more to the left throughout the swing. In addition, as he rotated his hips, his arms began moving naturally in response because there was more connection between his left and right sides. These movements, seen in Figure 8.18, are characteristics of a standard two-armed swing.

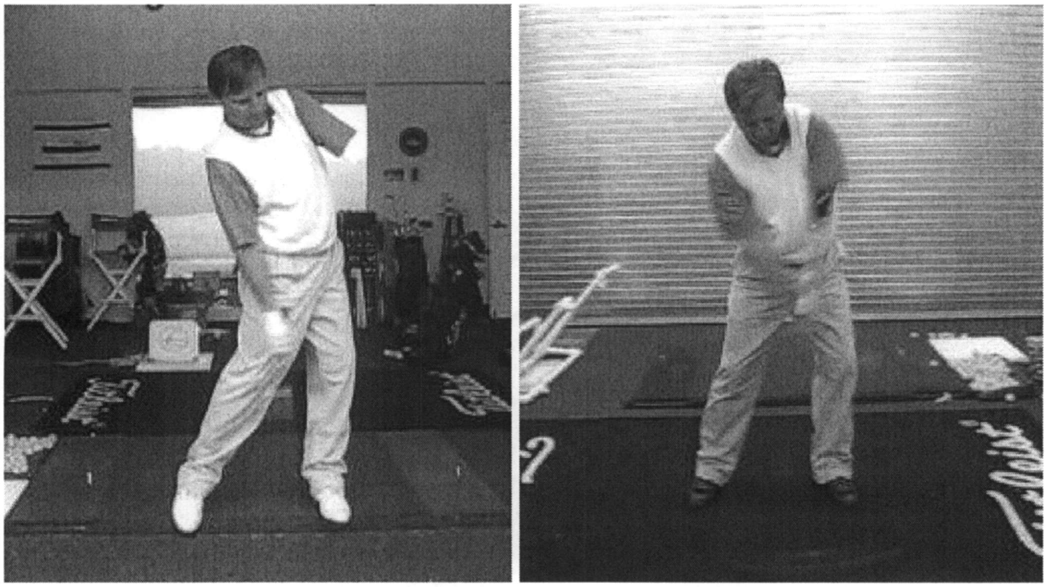


Figure 8.18 Gibson practice swinging without a ball (a) one-armed (b) with prototype I

Gibson proceeded to open the bay door of his private training room and started to hit balls. He needed to get feedback from seeing the ball flight and feeling the impact occur to assess properly and hone his swing. During this time, I tried to elicit Gibson's thoughts about the new dynamics he was experiencing. However, it was too soon for him to understand the effect of the prototype on his swing and Gibson's only response was that it felt "different".

8.6.2c Testing the Elbow

None of Gibson's swings had caused the elbow to bend past its bistable point. The shorter lower limb required more force to bend the elbow than the bench-level prototype that I had tested on my arm. I decided to show the elbow mechanism to Gibson and explain its purpose as I took off one of the springs. Realizing what the mechanism allowed for, he was able to induce the elbow bend in subsequent swings. Experimenting to evaluate its usefulness, Gibson mentioned that it would negatively affect the swing if the elbow bent during the downswing. As he became more comfortable with the motion, the joint was stiffened by adding the second spring back in parallel. With it, Gibson could still trigger the bistable switch in the follow-through, but the arm was guaranteed to not bend in the backswing or downswing.

8.6.3 Conclusions from Testing

A single day of testing was not enough to gather useful feedback about the overall motion of the prototype. Gibson needed more time to figure out the correct motions needed to swing with it, including whether or not the bistable elbow was necessary. Although Gibson was able to fully bend the elbow fully during the follow-through, he liked the prosthesis better when it did not pass the bistable point. Without more time to test the prototype, he could not figure out why this was the case. Unfortunately, the prototype could not be left with Gibson because certain parts needed to be re-machined to prevent rubbing and to improve ergonomics and comfort.

The component that bothered him the most was the grip mechanism. Although he liked how well it formed to different tapers of golf grips, it was uncomfortable to hold with his right hand. Other concerns were that his socket was excessively rotating about his residual limb and the combination of his club and prototype felt short. He offered to exercise his residual limb to build up its muscles to see if it would help alleviate the rotation problem and next time to use a longer club. He also commented several times that he disliked the weight of the prototype and felt that there were too many components. I tried explaining to Gibson that this was only a functional prototype to determine what motions were needed. After knowing the correct motions, we would design simple, robust mechanisms that would attain the motions desired. Until then, it was not worth the time to try and simplify a prototype whose mechanisms might not allow for the right motions to occur in a swing. Gibson was reassured that after finding the correct degrees of freedom needed for him to play with two-armed dynamics, the prototype would undergo many revisions so that the final prosthesis would be lightweight and simple.

8.7 Modifications to Prototype I & Prototype II: Removing the Elbow

From Gibson's feedback, the grip was re-sanded to make it smoother and more comfortable to hold and the parts that had rubbed against him were fixed. In addition, because Gibson seemed to favor the motion of the previous prototype when it did not fully bend, another prototype was made that had no elbow joint at all. For this prototype, seen in Figure 8.19, there was just one box extrusion that spanned from the socket to the wrist.

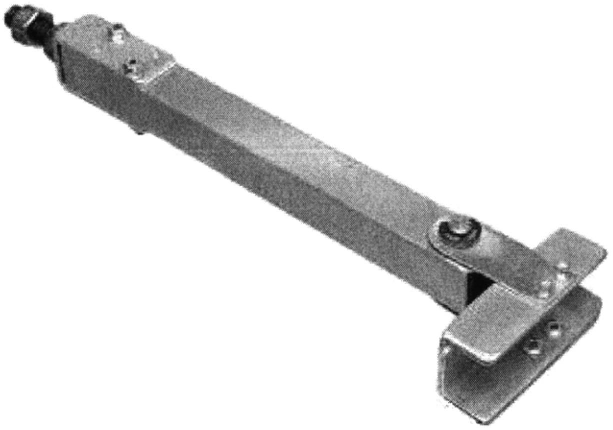


Figure 8.19 Prototype II

The other change was the grip component. It was made shorter in length so that Gibson would not have to grab over it with his right hand. Instead his hand would be in front of the grip mechanism on the golf club grip. The dimensioned drawing of the new grip can be found in Appendix A.

Reviewing the changes, Professor Frey suggested that a latch should also be attached on the prototype with the elbow joint. When unlatched, the elbow would be free to bend, and when latched, the elbow would lock in a straight position. The latch was placed on, as seen in Figure 8.20, with some modifications. Details of the modification are in Appendix B.

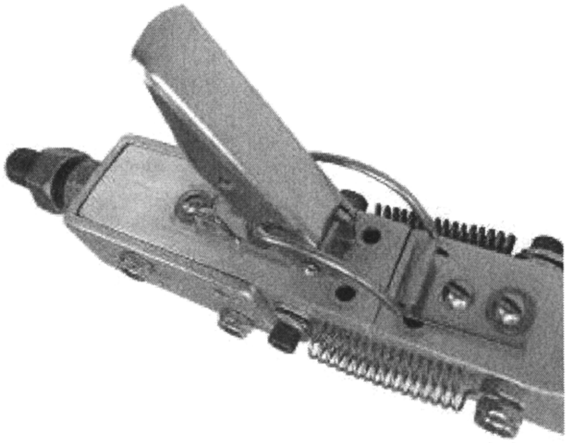


Figure 8.20 Latch on prototype I

The additions and changes to the two prototypes were explained as they were dropped off with Gibson. More time was needed to allow him to become accustomed to the prototypes before more feedback could be gathered.

8.7.1 Conclusions from Testing

Two weeks after delivering the prosthesis to Gibson, I went back out to Harmon Golf. During the two weeks, Gibson had only tried the prototype II because of his bias towards its simplicity and weight. His decision of which one to use was based only on which one looked more robust. He assumed that that particular one would perform better, so he gave it preferential treatment by using it more often. When I scheduled the appointment to visit him, I had reminded him to use both prototypes equally as much as possible so that we could fairly compare their dynamics against each other. However, it was not until that morning, before I arrived, that Gibson tried the prototype with the elbow joint.

To Gibson's surprise, he liked the prototype with the elbow better than the one without, but only when he did not fully bend the elbow joint in the follow-though. The small amount of give in the joint allowed him a little more flexibility in his backswing and helped slow down his swing in the follow-through. The wrist joint allowed enough pivot that Gibson did not feel the need for the elbow to bend fully. When he did try to bend it fully, the swing appeared more forceful.

