1.1 Introduction

The reason for this work was the design and development of a novel power wrist prosthesis. This new wrist is a single degree of freedom with an orientation based onrevious work [Stavdahl, 2002]. This work came up with an oblique plane based on testing normally limb subject performing tasks of daily living. This work involves designing and constructing a wrist to perform with this set oblique plane.

The wrist is generally over looked in prosthetic fitting a lot of the time because of control issues, the extra cost and the perceived lack of functional improvement. The reason for a wrist is to properly position the hand to better optimize its use. The control of the wrist has to be simple due to the lack of control sites in below elbow limb absences. A wrist should only be one degree of freedom (DOF) if control sites are limited. The current prosupination device is one DOF but this work questions if it is the best DOF or is there something better?

The new wrist is designed based on the pervious hypothesis which in theory is a good design. The testing included the testing of 20 normally limbed adults as a control group to verify the pervious work. Next a comparison of control group splinted compared to the unobstructed was preformed. Finally testing of a prosthetic users was conducted and compared with the previous two groups. The results of these tests were used to look at specific compensatory movements. Differences in these results were analyzed to show how the new wrist would compare to the older straight prosupination orientation.

1.2 Objectives

The overall drive behind the NTNU Revolute Wrist Device (NRWD) is to complete the two many objectives stated below to satisfy the requirements for an Masters Degree in Mechanical Engineering.

- The first objective was to design the NRWD and construct a working wrist.

- The second objective of this work was to determine if the NRWD is more kinematically functional then a conventional ProSupination device.

Chapter 2 Background

2.1 Upper Limb Prosthetics

When a person is faced with limb loss there are numerous concerns to deal with concurrently; psychological adjustments, delays in the healing process, management of physical and phantom pain, fitting and adapting to a prosthesis. This chapter provides an overview of the typical stages involved in an upper limb prosthetic fitting.

Upper limb prosthetics started to advance following each of the World Wars as a result of higher demand. Today in the United States there are approximately 90 000 people with upper limb deficiencies, roughly half of whom choose to wear some type of prosthesis. Of these 10% are under 21 years of age, about 60% are between the ages of 21 and 64, and the remaining 30% over 64 [Stark and Leblanc, 2004]. The faster that a person is fitted with a prosthesis after an injury the more likely that person is to accept it and learn how to use it [Leblanc, 1973]. As part of the rehabilitation process the person should be educated on all the options available to them and be questioned on what tasks they would like to accomplish. Their expectations should be tailored to what is achievable. The prosthetist should take into account the input from the candidate, their family, friends, the surgeon and the people in charge of rehabilitation. In addition to intellectual and emotional factors there are other factors to consider: socket design, the power type, the control plan, the prosthetic device, the training of the person for the duration of the fitting process and financial support.

2.2 Sockets

All prosthetic devices need some type of socket to link them to the body. A successful prosthesis is very dependent on how successful the socket fitting is. A poor fit will reduce the overall success and could cause the patient to stop wearing that prosthesis due to discomfort and pain. Figure 2.2.1 shows were the socket is located with respects to

the rest of the prosthesis. The socket must be designed to allow ease of donning and doffing of the prosthesis with minimal or no assistance. Whether the candidate has unilateral or bilateral limb loss will affect the design of the socket as well.

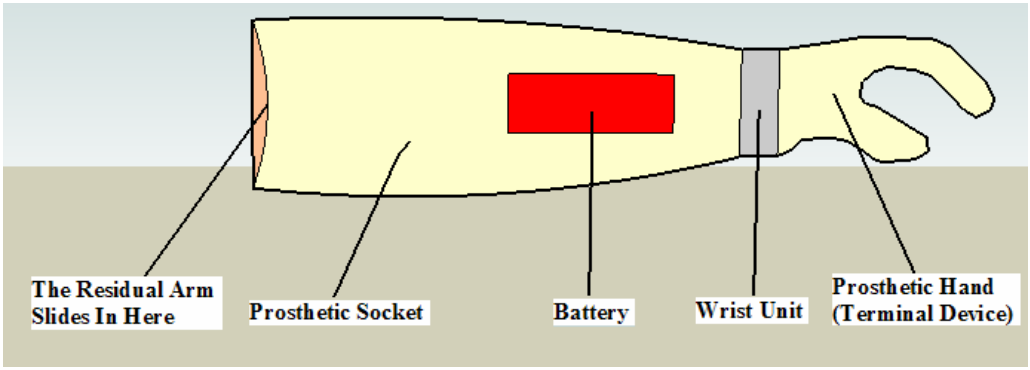


Figure 2.2.1: This is a sketch of a below elbow prosthesis to get you an idea of what is being discussed.

A typical below elbow prosthesis is suspended by a total contact socket. There can be some support added to the socket in the form of wings that protrude past the elbow joint for proximal below elbow socket and past the shoulder for above elbow; this is done to help secure it and can be seen in figure 2.2.2. If there is more support needed a socket

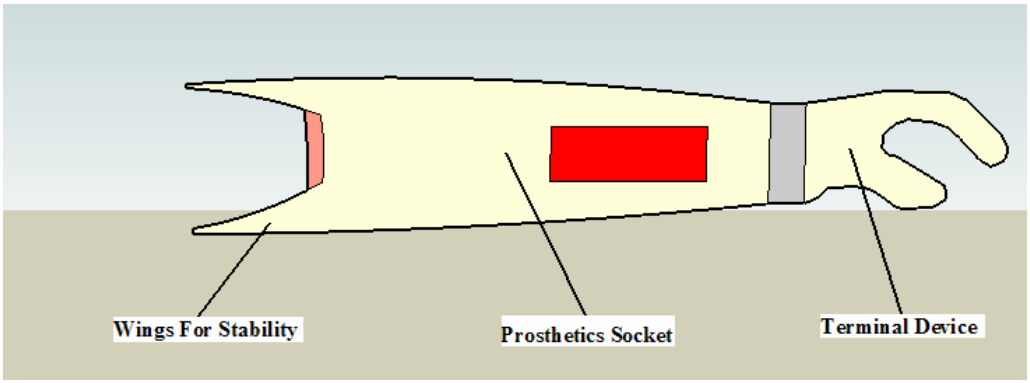


Figure 2.2.2: This is a sketch of a below elbow prosthesis with wings to support the load on the arm.

that wraps around the back of the elbow can be used, this is referred to as supracondylar suspension. The socket allows some of the load of the prosthesis to be supported by the

elbow and can be seen in Figure 2.2.3. There are some cases where suction type sockets are used [Bush, 2006]. This is when there isn't sufficient limb left to get a solid attachment with a total contact. These are usually used when the amputation is towards

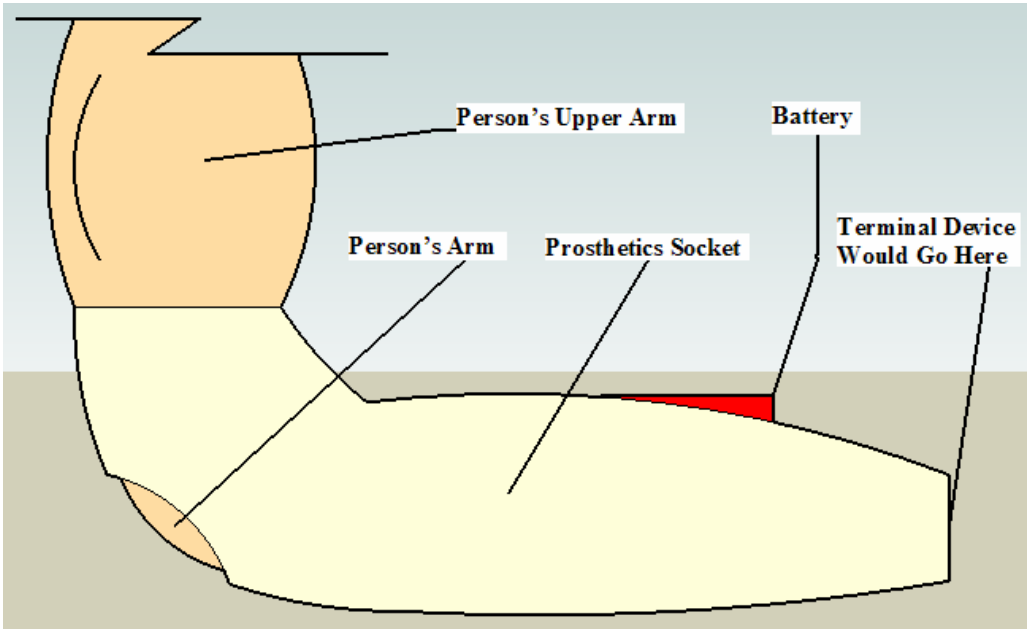


Figure 2.2.3: This is a sketch of a below elbow prosthesis with supracondylar suspension to support the load better. You see an air hole at the elbow for cooling.

the proximal end of the limb segment. Typically a suction socket is made of a silicon material with an air valve that expels air when the limb is push in to the socket. The valve can be operated with the condilateral hand to allow air to enter the socket so the arm can be removed. This would be used to keep the socket in the desired position.