By not using the bistable functionality of the elbow, the prototype with the elbow was fairly similar to the rigid prototype. With both prototypes, his backswings and downswings were better constrained. There was a solid connection between his left and right sides that allowed his shoulders to rotate together as a unit to achieve accurate and consistent swings. He no longer needed to use his right arm muscles to help initiate the downswing and instead he used the hip and thorax rotation to pull the left shoulder around naturally. Correctly using his hips and thorax, Gibson felt that with more training, he could increase the amount of energy he could generate and transfer. Interface-wise, Gibson much preferred the shorter grip mechanism. Holding on to the actual club grip gave Gibson more control over the prototype and was more comfortable. Lastly, the forces on his residual limb were tolerable, even when he chunked, which is when the club hits the ground before hitting the ball.

Overall, the visit went well and Gibson was seeing positive aspects of the prototypes. Yet, because I felt that this might have been the same reaction Gibson had when initially trying the Golf Pro, I wanted to give him even more time to use both of the prototypes to gain more insightful feedback to understand the underlying factors for why a swing felt and performed the way it did.

Two months elapsed before an updated opinion on the prototypes was sought from Gibson. He reverted back to liking the prototype without the hinge, this time, because it was not only lighter, but "easier to square up at impact." Feeling that he had ample time reach this conclusion, I felt more comfortable with the results. In addition to recording his opinion, I wanted to get quality videos of Gibson's swings with each setup to analyze and compare the swings fully. The setups included Gibson playing one-armed, with the Golf Pro, with the modified Golf Pro (titanium), with the prototype that had an elbow, and with the prototype that did not have an elbow. I also wanted to obtain quantitative data to see if it would support Gibson's feedback.

8.7.2 An Issue Becomes Apparent

The next visit was expected to be fairly straightforward, collecting video and data from FlightScope and iClub's Body Motion System. However, as the session started, Gibson mentioned that he had recently noticed a majority of his impacts were on the toe of the club when using the prototype without the elbow, as seen in Figure 8.21.

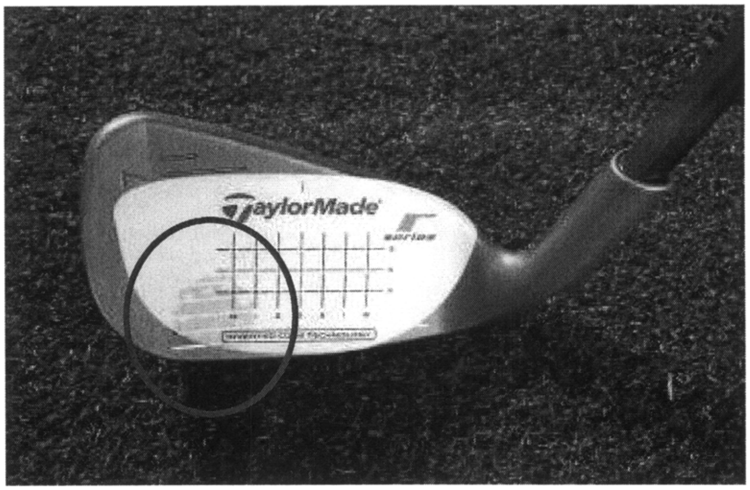


Figure 8.21 Impact on the toe of the club marked by Taylor Made's face impact tape

He was not sure of the exact cause but believed the shortness of the prototype contributed to the problem. He had been compensating for the shortened length and had not noticed it until he had fully examined his new dynamics and found that he was bending his body further forward at impact, even after switching to a longer club. The prototype should have been made the same length as his anatomical arm instead of two inches shorter. The prototype had to be re-machined before determining if the shortened length of the prototype was the direct cause of the impacts occurring on the toe of the club.

By chance, Cavicchi happened to walk by and as he observed Gibson's swing, he diagnosed the problem as the prototype not having enough forearm rotation. As soon as the top nut was loosened and the prototype was able to rotate, Gibson started to hit the ball on the sweet spot and he commented that the swing felt much less restricted than before. Still, he was compensating for the shortened length of the prosthesis so at the end of the session, the prosthesis was taken away to be modified. Two additional inches were added to its length.

Returning to Harmon Golf, the reworked prototype felt significantly improved over the previous week, mainly from the benefit of forearm rotation. Swing data was captured from the prototype without the elbow, both versions of the Golf Pro, and from Gibson's one-armed swing, leaving only the prototype with the elbow to test. After taking a few warm-up swings with it, Gibson commented that he had no idea why, but this prototype felt much better than all the others, including the prototype without the elbow. The slight give in the elbow made the overall swing smoother with less impact forces felt in his residual limb. It was not until additional data was analyzed could this be further explained.

9. Final Results

From close interaction with Gibson and testing several prototypes with him, it was determined that for Gibson to achieve a golf swing like that of a two-armed golfer's, a golfing prosthesis needs to include a wrist joint and forearm rotation. Slight elbow compliance was found to help in terms of comfort, by dampening the loads felt by the residual limb, and smoothness of the swing.

9.1 Wrist Motion

An anatomical wrist is a condyloid joint that allows all movements except for axial rotation. A condyloid joint is similar to a ball and socket joint, except instead of a spherical ball and a round cavity, the head is an oval shape and fits into an elliptical cavity. Golfers do not use all the wrist motions available while golfing. To constrain the swing properly, golfers keep their left wrist flat, only allowing their wrist to pivot in a plane that causes the thumb or the pinky to move towards the forearm. Figure 9.1 illustrates this motion.

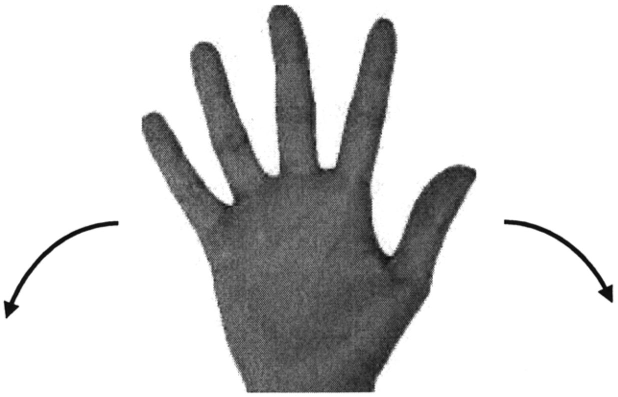


Figure 9.1 Radial and ulnar deviation

An anatomical wrist can be easily constrained to move only in this plane by using muscles subconsciously to hold other directions stiff. However, if Gibson is presented with a prosthesis with a wrist joint that incorporates all the degrees of freedom an anatomical wrist has, he will not be able to control the other degrees of freedom fully that are not needed. He will have to try to compensate for these. From analyzing the different versions of the Golf Pro and trying other in prototype designs, the results are that Gibson needs a wrist with an unrestricted pivot in the plane that causes the thumb or pinky to move towards the forearm, but be completely stiff in other directions. This can be achieved with a simple hinge joint.

9.2 Forearm Rotation

Forearm rotation is needed to keep the clubface accelerating in the correct direction through impact and allows the golfer to hit the ball on the sweet spot of the clubhead. Only using shoulder *rotation, it* was difficult to find the sweet spot and Gibson tended to hit the ball on the toe, or outer edge, of the club. Prototypes for Gibson in this project utilized the same ½"-20 threaded post that the Golf Pro used to connect the prosthesis to the socket. This was chosen so that Gibson could use the same socket that had previously been created for him.

Throughout most of the project, it was believed that forearm rotation might not be needed. Double nuts were used to prevent the prosthesis from rotating about the post at his socket, and no other mechanisms were considered to provide rotation. However, tightness in the swing prompted re-evaluation of forearm rotation. Once the prosthesis was free to rotate about the post, Gibson felt his swings become more natural, and saw greatly improved results. Although the setup allows for unlimited rotation in his left forearm, Gibson seemed to be able to control it with his right arm. He would like further testing on to try a damped rotation.

9.3 Elbow Movement

Three levels of elbow bends were tested in this project: one that could bend completely once a certain force was applied to the lower arm section, one that only allowed some flex but would not bend fully, and one with no elbow bend at all. The partial elbow that allowed for some flex was the most natural feeling and helped attenuate the forces transmitted to the residual limb. Both the prototype without the elbow bend and the one that allowed for some flex performed equally well and both performed better than the one with the full elbow bend. With the ability to bend the elbow fully, the design was less stiff, resulting in an impact that did not feel as solid.

10. Overall Analysis

Initial analysis seemed to indicate that the left arm provided little assistance in the swing. Gibson mostly focused on hip rotation. However, because of all the dependencies within the swing, the left arm was discovered to be essential for accuracy, consistency, and power.

10.1 Benefits to Swing Technique with the Prototypes

Because this project was to determine the dynamics of a golf prosthesis specifically for Gibson, Gibson's comments and feedback about the prototypes were the primary basis of evaluation. His responses stemmed from the feel of the swings, watching the resultant ball flight from the swings, and video comparisons between the swings. After assimilating to the prototypes, Gibson found that both of them helped him constrain his swing, which allowed for accurate and consistent shots. Additionally, the prototypes provided an extra element of connection between his right and left sides allowing Gibson to transfer energy better in the swing for a more powerful hit. The difference between the two prototypes was that the one with an elbow joint had a more natural feeling swing, but only when he did not force the elbow to go past the bistable point and fully bend.

The benefits of the prototypes that exceeded those provided by the Golf Pro are found mainly in the downswing and impact stages. Generally, it is difficult to observe the differences between the screen captures of Gibson using the Golf Pros and Gibson using the prototypes without the eye of a professional. To view a full set of frame-by-frame front-on and down-the-line screen captures of Gibson's swing with each setup see Appendix C. For illustrative purposes, the following comparison image is of Gibson practice swing without a ball. In this image, his body is looser and the contrast between the dynamics of his swing increases, making comparison easier.

With the modified Golf Pro, Gibson still rotates about his right side like his one-armed swing and his weight at impact favors his right side, as seen in Figure 10.1.

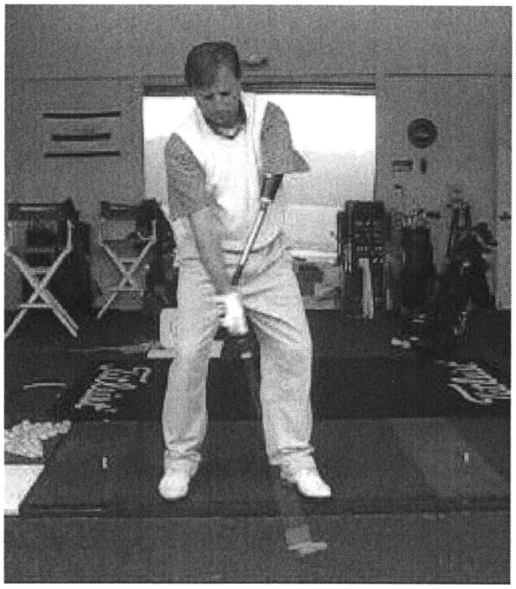


Figure 10.1 Gibson freely swinging with the modified Golf Pro

However, as previously described in Section 8.6.2b, using the prototype I, Gibson pivots about his left side, his weight shifts more to the left throughout the swing, and his arms rotate around naturally as his hips rotate. The motions that resulted from the prototype were common characteristics of a two-armed swing that Gibson could not properly deliver one-armed or with either configuration of the Golf Pro, could not properly utilize to deliver an accurate and consistent swing.

10.1.1 The Kinematic Sequence

Benefits of prototype I and II can be verified not only by Gibson's testimonials and video comparisons, but also by the kinematic sequences and quantitative data provided by FlightScope and iClub's Body Motion System.

The kinematic sequence of a swing with each of the prototypes can be seen in Figure 10.2 and Figure 10.3.

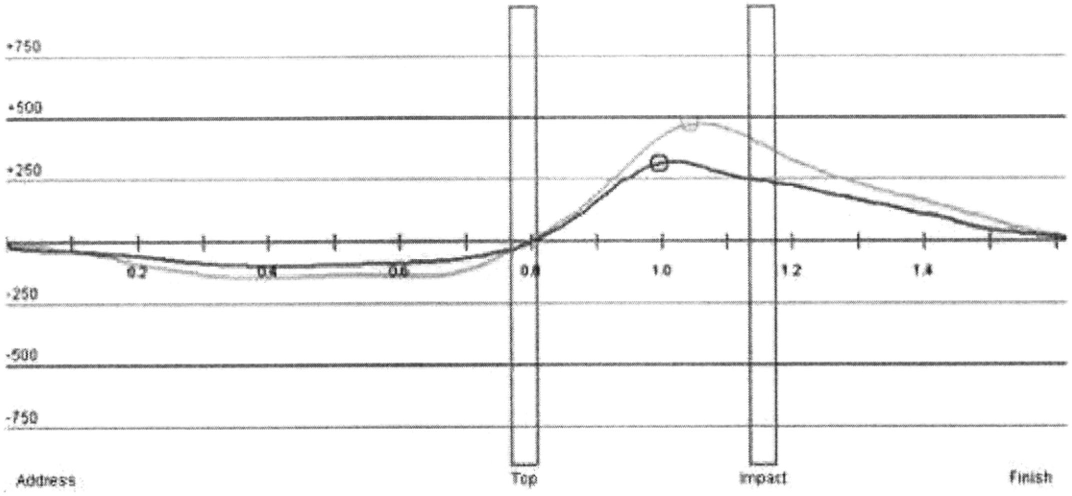


Figure 10.2 Gibson's kinematic sequence with prototype I, with elbow joint not fully bending in the follow-through, recorded with iClub's Body Motion System

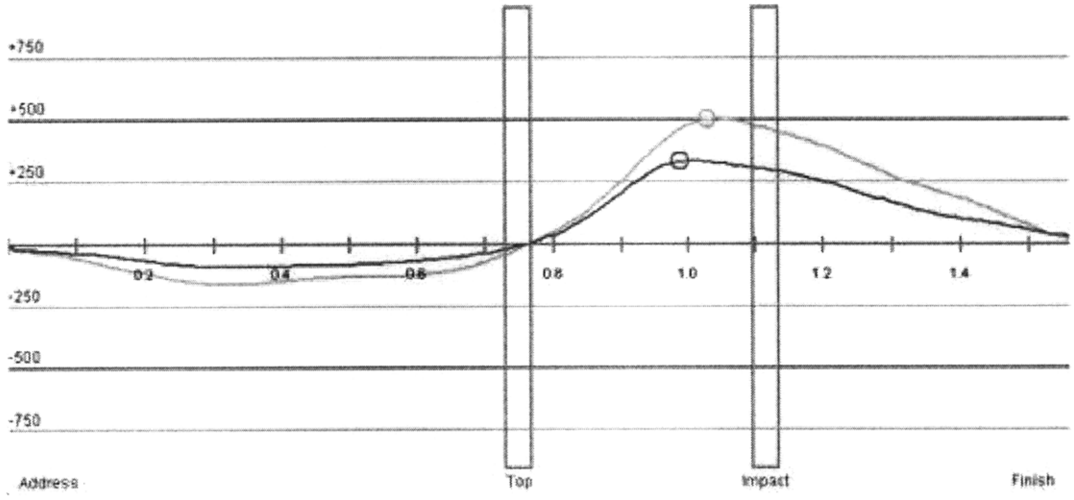


Figure 10.3 Gibson's kinematic sequence with prototype II, no elbow joint, recorded with iClub's Body Motion System

Both graphs have distinct peaks that occur sequentially, which signifies efficient energy transfer in the swings. A more careful study of the graphs show that the prototype with the elbow joint has a faster deceleration after the peak, which is why it provided the more natural feeling swing for Gibson. Both of these kinematic sequences are much improved over Gibson's one-armed swing in Figure 6.5 in Section 6.1.3a, and his swing with the original Golf Pro in Figure 6.16 in Section 6.2.3a. However, his kinematic sequence with the modified Golf Pro more closely resembles the kinematic sequence of the skilled golfer in Figure 4.5 in Section 4.2.3a. Even though the kinematic sequence of the modified Golf Pro was better, the kinematic sequence is only a measure of swing velocity, not of the positions of the club, arm, and body. The positioning using the prototypes more closely resembled that of a two-armed golfer than the positioning of the modified Golf Pro, and overall, the prototypes allowed for better performance in a swing.

10.1.2 Data from Flight Analysis and Motion Capture

The average data gathered about the swings by using FlightScope and Body Motion System in the final visit to Gibson is recorded in Table 1.

Table 1 Average data collected on Gibson's swings with various setups

Setup	**Club**	**Distance (yds)**		**Ball Speed (mph)**	**Type of Shots**
		Carry	**Total**		
One-Arm	8 Iron	103	104	85.2	Draw & Fade
Golf Pro (Original)	8 Iron	73	81	81.9	Mainly Draw
Golf Pro (Modified)	8 Iron	72	81	75.8	Mainly Draw
Prototype (With Elbow)	7 Iron	89	99	82.4	Mainly Push
Prototype (Without Elbow)	7 Iron	101	107	88	Mainly Push

To draw conclusions with the data one must take into account that golfers tend to hit ten yards further with a 7 iron than an 8 iron, that Gibson's golf swing changes slightly from swing to swing regardless of the setup, and that he has spent over twenty years perfecting his one-armed swing. With that acknowledged, the data shows that Gibson's one-armed swing out performed both configurations of the Golf Pros and the prototypes in terms of distance. However, the shots were less consistent, alternating between draws and fades. The prototypes from this project achieved more consistent results, with four out of six swings with prototype I and five out of eight swings with the prototype II resulting in push shots. Prototype I performed well in terms of ball flight distance. Although it is not as far as what Gibson could achieve one-armed with a 7 iron, Gibson believes that with more time, he could significantly increase the distance that results from either prototype and in the future, perform better than his one-armed swings.