2.3 Power

In upper limb prostheses there are three different categories of devices; body powered (BP), externally powered (EP) and passive. BP devices are operated by movements of another part of the body that transmit the movement to the prosthesis via a harness and cables. The EP device is one that relies on power from a source other than that of the body, usually in the form of electricity from a battery. There are also hybrids that allow

greater flexibility when fitting the user, in turn increasing the success rate [Michael, 2004]. Each form has its own merits. The BP device requires more physical energy to operate; it can be a more robust device which usually translates into lower overall cost, including fewer repairs, but, although it can depend on the user. The BP device can sometimes have a less natural look to it as well. There are usually harnessing and a bigger socket that covers more of the person's skin, with BP devices which result in more comfort and body temperature control problems. When the socket is on the user the arm is completely cover up to where the prosthesis ends. The socket is quick thick (5-15 mm) and does not breathe so that part of the body cannot get rid of the heat produced when performing daily activities because the socket acts as an insulated barrier.

2.3.1 Body Powered

Harnesses can serve a dual purpose, as the power source for the activation and control of the prosthesis. The harness can be connected to the terminal device (TD) via a cable. Body movements are relayed though the harness to control the TD. "Although the use of EP prostheses is increasing, current estimates are that about 90 percent of individuals who wear upper limb prostheses use the body-powered types because they are relatively inexpensive, functional, reliable, and have some sensory proprioceptive feedback" [44]footnote [5]. The BP is the most common prosthetic device and derives its power from movements of the body motion is transmitted through harnesses and cables. The BP devices are widely used because they are usually lighter, cheaper and easier to master then EPs. Figure 2.3.1 (a) shows what a typical below elbow BP looks like. Figure 2.3.1 (b & c) shows what a typical above elbow BP looks like. The user must rely on their strength to open the device and elastics to close it. This means the pinch force is dictated by the user's ability to oppose the rubber bands which can be viewed on the TD in figure 2.3.1 b and c. In some clinics the BP device is fitted first even when an EP device is planned for the future. The advantages help when the residual limb may still be shrinking is size due to the oedema and may need refitting, as well as the user can be fitted very quickly (usually fitted within 45 days of surgery) and this allows information to be gathered for future fittings [Stark and Leblanc, 2004].

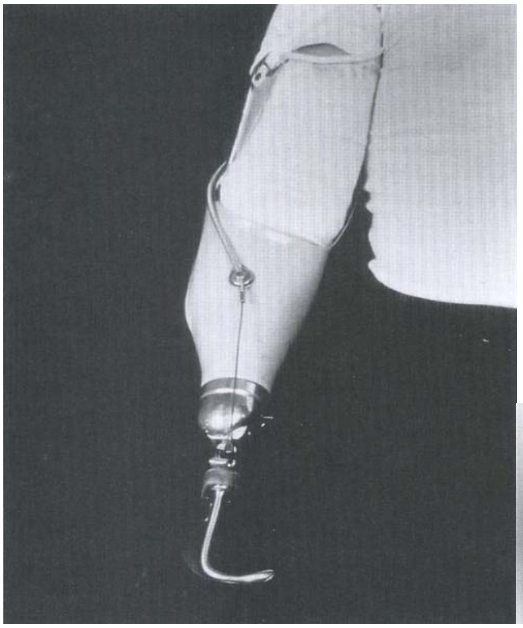


Figure 2.3.1-a: Transradial (Below Elbow) Prosthesis. [Stark and Leblanc, 2004].

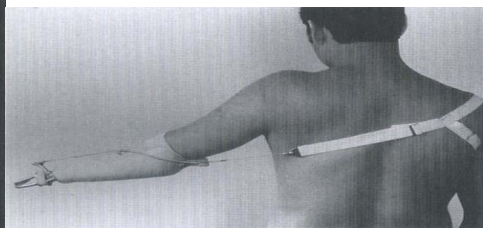


Figure 2.3.1-b: Transradial prosthesis showing A "Figure 9" harness. [Stark and Leblanc, 2004].

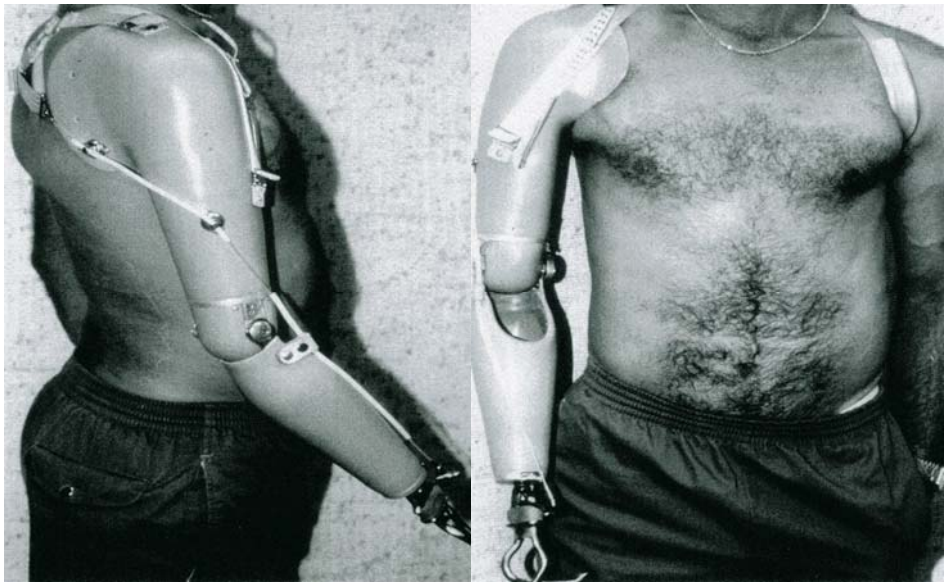


Figure 2.3.1-c & d: Transradial (Above Elbow) prosthesis. [Stark and Leblanc, 2004].

Following this first fitting the viability of an EP prosthesis can be assessed and, if warranted, can be best fit to the person's needs. This helps to reduce overall costs of EP fittings by getting it right the first time. In the clinic where this research has been conducted an EP is usually fitted right from the start, if that is the long term plan for that person. [Bush, 2006]. This is to show you the reader that there are multiple views on the fitting procedures and the author can't claim that any one protocol is superior.

2.3.2 Externally Powered

EP devices are generally operated with an electric motor powered by a battery. There have been other types of power used experimentally such as pneumatics and hydraulics, but battery power is the only commercially used solution at this time [Michael, 2004]. As a power source, EP's have relied on several battery designs; Nickel Cadmium (NiCad) have been used in the past with Nickel Metal Hydrite (Ni-mH) and Lithium Ion replacing them due to their longer battery life, faster charging and lack of memory problems that NiCad's. The Ni-mH battery is not as popular a replacement as the lithium ion battery. There have been great improvements over the last few years due to the industry improvements in battery, such as in the cell phone, hand held organizers and laptop computer batteries. These batteries give increased life with less weight and more versatility in charging [Michael, 2004].

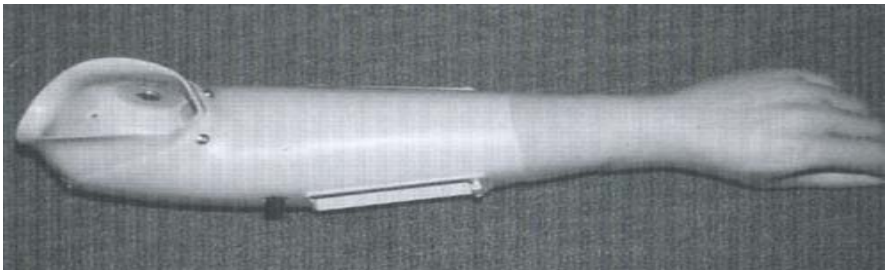
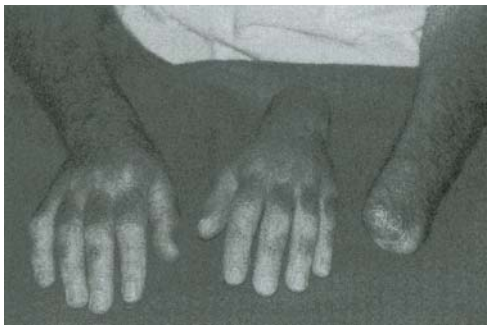


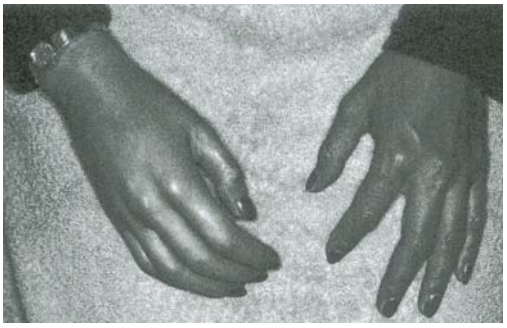
Figure 2.3.2.1 This is a below elbow EP prosthesis, with a hand type TD. [Michael, 2004]

A typical below elbow EP prosthesis as seen in figure 2.3.2.1 consists of a powered TD, a battery mounted in the socket; some type of control mounted either in the TD or in the socket and in some cases a wrist between the TD and the socket. The wrist unit isn't usually used due to limited control sites and the extra weight that it can add [Michael, 2004].

2.3.3 Passive Devices

There are cases where the person only wants to look unobtrusive, and for them a passive device is appropriate. Some people are most worried about there aesthetic appearance and the passive solution works best for them. For a person with a limb loss there can be residual pain such as phantom pain and nerve pain, but there can be physiological related. For these people hiding the limb loss is the best solution, these devices are neither EP nor BP but they serve the intended purpose. Even though they are passive, they are still functional, but only as a tool to hold, push and stabilize. This is the simplest prosthesis preferred by some users. Although relatively simple it can be just as costly when you get into prosthesis that match the contra lateral arm right down to hair and age spots and well as skin matching colors as seen in figure 2.3.3.1[Furlong, 2004].