10.2 Benefits to the Mental Game with Prototypes

During the testing process, Gibson mentioned that the prototypes gave him additional confidence. He has never felt insecure about his condition or any less capable than two-armed players. Yet being able see the similarities between his body positions with the prototypes and those of great two-armed players greatly increased his confidence. The potential of the prototypes has strengthened the interest that he has in the game.

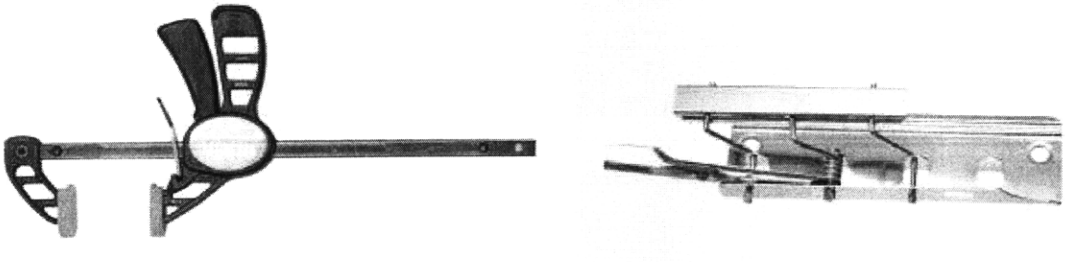
11. Future Work and Recommendations

11.1 Further Development of a Golfing Prosthesis

The recommended next step is to improve further and hone the performance of a prosthesis for Gibson. To do so, a more in depth study of whether the forearm rotation should be damped and what the right stiffness should be in the elbow joint needs to be conducted. After completing a full analysis to understand all the degrees of freedoms needed in a prosthesis for Gibson, action should be taken to develop a universal golf prosthesis for other users. The conclusions from working with Gibson should be tested by amputee golfers of all skill levels to see if the same configuration allows them to have an improved swing that feels natural. Additionally, it should be determined if standard two-armed techniques and instructions without major modifications can be readily employed using this configuration. After determining if the configuration supplies the motions needed by a range of users, mechanisms can then be further developed for a universal prosthesis.

The main priorities of mechanism design should be to incorporate the motions needed, improve robustness, and make it as lightweight as possible. Simplicity and ease of manufacturing should be of secondary concern. Whether or not the components should be of polymer design depends on the motions needed. The material is useful for keeping joints simple and lightweight, but will inherently have some resistance to motion that may not be ideal for certain joints.

In addition, usability of the device needs to be examined, especially in the grip component. It should accommodate various tapers and sizes of club grips while allowing easy insertion, removal, locking and unlocking of the club. The angle brackets used in this project were a good starting point, but did not have a simple, one-handed way to lock the club in without using hose clamps. Using solutions like a quick-grip clamp or spring binder clamp, seen in Figure 11.1, are two possible mechanisms to adapt for the grip.



(a) (b)

Figure 11.1 (a) Quick-grip clamp and (b) a spring binder clamp

11.2 Design Process

The design process for consumer products is complex and differs for every project because it is highly influenced by the opinions of the consumer or what is understood to be the consumers' stand point through activities such as scenario and persona building. Peoples' opinion can be highly variable and change over time. Information that would help develop a successful product may not come about until the right question is asked, or a specific behavior is observed that was not brought up through questioning. At times, information may come late in the design process. It is up to the designer to determine whether or not it is worth extending time and budgets to incorporate new findings into current design plans. Although the design process is complex and no single correct approach works for every project, there are some general suggestions that I would recommend based on my experiences from this thesis and other design projects.

For any project, it is critical that to start with a well defined objective. As in this thesis, the subject matter may be broad and interdisciplinary, making the problem overwhelming as a whole. Breaking the objective into smaller components will help divide the problem into more manageable pieces, allowing the researcher to have a better scope of the project. Additionally, as the researcher learns more about the subcomponents, he or she can rank them in terms of importance to achieving the objective and determine the most efficient sequence to address them. Afterwards, the researcher should list several ways to approach each component and understand why a certain approach might be better than another for a given circumstance. This will allow the researcher to tackle each component with an educated view point, and incase one approach becomes a dead end, he or she will be able to be quicker at finding alternative routes.

The most essential part of the design process is to spend time with the end users. It is necessary to observe, ask questions, and be interested in who they are and what they do in order to develop a product that they will want to use. From this project, I have learned that even when you do not have much background in a certain field, it is still easy to make biased assumptions about consumer behaviors and what characteristics the consumers would want in a product. Spending time with end users helps eliminate personal biases and instead, focus on what the end users think and feel to determine the needed design characteristics for a product to be successful for a consumer group.

12. Conclusions

The game of golf has many subtle intricacies and only through close interaction with a transhumeral golfer was it possible to determine the motions needed in a transhumeral golfing prosthesis. It was determined that a golfing prosthesis does not need to have all the degrees of motions of an anatomical arm to achieve the precision and power needed to play golf. Instead, it was found that the combination of an elbow flexon, wrist cock, and forearm rotation, is vital to achieving a smooth swing and allows the amputee golfer to dictate how the clubface contacts the ball at impact. Most importantly, with these motions, the amputee golfer can swing like a two-armed golfer and get can hit the ball squarely with the sweet spot of the clubface.

This prosthesis hopefully will not only allow current transhumeral players to lower their scores, but also provide a means for new and old amputees, whether it be veterans returning from war, those involved in industrial accidents, or cancer patients, to start playing golf and find refuge in the game. It is a sport that offers companionship and competitiveness, a reason to let go of negative emotions and thoughts, and the opportunity to be reflective and grateful for what they have.

The research done in this thesis is a step towards producing a high performance golf prosthesis that can help transhumeral amputees at all levels to play golf as if two-handed. Although it is possible to play well with only one arm, the advantages of having two arms for this sport are clear. Instead of struggling to develop the correct dynamics for amputees to swing with one arm, amputees will be able to learn and utilize the abundant amounts of instruction and analysis for two-armed golf techniques. Put on a level playing field with two-armed golfers, amputees will be able to play along side them and increase the social benefit of the game.

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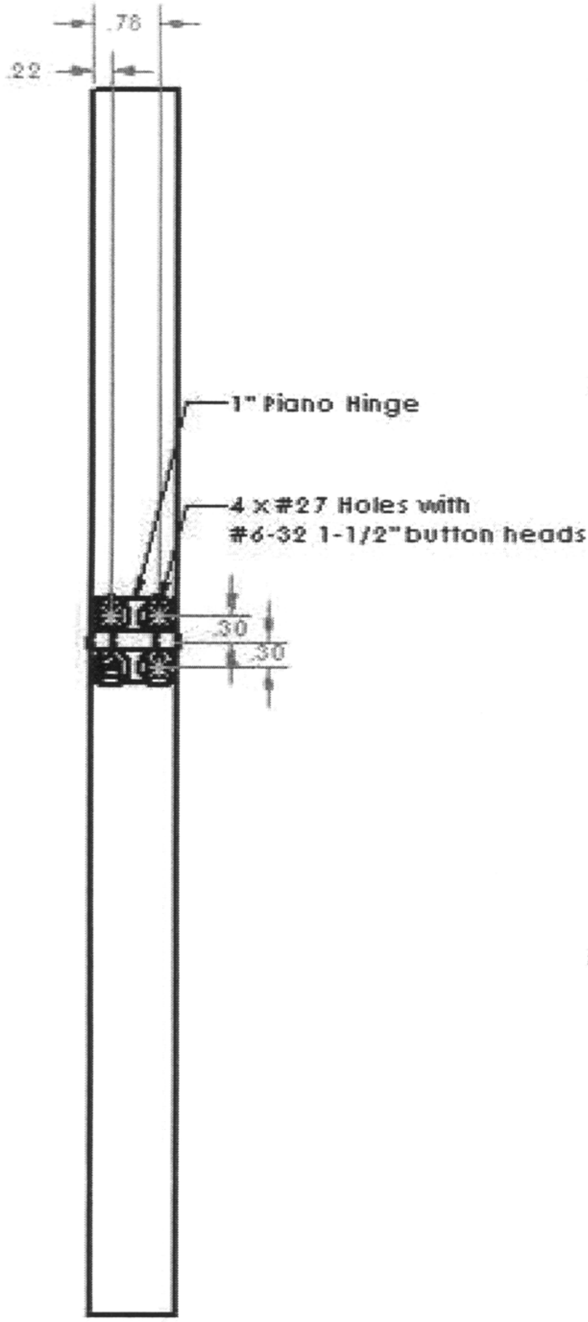
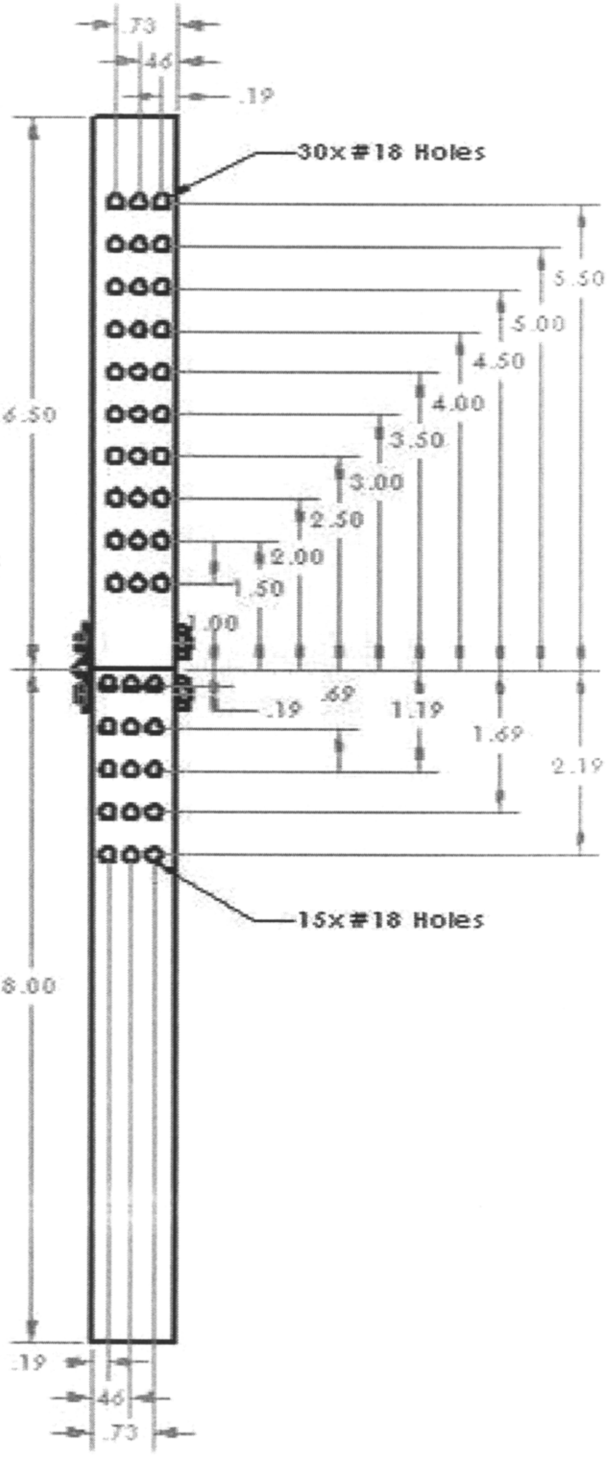
Appendix A: Dimensioned Drawings

Dimensions are all in inches unless otherwise noted.

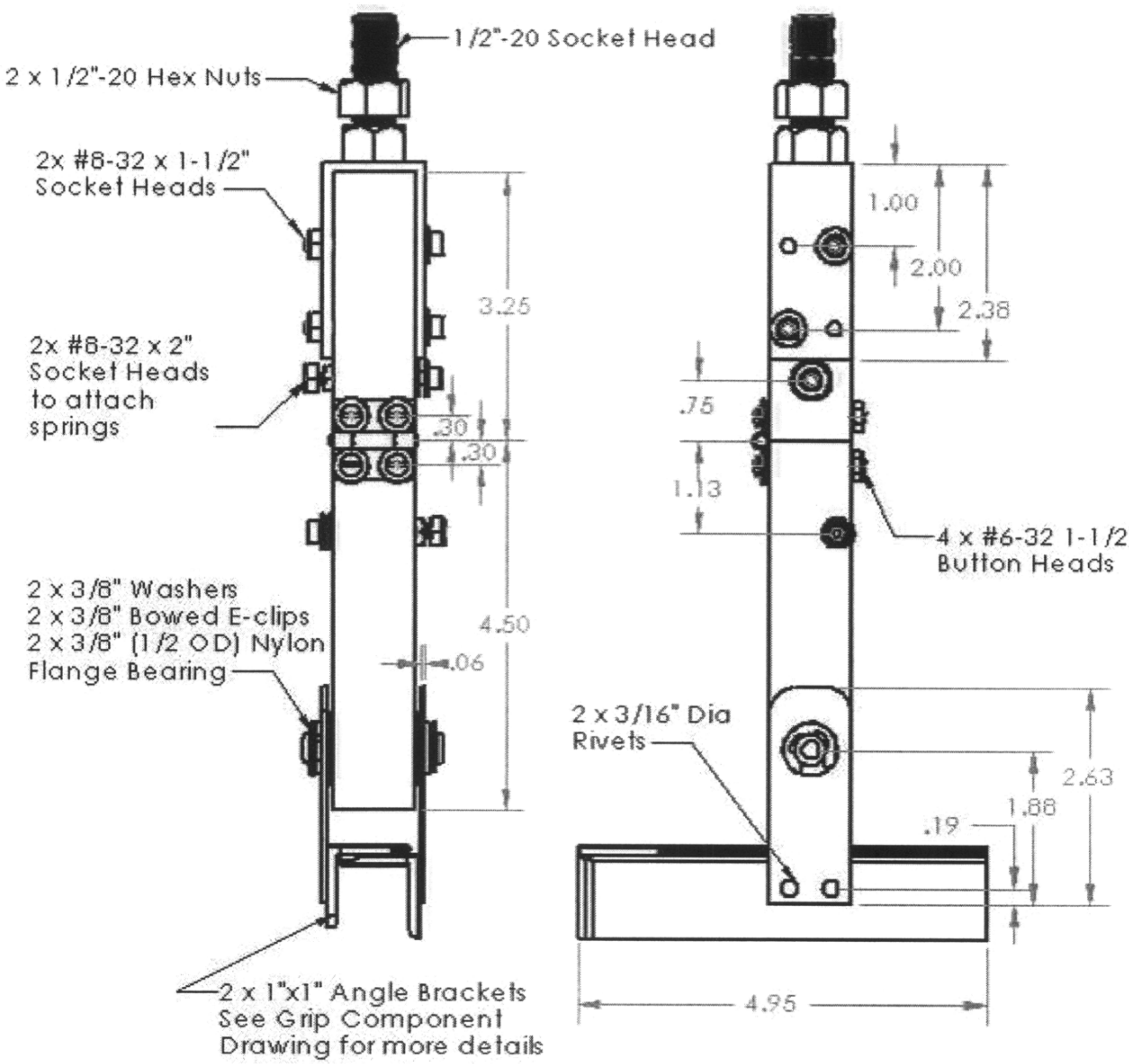
Test Setup for Bistable Elbow





Springs Tested:
One of the springs was 1 ¼” long with an outer diameter of 5/16” and had a spring constant of 5.2 lbs./in. The other was 1 ½” long with an outer diameter of 3/8” and had a spring constant of 12.69 lbs./in.

Prototype I with Bistable Elbow, Long Grip

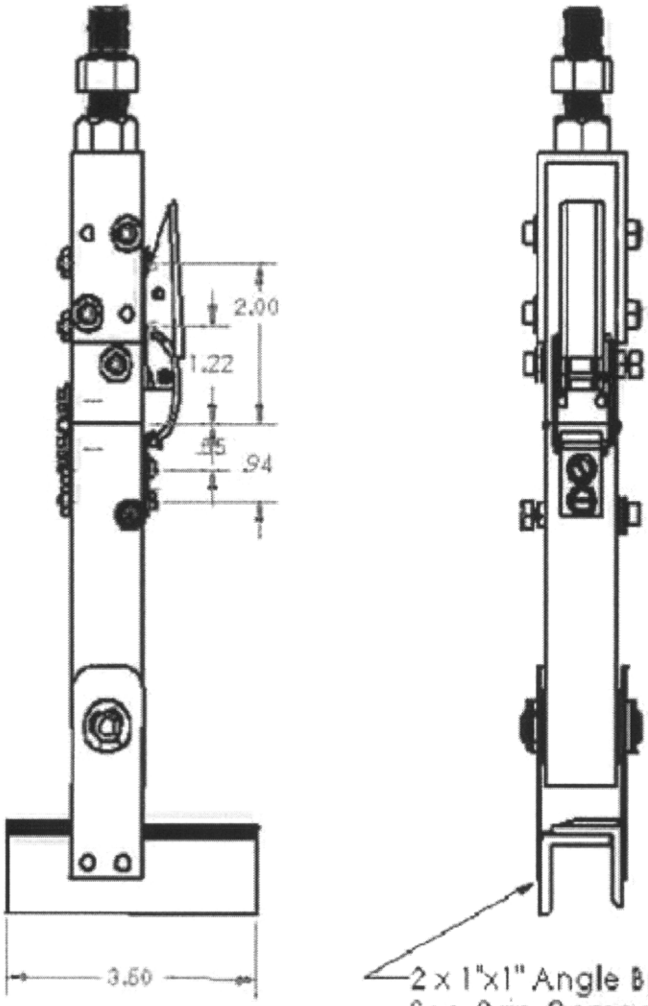


Springs Used in Configuration:
Two springs in parallel. The springs were 1 ¼” long with an outer diameter of 5/16” and had spring constants of 5.2 lbs./in.