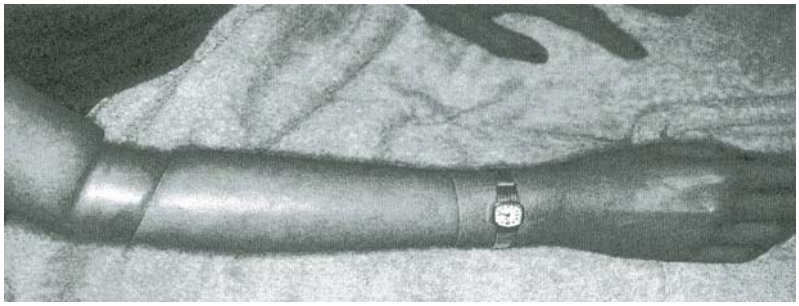


Figure 2.3.3.1 a, b, c: These are some different passive type prosthesis. [Furlong, 2004]

2.3.4 Hybrid Devices

When more than one active joint is replaced there can be a combination of devices used this is usually referred to as a hybrid solution. Hybrid designs are prosthetic devices that use more than one of the above options together. These options allow for different types of fitting where strength, lack of myoelectric signal sites or weight are issues are present giving a more functional end result. [Michael, 2004]

2.4 Control

Control options must be considered in the overall prosthesis fitting process. "A control strategy defines how the inputs from the user are used to control the prosthesis." [16] This control strategy has to be user friendly and reliable because "an amputee cannot be productive if a large portion of his or her energy and concentration is spent controlling an artificial hand."[17][Myoelectric Teleoperation of a Complex Robotic Hand] The decision of control type is complicated and should include input from the candidate, and their family as well as the prosthetist. The costs versus the resources available (insurance and charities) are other important factors to be weighed in the final decision. The ultimate goal is to accommodate the user with the best solution for their situation. The following illustrates some of the available options for EPs and the concepts behind them.

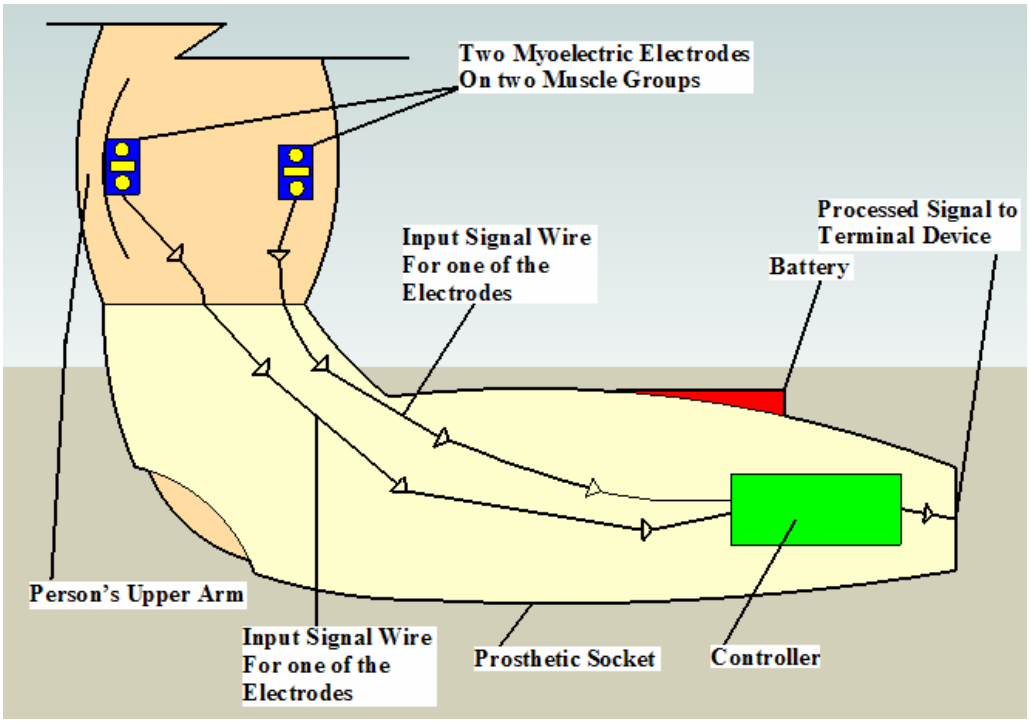


Figure 2.4.1: This is a diagram of a typical two site myo-electric setup for a below elbow. Note, that the myo-electric electrode would typically be on the forearm, but for a cleaner illustration they are place on two muscle groups of the upper arm.

2.4.1 Inputs

External Powered or EP devices can be controlled in a number of ways. These options are based on the sensors used including myoelectric, servo, the dual action switch or force sensing resistors (FSR). The most common of these is myoelectric control, but each type has its place depending on the type of limb loss [Michael, 2004]. The type of loss can dictate the control based on the number of control site available, the amount of signal that can be produced, and the physical constraints for the fitting as a result of the loss. All sensors and switches work on the same underling principles. The user wants a specific movement of the prosthesis, so there is a muscle signal produced by the user on the body, such as a muscle contraction. That movement is caused by an electrical pulse which the brain sends to that muscle to tell it to move, so when you contract a muscle the

control signal is what is looked for. This signal is picked up by a sensor and converted to an electrical signal (usually amplified and filtered). The controller uses the signal(s) to produce the desired movements of the prosthesis. This set up can be better explained with figure 2.4.1. The duration (time) of the electrical signal or the amplitude of signal strength produced (voltage level) can be used as the control input.

2.4.2 Duration and Amplitude

Duration and amplitude of the signal are used for control, because they can be varied easily. The duration of the input signal gives a usable signal which increases the amount of inputs that can be exploited from one site. The use of amplitude of the signal which is the force produced as a variable for control giving another form of control from that input. Effort can give two control options; basically, a little or a greater. Thresholds can be set to give two usable signals which correspond to open and closed. The way the thresholds are set dictates how many separate signals can be produced by one site typically an upper and lower threshold. Multiple thresholds may appear to give more control states, but this becomes too complicated for the user. Proportional control is also possible with the use of force, giving the user the ability to control speed, angular position or the amount of force applied by the prosthesis, but two sites are generally required. A mixture of temporal and force can be applied, but this is likely to increase the amount of mental effort required.

2.4.3 Voluntary Open / Voluntary Closed

A voluntary open hand or other terminal device (TD) is normally “closed” and depends on some action by the user to open. A prosthetic hook with rubber bands as seen in figure 2.4.3.1(a) to provide force to hold it closed is an example. The user pulls on the cable to open the hook and closes on its own with the assistance of the rubber band(s) when the

Figure 2.4.3.1 a & b: a) BP Hosmer 5XA hook. [Stark and Leblanc, 2004] b) BP TRS VC Grip prehensor. [Stark and Leblanc, 2004]

cable is released. Figure 2.4.3.1 (b) shows the VC grip prehensor, a voluntary close BP device by TRS. Single signal control is set up to control one movement voluntarily with the counter movement being involuntary. This alloys a person to control a device when there is only one viable control signal which cannot produce two distinct signals. So for a hand when the control signal is produced the hand will open and when the signal stops the hand will close automatically [Michael, 2004]. This is the control concept that is used for most children in their first EP device. It's referred to as the "cookie crusher" type of control. The type and brand of prosthetic hand will dictate how and when the hand will stop closing. It might stop when the motor stalls or it may have a sensing system and could be programmed to stop at a preset amount current drawn by the motor. The addition of force detection and slip is an enhancement available on some prostheses which could allow for a program to stop at a predetermined amount of force. This allows the use that can only have one input signal to perform two functions. Voluntary open is the most common with voluntary close being used only in speciality EP devices. With the types of control options mentioned, a prosthetist is given the tools to fit most forms of upper limb loss. These concepts allow the use of a single site or multiple sites with a

whole array of different combinations to accommodate the user's needs and abilities [Michael, 2004].

2.5 Mechanical Devices

For upper limb prosthetic replacement there are hands (terminal devices, TD), wrists, elbows, and shoulder units. "The artificial arm problem has not yet been solved. 'Adequate replacement of the human hand and arm is one of the most difficult problems facing medical technology'." [Michael, 2004]. BP, EP, passive, and hybrid designs are available for most prosthetic applications. There are three different categories; actuated hook, anthropomorphic hand and specialized devices (specific to an activity or task). The type of device and the way that it is fit depends on the extent of the limb loss and the desired outcome. Numerous factors have to be considered when choosing the device including; the type of injury, the level of amputation, the abundance or lack of control possibilities, strength of the residual limb (prosthetic weight issues) and the desired outcome [Stark and Leblanc, 2004].

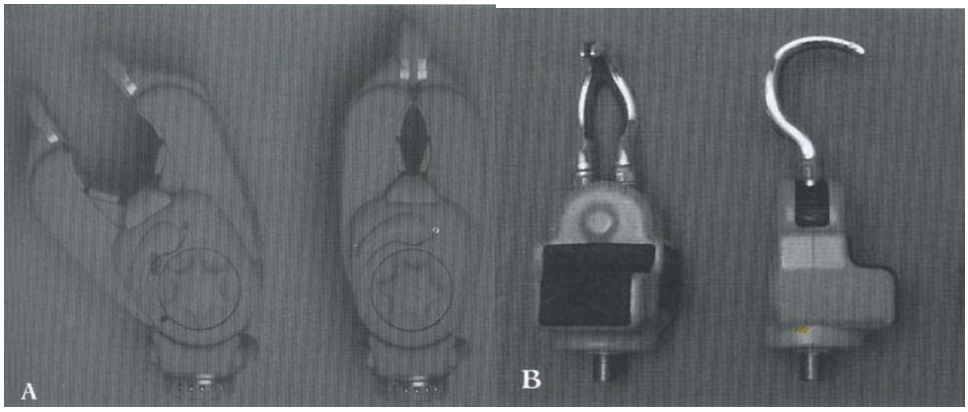


Figure 2.5.1 a & b: a) This is a Greifer, Courtesy Otto Bock Orthopedic Industries, Inc. b) This is a Hosmer Synergetic Prehensor, Courtesy Prosthetics Research Laboratory. (Northwestern University/ VA Chicago Health Care System.

2.5.1 Terminal Devices (The Hand)

The natural hand is one of the most complicated parts of the arm with its degrees of freedom and sensory feedback, which is why it is the hardest to replace. Being the furthest extremity from the body's midline, it is the first part of the upper limb to be removed due to trauma; also it always lost when there is trauma incurred further up the

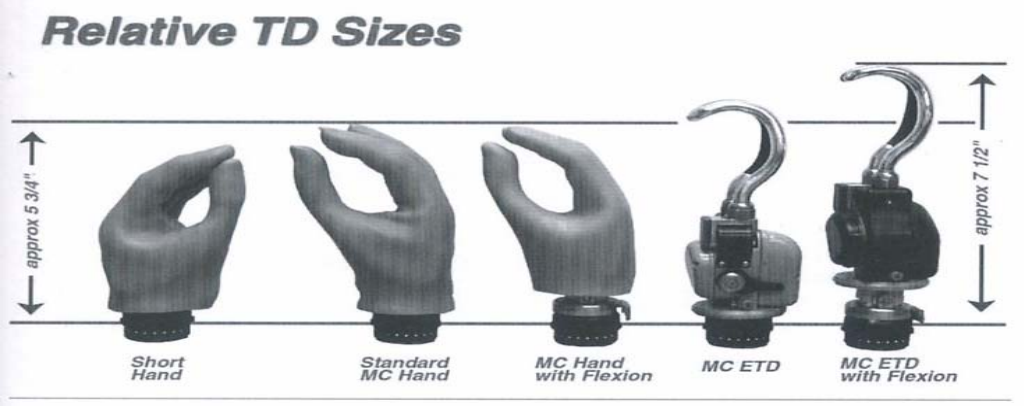


Figure 2.5.1.1 These are some different EP TDs, Courtesy of Motion Control, a subsidiary of Fillauer, Inc.

arm so that an amputation is required. With respect to hand replacement there are two general design concepts; the split hook and the anthropomorphic hand as seen in figure 2.5.1.1. The split hook is usually a BP, voluntary open device with rubber bands controlling the closing. The split hook is used for more precise work due to its narrow finger tips and the lack of obstructed view. The anatomical hand can be BP, EP or passive and has a cosmetic look to it. The EP can provide a higher pinch force with less effort than the BP [Michael, 2004]. There are also other TDs to choose from in EP, BP and passive designs. There are companies that also design and sell a lot of speciality TDs that are built especially for certain tasks. These tasks can be work related or recreational. TRS sells all sorts of speciality TDs for a variety of tasks that can be seen in Figure 2.5.1.2 [Radocy and Furlong, 2004].

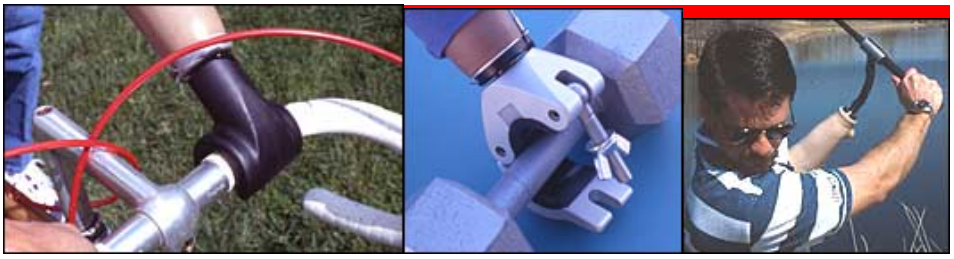


Figure 2.5.1.2: Some different speciality TDs Courtesy of TRS Inc.

2.5.2 The Wrist

The wrist is an important part of the arm and can be replaced with a mechanical one when it is lost, though it is not as efficient as the original. There are a wide range of injuries that facilitate the need for a wrist, and types of amputations can make replacement hard, such as wrist disarticulation or a distal transradial amputation. With these types of amputations, there can be a lack of space for a wrist unit without increasing the overall length of the arm past what the original arm would have been. There are pre-positioned, BP and EP type wrists available. The pre-position type are positioned by the normal limb and are either a ratchet system or an adjustable friction type. The BP type wrist uses a cable and body movement to rotate, while the EP type is battery powered and usually can only rotate, although usually more then 360° [Michael, 2004].

2.5.2.1 The Natural Wrist

The natural wrist and forearm have a combined three degrees of freedom which can be utilized in tandem, giving full range of motion of the joint. These motions are overlooked because the function of the hand overshadows them. The wrist seen in figure 2.5.2.1 produces two degrees of freedom: flexion – extension and ulnar- radial deviation. The third degree of freedom is prosupination which is actually a function of the forearm and not the wrist, but is simpler to reproduce in the wrist. The wrist is used to properly position the hand in space so it can be properly exploited. The wrist is very important but

is not thought of much till it is lost. [Michael, 2004; Stavdahl, 2002]

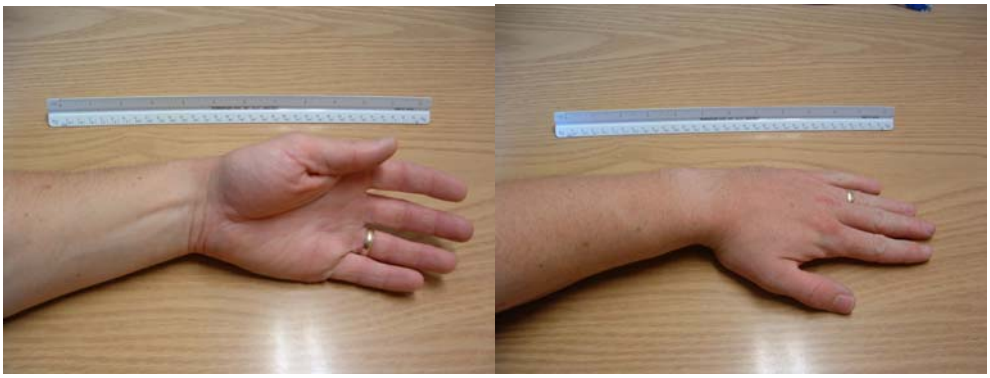


Figure 2.5.2.1: These are two pictures of a healthy wrist.

2.5.2.2 The Prosthetic Wrist

In a prosthetic fitting, the powered wrist comes up short when compared to the natural wrist. Usually they are a single degree of freedom with prosupination being the most common. With currently available control options the wrist can get passed over for the prosthetic hand. If control options are limited to operate the hand it will mean that a wrist device may be neglected. "Since the advert of easily controlled and convenient control systems, electric wrist rotation is utilized in a high proportion of the electric arm prosthesis fittings in the U.S. and Canada (estimated 30-40% of myoelectric fittings)." [P127] It has been stated that the added degree of freedom allows better positioning of the TD to better utilize its function.[30 footnote] [P127] The control is usually shared with the TD and some sort of switch or contraction to change back and forth. [Williams, 2004]

2.5.2.3 Friction Wrists

There is a complete range of pre-positioning wrists as well the externally powered devices on the market. These wrists are designed so that the user can preset the position the hand where it can be most effective for a specific task. There are prosupination and flexion-extension wrists available if the friction, preset type devices. There are

advantages over the powered types, which include less weight, less space requirements and lower overall cost, making them more common. [Uellenddahl and Heckathorne, 2004]

2.5.2.4 Powered Wrist

There are a few different designs on the market most of which are prosupination devices with a flexion-extension types now available. Most of the flexion-extension types are included with a TD together as one package. With the prosupination devices "the wrist unit is round allowing for 360° of rotation and has a disconnect facility allowing the terminal devices to be changed." [Engstrom and Van de Ven, 1999]. The Otto Bock

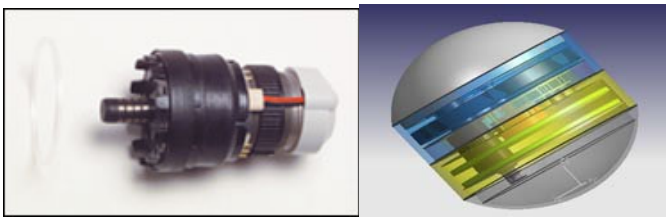


Figure 2.5.2.4: This is a 10S17 Otto Bock Electric Wrist Rotator on the left Courtesy Otto Bock Orthopedic Industries, Inc. and the NRWD unit on the right.

prosupination wrist rotation 360° as seen in figure 2.5.2.4 which is unnatural, but some users that find it functionally essential.