*The lower box extrusion should be 2” longer to match Gibson’s anatomical arm length

Prototype 1 with Bistable Elbow and Latch, Short Grip

Overall dimensions of this prototype are the same as Prototype 1 with Bistable Elbow, Short Grip except for the grip component

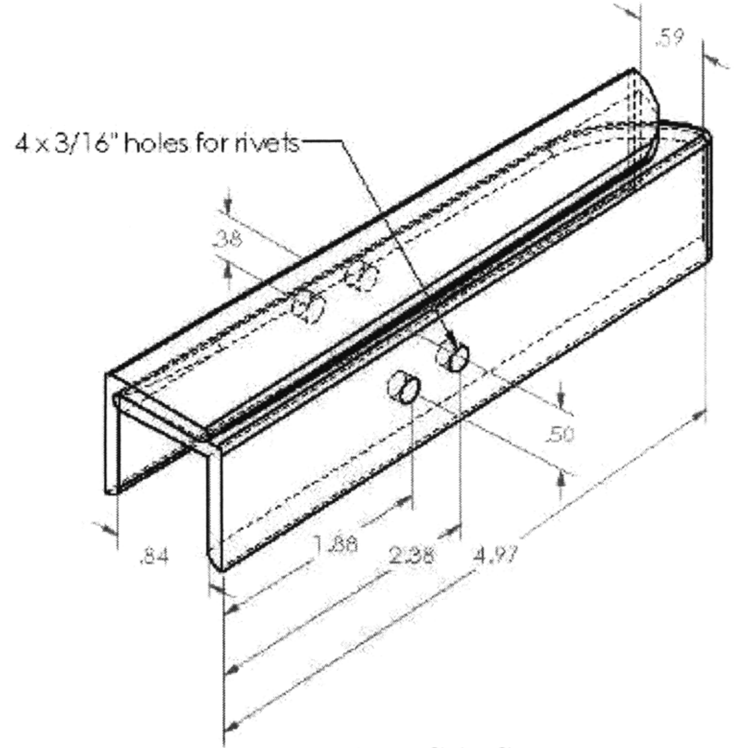


2 x 1"x1" Angle Brackets
See Grip Component
Drawing for more details

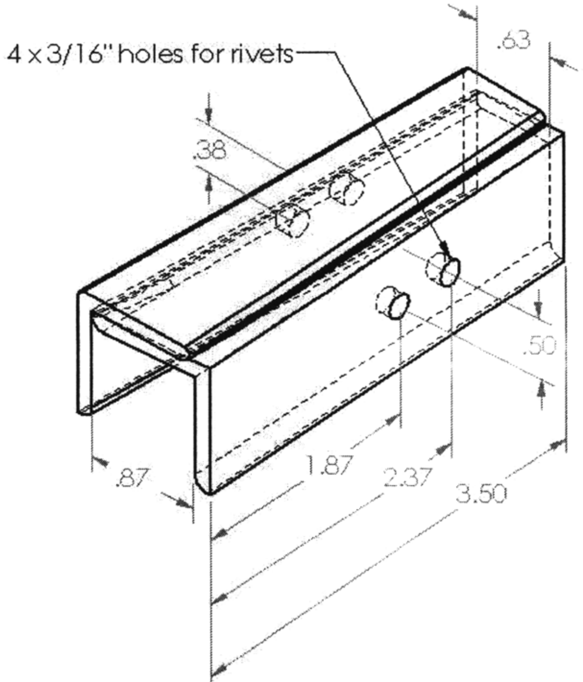
Spring Used in Configuration:
Two springs in parallel. The springs were 1 ¼" long with an outer diameter of 5/16" and had spring constants of 5.2 lbs./in.

*The lower box extrusion should be 2" longer to match Gibson's anatomical arm length