2.6 Training and Recovery

Rehabilitation and training are a part of the prosthetic prescription. The training can begin only after sufficient recovery of the residual limb has taken place post amputation. For congenital limb absents the training can begin as soon as the person is old enough to train. The right age of the child is subjective and depends on that child and the prosthetist performing the fitting. The rehabilitation starts soon after the accident or surgery if it is a traumatic loss. There are cases where the surgery is done later to increase the chance for a successful fitting, in these cases rehabilitation can be performed before to better the

outcome. The recovery starts after the surgery has been preformed and in concurrent with the rehabilitation.
As soon as the person is able, the training will start with practice of control movements for a BP fitting and signal control if an EP is to be used before the fitting is complete. When introduced, these aspects along with the fitting of the prosthesis early will help with the final outcome and the overall acceptance of the situation. [Alley and Migueliz, 2004]

2.6.1 Recovery

The recovery begins immediately following the accident or after surgery has been completed. The healing of the residual limb and the pain issues are part of the recovery stage, although a person with a newly acquired limb loss could also have psychological problems that should be addressed as soon as possible. The rehabilitation process should be designed to speed up the overall recovery, to facilitate the person fitted and start the training stage. To increase acceptance and willingness to train, the first fitting should be around 30 to 45 days post-op but no longer. When fitting is delayed, longer then 45 days the person is forced "to become 'one-handed' and 'forget about' bimanual activates."[4][35] "If the amputee voluntarily chooses life without a prosthesis, this choice is a positive one and should be supported. But, it is clearly detrimental to delay prosthetic fitting any longer than absolutely necessary for those who wish to adapt to this technology."[4][36 footnote]

2.6.2 Rehabilitation

Rehabilitation should include strengthening, shaping and conditioning of the residual limb. The therapist should have the patient start exercising and stretching the limb as soon as it comfortable to do so after surgery. The residual limb can also be bandaged to promote reshaping allowing the shape to be controlled as the healing progresses and to allow for the best possible fitting. Once healed, the limb will keep that shape and it will give a good surface for the prosthesis to fit to. The person may have heightened

sensitivity in the residual limb after healing, so they are encouraged to condition the limb by rubbing it with the contra lateral hand and with different textured materials. In some cases this can help to desensitize the limb to touch and make the fitting and wearing of the prosthesis more tolerable. [Alley and Migueliz, 2004]

2.6.3 Training

The training should start as soon as the fitting is completed, and should include physical conditioning as well as control training. The training of control sites for EP and the muscle movements for BP may begin even before fitting is completed. The muscles in the residual arm will be somewhat inactive and stiff due to lack of use. This means that the person's training should be progressive taking comfort into consideration. Training includes learning to use an existing muscle to get a usable and controllable signal or motion, and once the control is strong enough and consistent then task specific training can be started. The task training can be customized to fit the needs of individuals, and includes bilateral tasks to get the person using the prosthesis for activities of daily living. The faster the person learns bilateral tasks, the better the prosthesis will be accepted in all aspects of living.

The training is an important part of the prosthetic prescription that is sometimes overlooked, but it gives the person the best chance at accepting the prosthesis instead. Having a successful fitting is dependent on the recovery, the rehabilitation and the training. Without all three together a prosthetic prescription will not end up being as successful as it could be. [Atkins, 2004]

2.7 Prescription

When working on a prosthetic prescription there are a lot of factors to consider, as fitting a person with a prosthetic device or devices is a complicated job. The person being fitted

is dealing with a lot different things at once including the actual limb loss, psychological factors, healing, and pain. Knowing that the faster a person is fitted after an injury the more likely that person is to accept and learn how to use it, leaves little time and agreat deal to get right. The type of power and control should be looked at first as well as the input from all the people involved such as the candidate, their family, friends, the surgeon and the people in charge of rehabilitation. What the person would like to accomplish from this outcome is important as well. Then the type of device that will be used will depend on these choices. First and foremost the weight will always be an issue with fitting. When all matters are considered, the best prescribed prosthesis should result along with the correct rehabilitation and trained. This should give the person the best chance of a successful fitting and continued use.

In 1985, LeBlanc, 2004 [40 footnote] stated, "Standard body-powered upper-limb prostheses have not changed significantly since developments in the 1950s [that] were spurred by World War II. [Prosthetists] still employ ancient technology using a shoulder harness and steel cables for operation." This observation still holds true today. The artificial arm problem has not yet been solved. "Adequate replacement of the human hand and arm is one of the most difficult problems facing medical technology" (2) [41 footnote].

3.0 The NTNU Revolute Wrist Device (NRWD)

The NTNU Revolute Wrist Device (NRWD) is a concept based on the work of Dr. Øyvind Stavdahl at the Norwegian University of Technology and Science, Trondheim, Norway [ref]. The dissertation explored which single axis represents the ideal 1-DoF approximation of the healthy wrist's functional workspace" [Stavdahl 2002]. With a unilateral absence, the dominant arm is invariably the sound limb which would relegate the prosthesis to a support role [ref]. Therefore the research considered the

single degree of freedom wrist in tasks where the prosthesis is in the non-dominant role only. While prosupination is the usual choice for powered wrists [1 or 2 refs needed], no rational for this arrangement is ever stated so it was proposed that a rotator set on some oblique plane may increase functionality.

Comment [MSOffice1]: You need to back that up with references.

3.1 Background

In order to validate their claims, tasks of daily living were performed with eight right handed (18 to 30 year old) healthy subjects, while they performed 15 different ADLs. All tasks were all bilateral and were used to assess the wrist in the non-dominant role [Stavdahl and Skjelten, 2005]. Their data was validated by analyzing those from a separate pilot study which explored the compensatory movements of the elbow, shoulder and torso with persons who have a trans-radial limb loss [Stavdahl 2002]. From this study the optimal orientation for a single degree of freedom was determined to be:

Comment [MSOffice2]: Do you cover the ADL's anywhere for an apples-apples comparison?

- Pronation Angle of 3 °
- Extension Angle of 7 °
- Ulnar Deviation Angle of 5 °

The above angles define an oblique plane that varies from a perpendicular plane to a vector that originates at the elbow and passes through the wrist of motion [Stavdahl, 2002]. These findings were used in the design of the new wrist prosthesis and will be used to further test the previous hypothesis.

3.2 DESIGN

The new wrist design is the result of a collaboration between the members of the NTNU and the IBME. The mechanical design and testing of the wrist was performed at UNB while the electronic controller and control program were produced elsewhere.

Comment [MSOffice3]: You should be stating what you are going to report in the thesis in the intro – 1st page

3.2.1 Design Criteria

The criteria for design are based on commercial products [refs].

The Criteria:

- less then 65 millimetres in length.
- weigh less then 100 grams.
- rotational speed of at least 1.42 radians per second (13.5 rpm).
- stall torque of at least 35 mNm.
- ability to adjust the oblique plane of rotation.
- overall diameter that is less than or equal to the diameter of narrowest part of a healthy adult male wrist.

Comment [MSOffice4]: Male ? Female? They are very different sizes.

3.3.1 Mechanical Design

Comment [MSOffice5]: Only put in your final design. I had like 5 design iterations for my foot but only reported on the one that worked. Only report on what was tested. If it was not tested or was scrapped, it is not in here. Having that said however, you need to back up why you have the design the way it is such as strength calcs, size modeling… etc.

The original NTNU motor was found to occupy a too large of a volume to meet the size constraint. To meet the aforementioned criteria, a Faulhaber 0620 K 006 B motor was coupled to a Faulhaber 08/1K 16:1 transmission. The most significant change to the original design was making the angle of rotation of the wrist adjustable at the both ends. See Figure 3.1. The smaller dimensions of the motor and transmission along with the

Comment [MSOffice6]: If you are not going to use the previous motor, then it should not be in here.

alignment changes allow for greater flexibility as well a reduction in the complexity of the machining needed

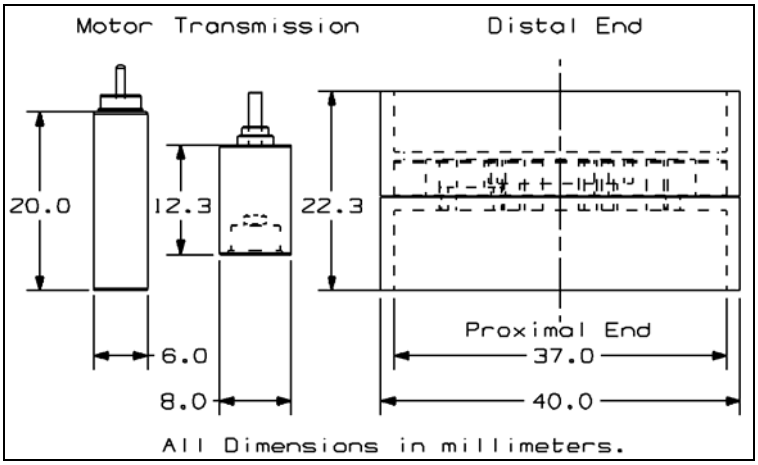


Figure 3.1: The NRWD along with the 6 mm motor and 8 mm transmission that are in the current design, along with the zero angle wrist case.