Grip Components

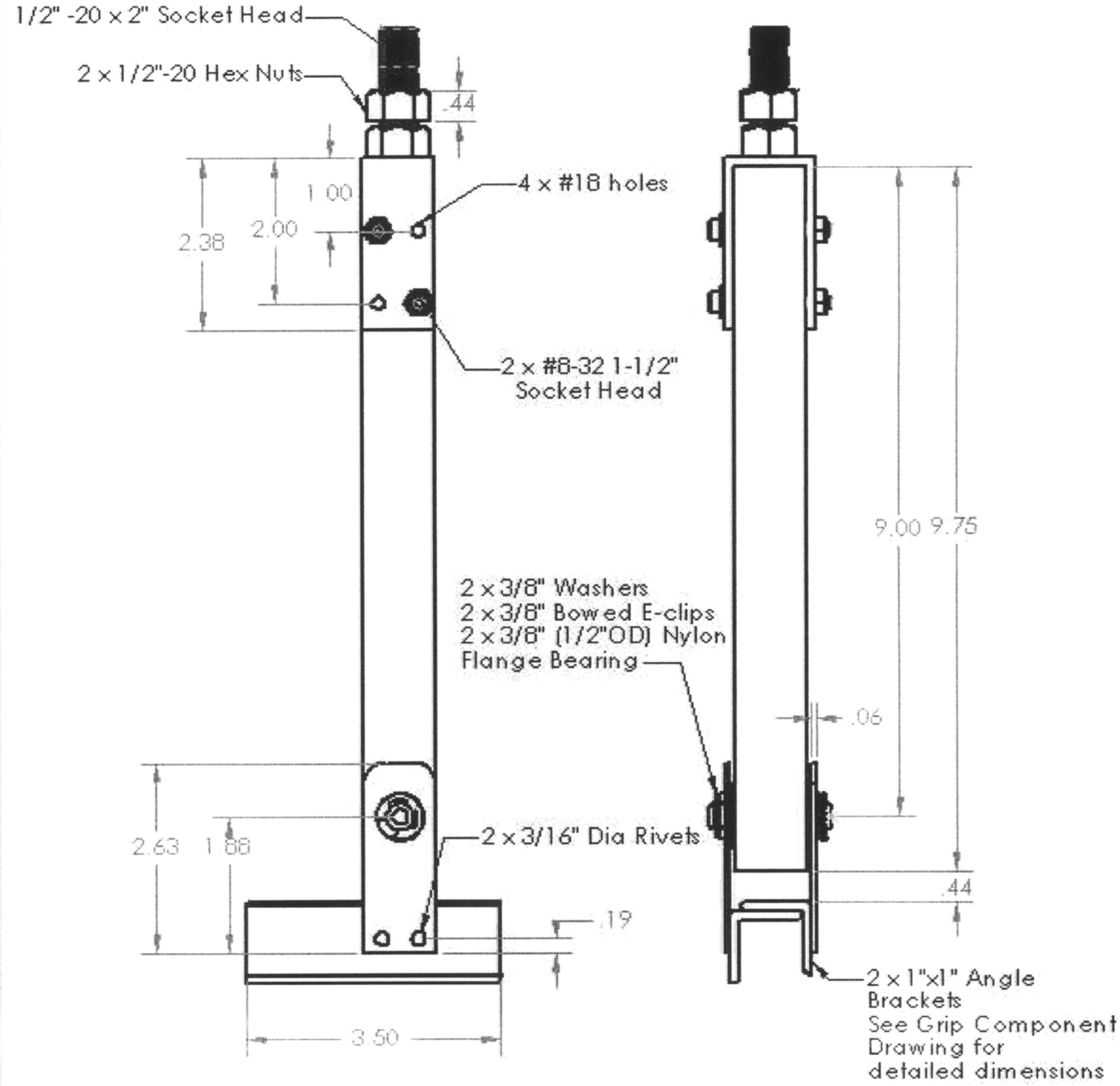


Long Grip Component



Short Grip Component

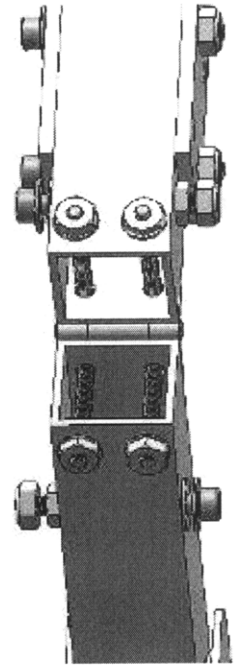
Prototype 2 with No Elbow



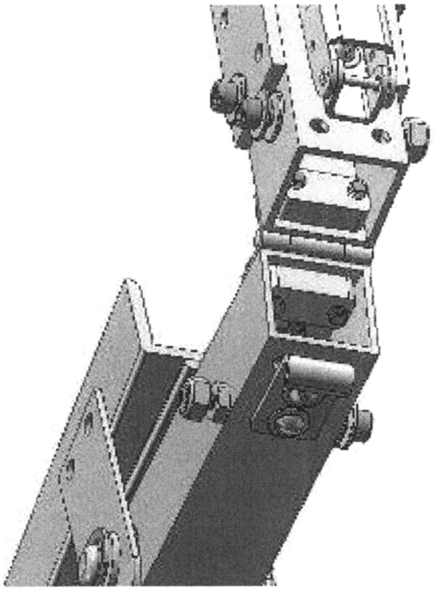
Spring Used in Configuration:

Two springs in parallel. The springs were 1 ¼" long with an outer diameter of 5/16" and had spring constants of 5.2 lbs./in.

Appendix B: Modification with the Latch



Without the latch

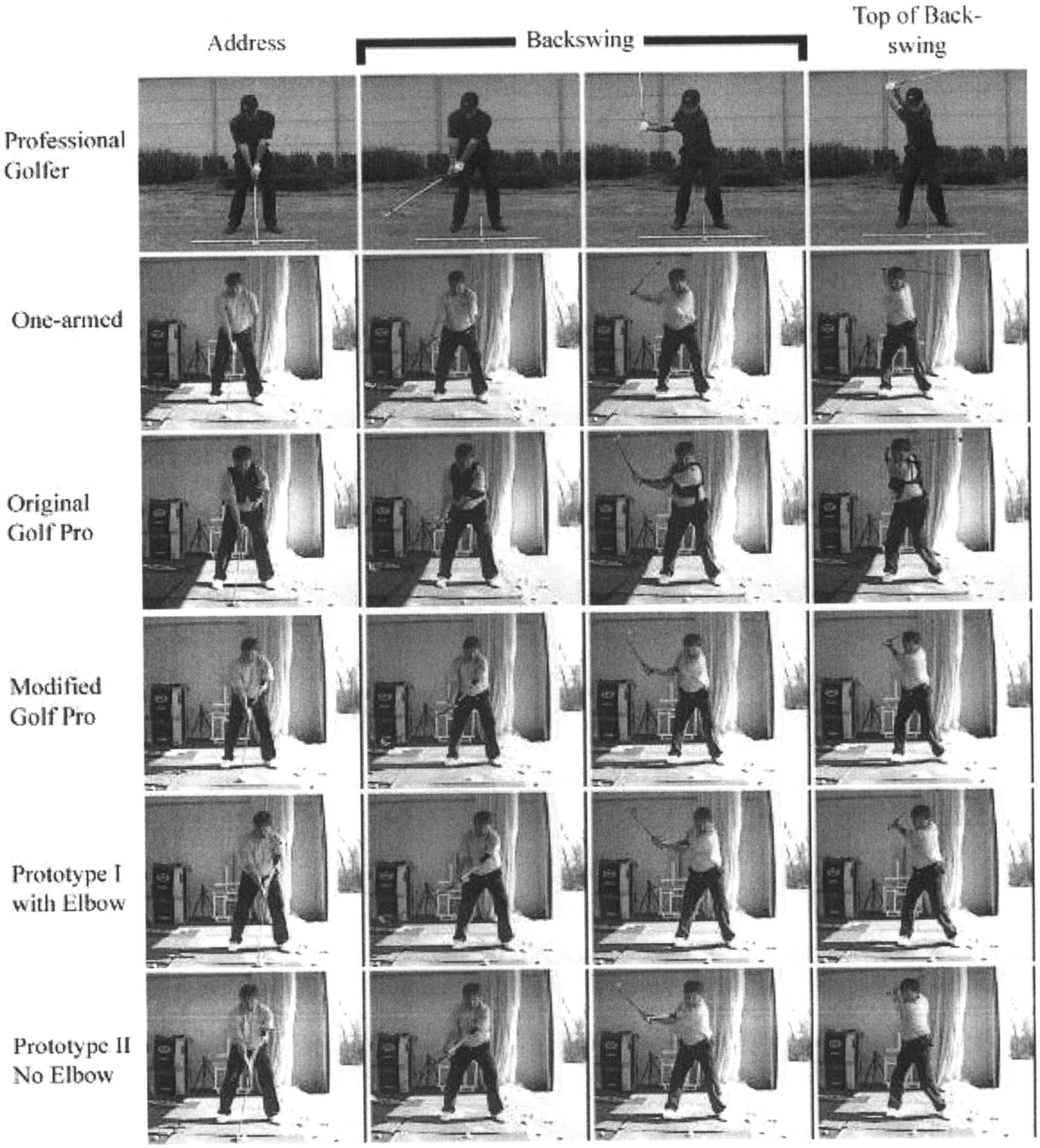


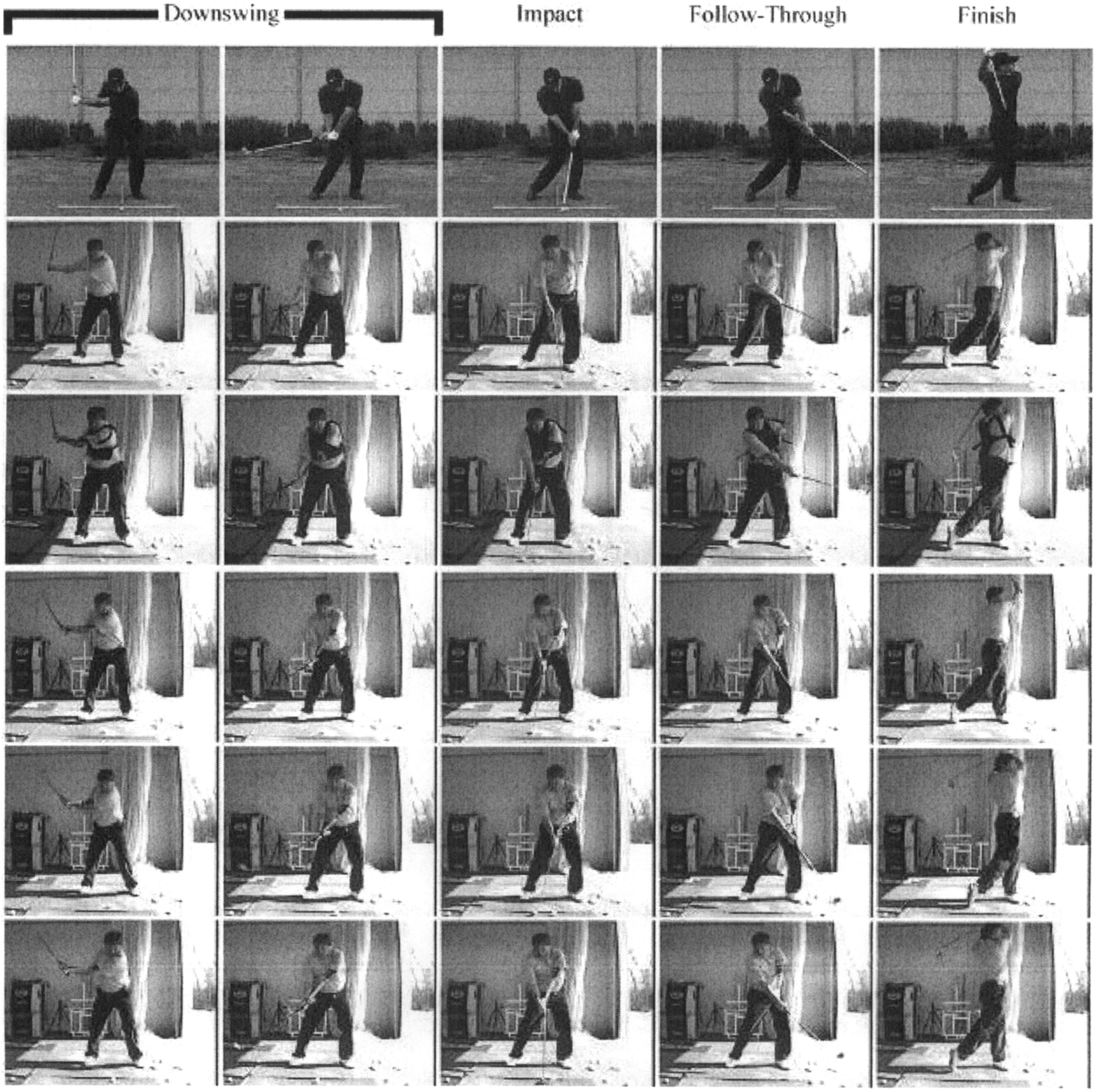
With the latch

For prototype 1, without the latch, the screws attaching the hinge to the box extrusions spanned across the whole box extrusion. However, the optimal position of the latch interfered with the nuts and screws that attached the hinge. Blocks of aluminum were drilled and tapped to allow for shorter screws to attach the hinge without interfering with the latch.

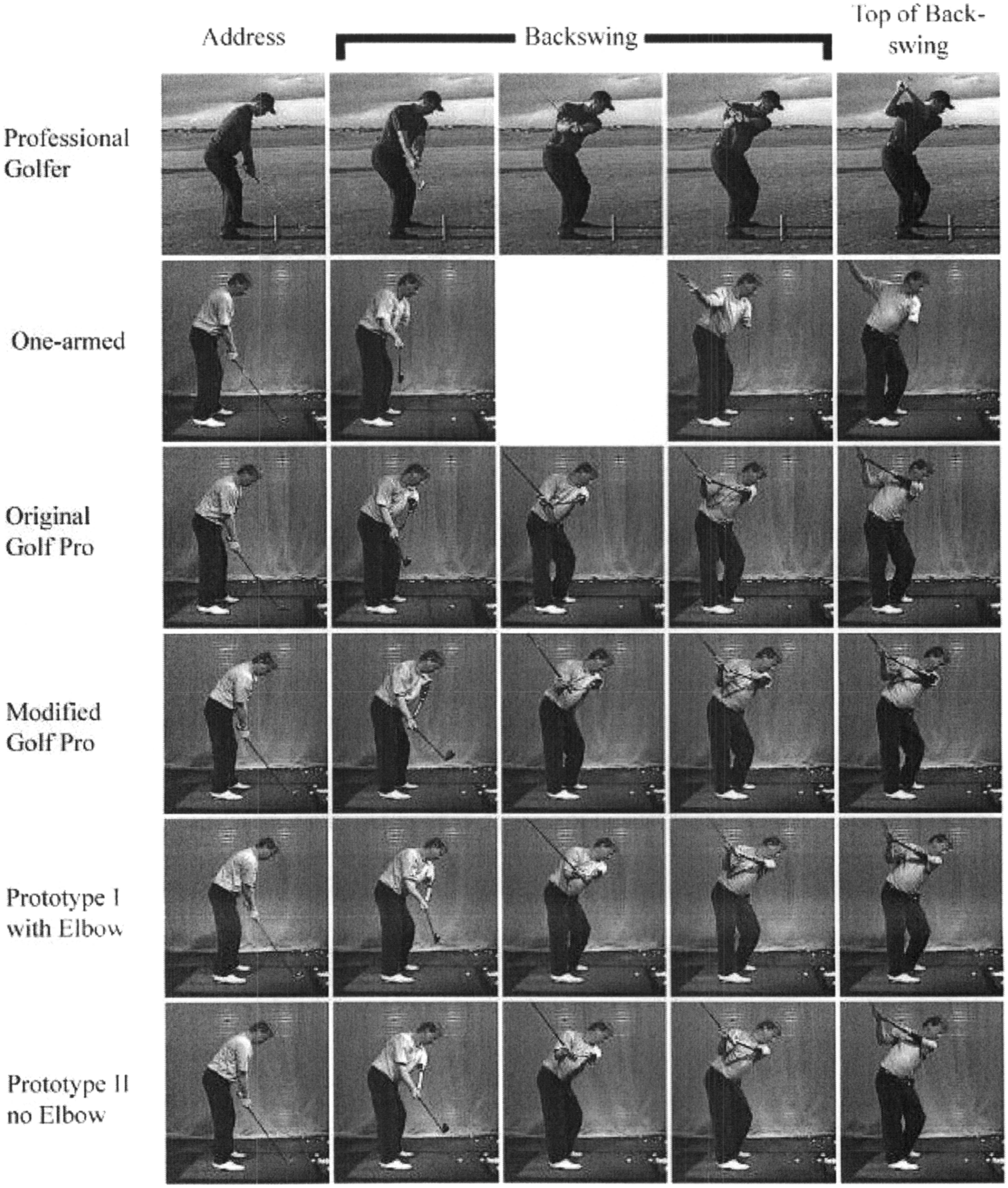
Appendix C: Array of Swing Sequences

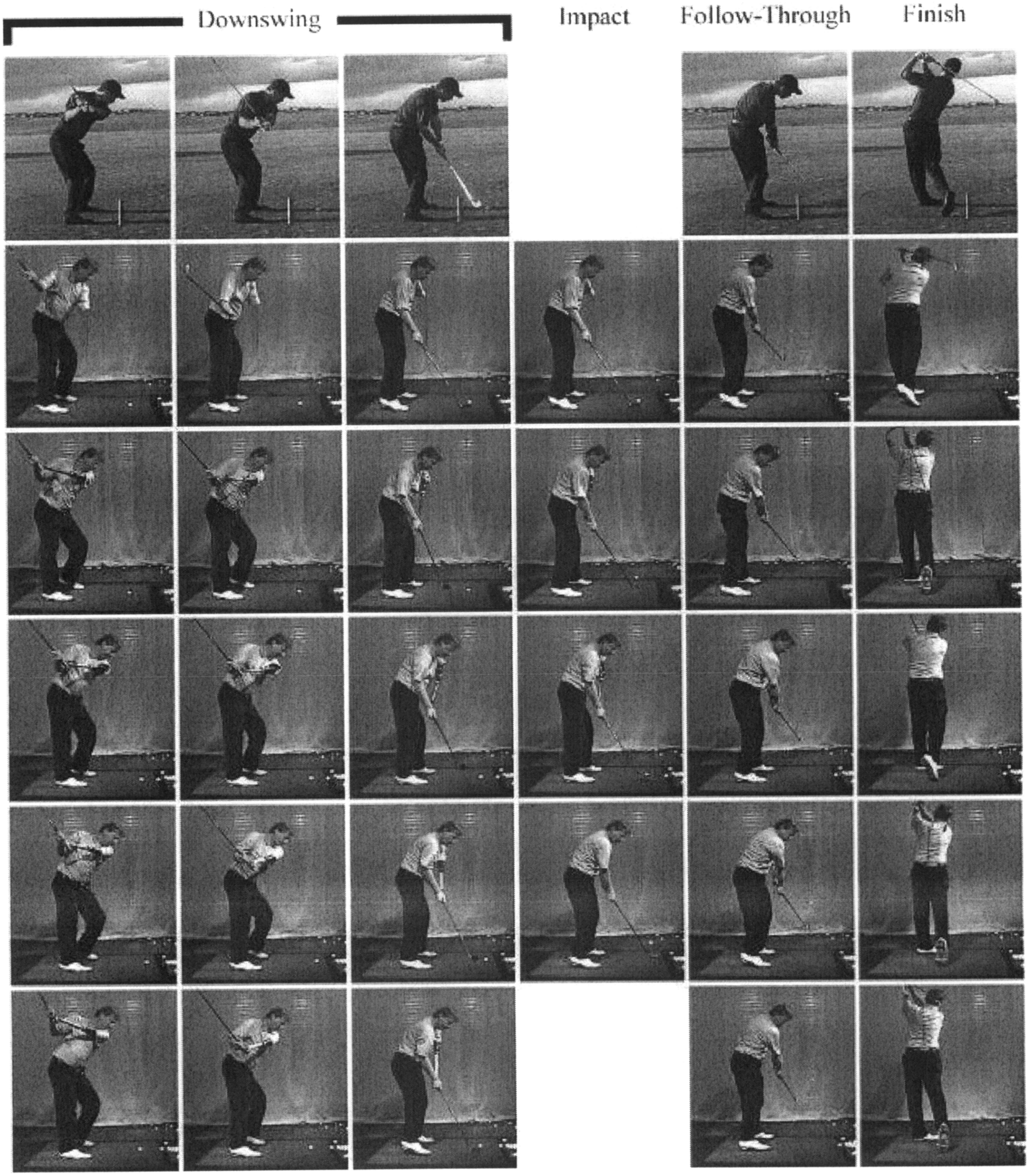
Front-on View




Downswing
Impact
Follow-Through
Finish

Down-the-Line View




Downswing
Impact
Follow-Through
Finish