The main bearing size 37 x 30 x 4 mm part number MR6706 was retained due to the limited range of available sizes, but the outer diameter could be decreased to 40 mm with the same wall thicknesses. Although the center opening between the distal and proximal sections remained unchanged at 27mm more room for components became available due to the drive train modifications. .

3.3.2 The Drive Train

The required reduction ratio was accomplished using three separate stages consisting of a belt stage, a planetary gear second stage and a ring and pinion third stage

Comment [MSOffice7]: You REALLY need a table that clearly displays each stage and its torque. What you have now is not that clear at all. You should not need to leaf across pages to see how it all interacts.

(Figure 3.2).

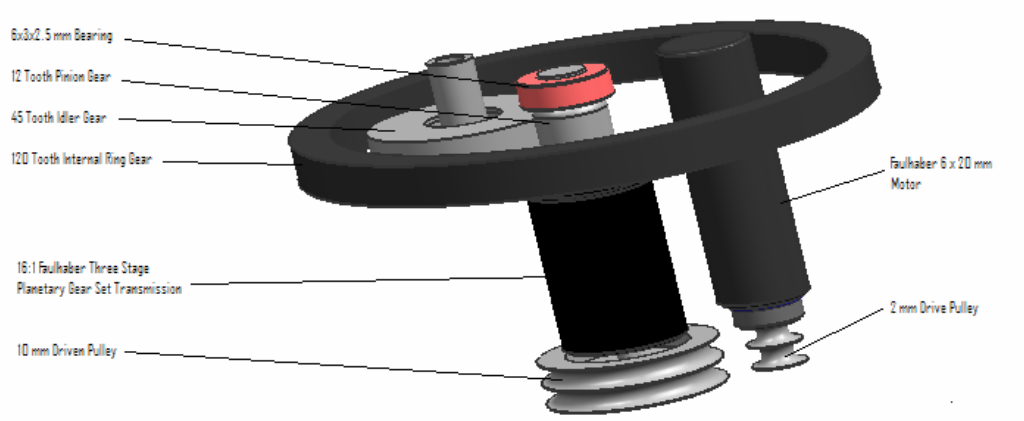


Figure 3.2: Transmission assembly.

Belt Stage

The first reduction stage is a multi belt-stage between the Faulhaber 0620 K 006 B motor and the Faulhaber 08/1K 16:1 planetary gear box. Compared to metal gears, a belt design was chosen for its noise reduction characteristics in addition to providing the appropriate reduction ratio. The motor was fitted with a 2 mm diameter drive pulley that accommodated two belts (#014 rubber O-rings). The belts are attached to a 10 mm driven pulley which produces a reduction of 5:1. Based on belt calculations in Appendix B for size, one 0.81mm belt will be needed. This design incorporates two 1.7mm belts two increase the safety factor and keep size down. Two belts allow for 13.76 W to be transmitted and the maximum power provided is 3.593 W, so a design factor of 3.8. Friction calculations shown in Appendix B show that the double o-ring design has against slippage by a factor of 2.2.

$$TOT = TOR \times MST$$

$$TOT = 5 \times 0.73mNm$$

$$TOT = 3.65mNm$$

TOR =*Reduction Ratio*

TOT =*Transmission Output Torque*

MST =*Motor Stall Torque*

$$Vout = \frac{Vin}{TOR}$$

$$Vout = \frac{47000rpm}{5}$$

$$Vout = 9400rpm$$

This increases the torque to 3.65 mNm while reducing the rotational velocity to 9400 rpm.

Planetary Gear Stage

The output of the large pulley is used to drive the sun gear of a three stage planetary gear set that produces a reduction of 16:1 with at an overall efficiency of 80%.

$$TOR_2 = TOR_1 \times RR_2$$

$$TOR_2 = 5 \times 16$$

$$TOR_2 = 80:1$$

TOR_2 =*Reduction Ratio*

RR_2 = *16:1 reduction Ratio*

The reduction ratio at the output of stage 2 is 80:1.

$$TOT = TOR_2 \times MST$$

$$TOT = 80 \times 0.73mNm$$

$$TOT = 58.4mNm$$

TOR =*Reduction Ratio*

TOT =*Transmission Output Torque*

MST =*Motor Stall Torque*

$$Vout = \frac{Vin}{TOR_2}$$

$$Vout = \frac{47000rpm}{80}$$

$$Vout = 587.5rpm$$

This will reduce the speed to 587.5 rpm and the Increase the torque to 58.4 mNm after loses are considered. This is below the continuous torque rating of 60 mNm and the intermittent troque rating of 120 mNm.

Ring and Pinion Stage

Made up of a part number PS96S3-12 for the pinion, P96S19-45 for an idler gear and a N96S2-120 for the internal ring gear. All three of these gears are made of 303 stainless steel, having a pitch of 96, and face width of 3.175 mm (1/8”) and a pressure angle of 20°. The third stage increases the overall reduction ratio to 800:1 which increases the torque to 584.0 mNm and reduces the speed down to 58.75 rpm. The pinion is attached to the output shaft of the planetary gear set. The idler gear is used to transmit the power to the ring gear without having to move the pinion closer to the outer part of the wrist and allows the second stage to remain closer to the middle so not to interfere with the wrist’s rotation. The choice of the idler design had to take into consideration the side loads that would be applied to the second stage transmission at the output shaft. When the pinion and the idlers are put in line the side loads on the pinion would be

cancelled out. The pinion and idler are now stabilized by a support over the top of them to control the forces incurred. The idler turns an internal ring gear which is attached to the outer shell of the distal half of the wrist. The power flows from the wrist prosthesis into the hand at this junction.

$$RR_3 = \frac{DrivenGear}{DriveGear}$$
$$RR_3 = \frac{120Teeth}{12Teeth}$$
$$RR_3 = 10:1$$

$$TOR_3 = TOR_2 \times RR_3$$

$$TOR = 80 \times 10$$

$$TOR = 800:1$$

$$TOR = Reduction\ Ratio$$

The reduction ratio at the output of stage 3 is 800:1.

$$TOT = TOR \times MST$$

$$TOT = 800 \times 0.73mNm$$

$$TOT = 584.0mNm$$

$$TOR = Reduction\ Ratio$$

$$TOT = Transmission\ Output\ Torque$$

$$MST = Motor\ Stall\ Torque$$

$$Vout = \frac{Vin}{TOR_3}$$
$$Vout = \frac{47000rpm}{800}$$
$$Vout = 58.75rpm$$

Comment [MSOffice8]: Import a table from Excel to summarize the info better.

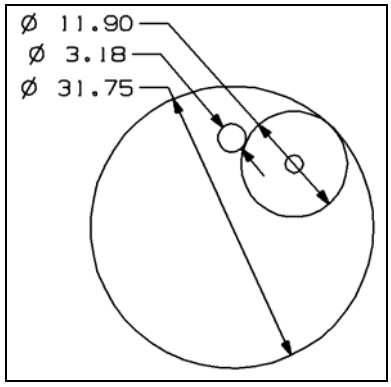


Figure 3.3: Two idler setups. A single idler gear and parallel idlers gears.

The 6 x 3 x 2.5 mm part number MR63-ZZ (Boca Bearing Company) bearing is used in the support position is indicated in figure 3.4a by the arrow. Figure 3.4b shows a CAD representation of the support. It connects to the idler shaft and the support shaft as in figure 3.4a. there is one bearing on the pinion shaft opposite to the 16:1 transmission output to support the pinion under load. The other MR63-ZZ (Boca Bearing Company) bearing has the idler gear riding on it with a support shaft through it. The bearing support and idler shaft are held in place by two 2 mm screws.

Comment [MSOffice9]: Where does the bearing fit into all of this again?

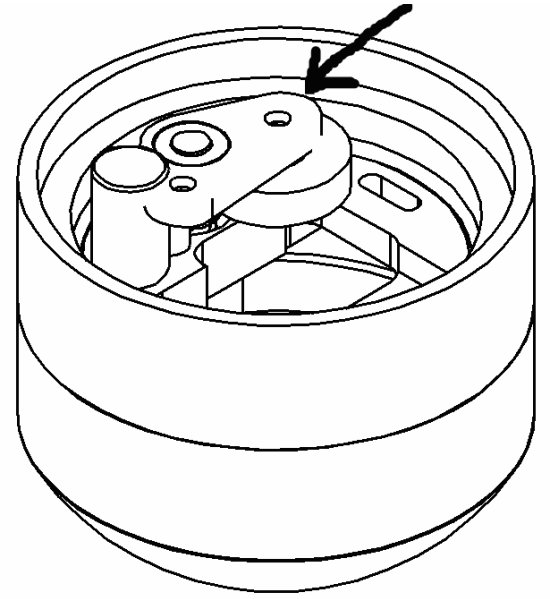


Figure 3.4a: The arrow points out the bearing support.

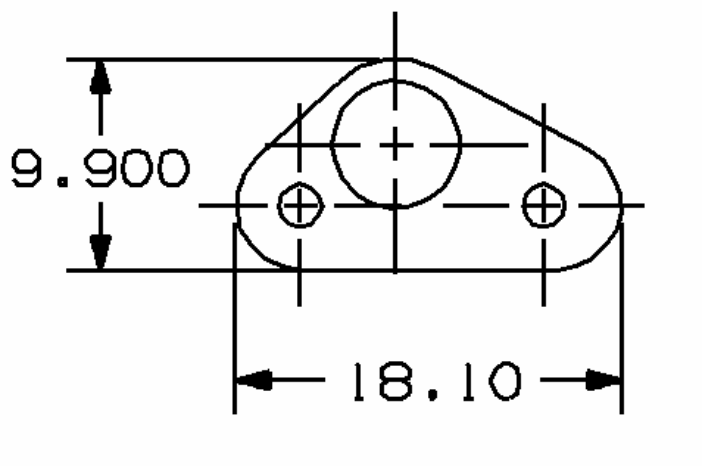


Figure 3.4b: This is a CAD representation of the bearing support.

3.4.1 Wrist Design

The main body of the wrist is made of two sections referred to as; the proximal and the distal sections. These two sections are the housing for all the components of the wrist are in figures 3.5 a and b and are joined to each other by a 37 x 30 x 4 mm part number MR6706 bearing (Boca Bearing Company).

Comment [MSOffice10]: Give bearing model so people can look it up

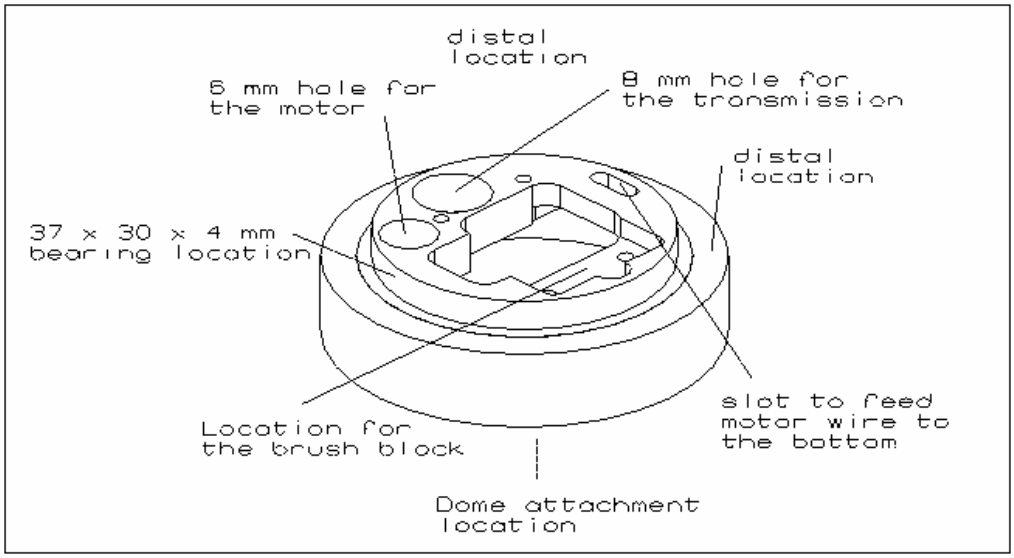


Figure 3.5a: Proximal section of the main body.

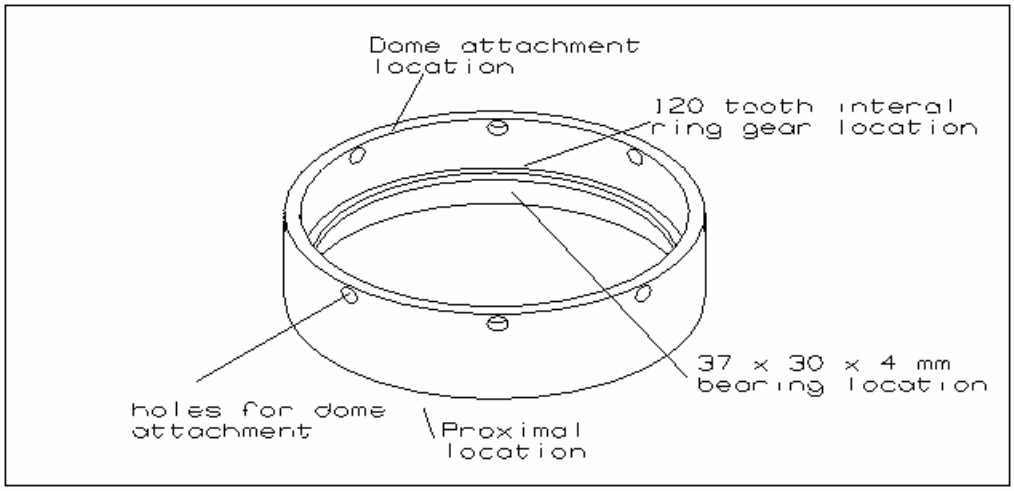


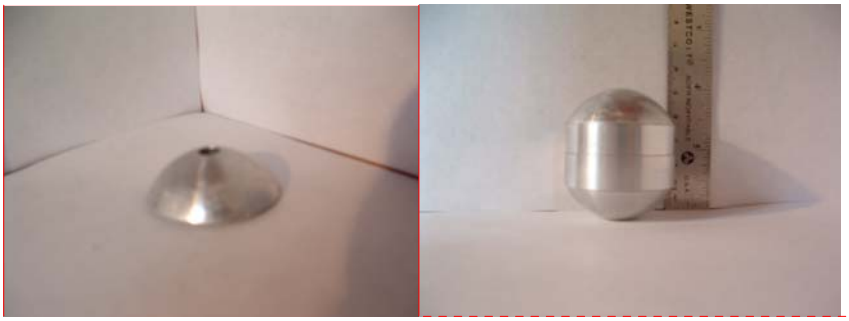
Figure 3.5b: Distal section of the main body.

The wrist to rotates at this bearing, giving the wrist its single degree of freedom. The bearing is a press fit into both sections with adhesive being used to ensure that it stays together. The main body has a slotted dome at either end which is held in place with six 3 mm screws around the circumference of each end of the main body. This allows the easy servicing of the internal components.

Comment [MSOffice11]: That seems excessively bulky! Why not just some M1.6's???

3.4.2 The Domes

The domes serve to both seal the main body (figure 3.6 a and b) ,allow for adjustments in the orientation of the main body with respect to the arm and hand allow for more than one orientation of the plane of rotation to be tested.



Comment [MSOffice12]: Lousy resolution – not clear. Need better pics

Figure 3.6 a and b – The dome and the dome attached to the main body.

The adjustment is about the center of the wrist and without having to redesign or construct new parts. and are achieved by having a slot machined in to each of the domes. These domes along with the slots are here to allow the orientation of the wrist to be set in the desired position. The slots can be seen in figure 3.7 cap screw to go through it and attach it to the arm or at the distal end. These slots allow the dome to slide along this cap screw which is how the wrist is adjusted. The locking mechanism discussed in the next section.

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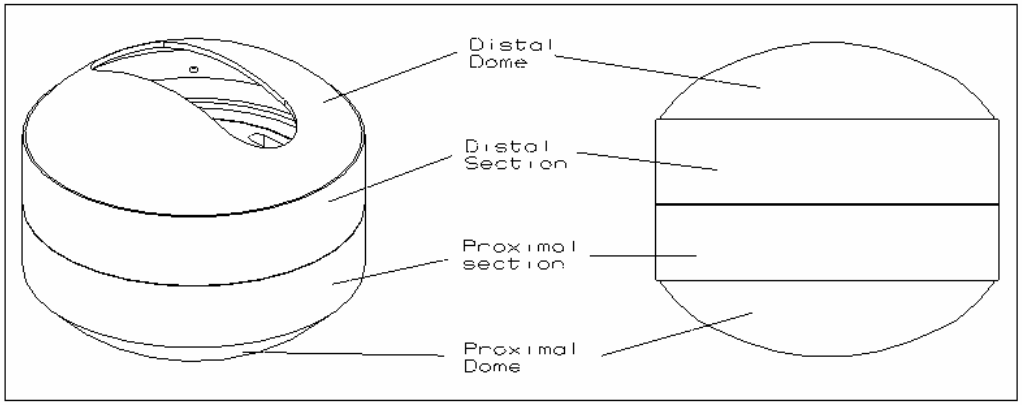


Figure 3.7: Schematic of the attachment relationship of the domes and the wrist.

3.4.3 The Adjustable Ends

Made of 6061-T aluminium, the ends facilitate attachment of the domes to the socket of the prosthesis at the proximal end, the prosthetic hand. See figure 3.7. The geometry reduces the over all length and allows the wrist's domes to slide in the concaved sections. The center cap screws thread in to the attachments (figure 3.8).

Comment [MSOffice14]: Lousy resolution…Peter will definitely ask for better pics

Figure 3.8 – This is the concaved section of the attachment and one of the domes.

The wrist was designed as a sphere with a diameter of 45.5 mm, with the proximal and distal ends left rounded and the center sections machined down the 40 mm to reduce the overall mass and size. The sphere shape was used to allow the wrist to be positioned in many configurations without having the hand offset from the arm at more extreme angle from the forearm. These ends consist of the concave piece, a center bolt, two concave crescents and two 3 mm diameter x 15 mm screws. The concave section is 39 mm in diameter and has a 30 mm diameter recess machine in the center and where the two crescent pieces reside. The dome set in the concave section and the center bolt passes through the dome's slot and threads into its respected end section. The center bolt

is tightened up until it touches the inside surface of the dome without obstructing the dome ability to slide freely. This center bolt is held in place with green lock tight. The crescent sections are concaved but set below the concave section. Two screws going in perpendicular to the forearm vector go thought the one section and thread into the other. When these two screws are tightened up they pull the two crescent sections together around the center bolt, as they come together they put pressure on the dome which locks it in place. These ends allow easy adjustment of the main body relative to the forearm vector and the position of the hand relative to the wrist's main body.

3.4.4 The Internal Components

The main body of the wrist houses the drive motor, drive train and the controller. The battery and the electrodes are housed exterior to the wrist, within the socket. The proximal section houses the motor, transmission, as well as the first two stages of the three stage reduction and two thirds of the final stage. In addition to the mechanical components, the NTNU developed controller was designed to fit on the four surfaces of the two 36 mm diameter circuit broads that stack and fit into the proximal section. The motor and the transmission fit through the both circuit boards (Figure 3.9).

Comment [MSOffice15]: I don't understand

The distal section houses the 120 tooth internal ring gear that is a press fit in that housing. The section also houses the slip rings, with the brush block being attached to the proximal section which allows the control signal and power to be carried on to the hand. These slip rings allows the wrist to rotation more than 360° without binding.

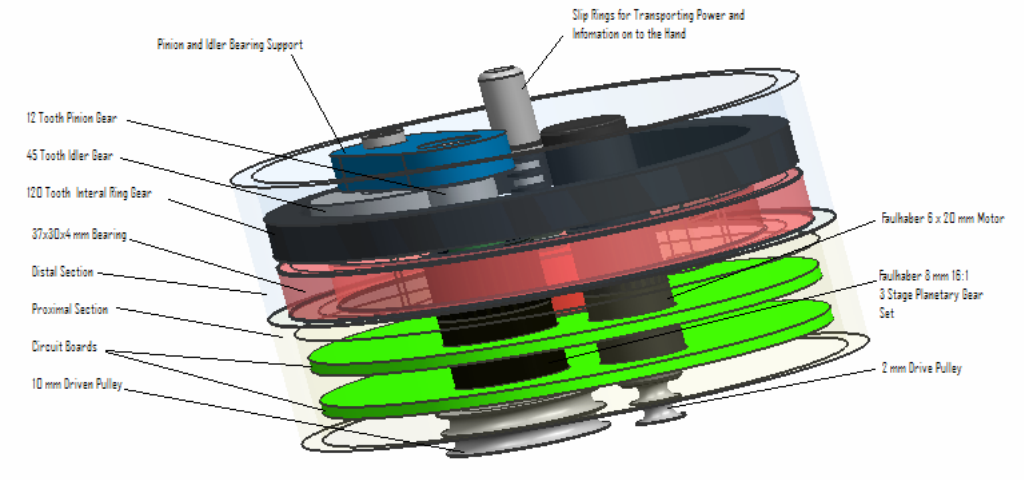
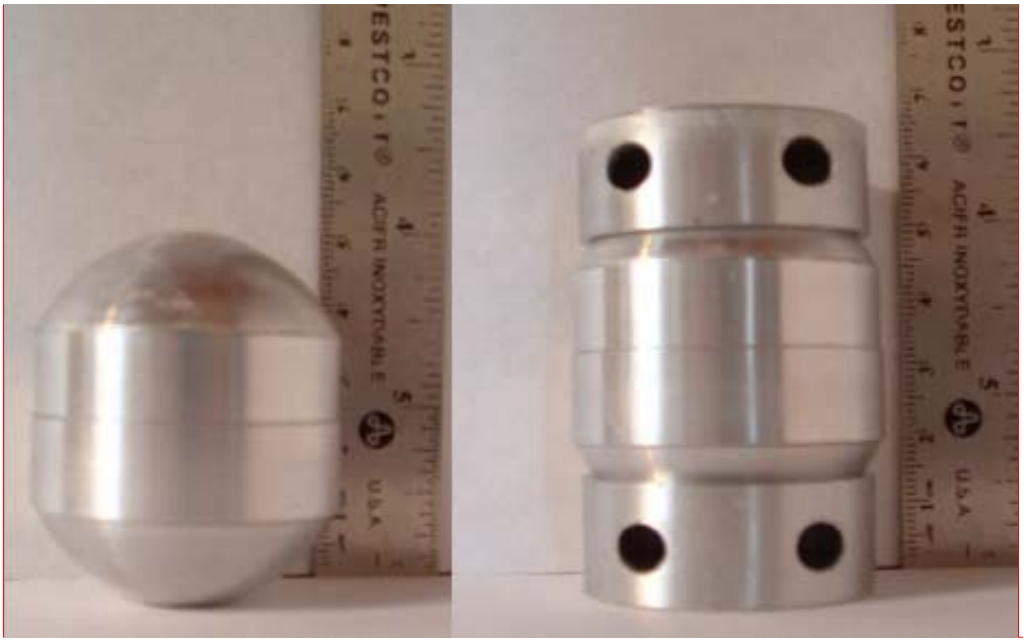


Figure 3.9: This shows the placement of the internal components of the wrist

3.4.5 Assembly

The wrist when assembled without the attachment sections measures 40 mm in diameter and has a length of 45.5 mm (Figure 3.10a). With the additional sections it measures 61 mm long (Figure 3.10b), which is within the criteria.

Comment [MSOffice16]: You have to at least mention an assembly drawing in the Appendix. Where is it?



Comment [MSOffice17]: Again, bad pics

Comment [MSOffice18]: What are the attachements??

Figure 3.10: a. Complete 45.5 mm wrist. **b.** Wrist with attachments

3.5 The Controller

The Control of the wrist is achieved by a microprocessor controller that is mounted in the proximal part of the wrist. The controller uses a ATML #### processor. The controller was designed, constructed and programmed in Norway. The control will process signals detected by Otto bock electrode amplifiers The user will either control the wrist or the hand depending on which is selected. The selection will be preformed with a co-contraction of the two muscle groups. The velocity and torque will be adjustable. This allows the wrist to be tuned to the user or to mimic other wrists on the market.

4.0 Experimental Method

4.1 Experiment Design

The experiments in the project are designed to help show that the NRWD will or will not reduces the compensatory movements when compared with a standard prosupination wrist rotator. The Wrist was designed around pervious work [Stavdahl 2002] as stated in chapter 3. Now that the wrist is designed and constructed it has to be tested to see if it will produce the required movements and to see if there is some functional advantage by using. To give the wrist credibility the wrist will be tested in a similar way to the way the oblique plane was arrived at. To do this the experiment will use six tasks of daily living from the original task set and will be performed in the motion lab here at UNB. The tasks will be tracked using the Vicon Motion capture system and the anglicised using statistic with the help of Dr. Maureen Tingley.

4.1.1 Compensatory Movements

When normally limbed people perform a physical task there are some motions usually required. Compensatory movements are the extra movements that are required to perform the same task with prosthesis. These are extra movements such as more elbow flexion / extension; more should excursion; and more humeral rotation. The movements help complete the task at hand but can cause other problems such as joint pain and even injury.

4.2 Participants

For this thesis there will be tests preformed on two groups of people, prosthesis users and normally limbed subjects. Both groups will be setup in the Vicon lab to do the same six

ADLs. There are some differences in the setup before the activities are performed depending on the test group. These differences will be explained in the next two sections.

4.2.1 Prosthesis Users

There will only be two prosthesis users asked to participate in this thesis due to the inconveniences involved. The users will be below elbow unilateral limb absents. The subjects that are asked and accept will be involved in the testing over a six week period. This time will include an initial visit to go over the consent and any concerns as well as the first tests. Two subsequent visits, one and two weeks and one at four weeks will be required as well.

4.2.2 Normally Limbed

There will be at least 15 normally limbed subjects in this part of the experiment. For the statistical analysis more is always better so more then 15 will be tried for, time permitting. The subjects will be able to complete their requirements in a single visit unlike the prosthetic users. The entire visit should take two to three hours from start to finish. The subject will be test on the non-dominate forearm and hand will by reducing the function of that arm using cast material splint. The idea is to mimic a below elbow

prosthesis with the best wrist that a person could possibly have, the human wrist. The subject will perform the same six tasks as the prosthesis users, but it will be a one visit session and no follow ups.

4.3 Vicon System

The experiments for this Master's Thesis will be performed using the Vicon system. When a subject arrives at the Motion Lab to be tested the first thing is to go over the information sheet and the Informed Consent form. Once all questions and concerns have been address and the consent form has been signed the testing can begin. The person is asked to change into a tank top to allow better access to the bony landmark ob the upper body where the markers will be attached with double sided tape. The person will be told in advance of the tank top requirements so they can bring their own if they feel more comfortable. The Informed Consent and Information sheet can be found in Appendix A. Before the person arrives at the lab the camera setup, the calibration and retrieval of the

proper materials for the experiments will be all ready completed to reduce the time they are needed.

4.3.1 Motion Capture System

To capture the data produced when the experiments were performed the VICON M-cam system was used. This system was developed and is manufactured by Oxford Metrics (Oxford, England). The system being used for the wrist experiments is an eight camera Vicon system in the Institute of Biomedical Engineering building at UNB. This system use infrared strobes on the cameras to track the positions of reflective markers attached to the desired subject. The cameras are mounted on tracks on the walls of the motion lab. They can be taken off the wall and positioned on tripods if needed, but both can be adjusted in the roll, yaw and pitch directions. Figure 4.1 shows the motion lab as well as the cameras on the wall track and tripods.

Figure 4.1: VICON M-Cam Motion Lab at UNB

The motion capture system used here tracks reflective marker balls that are attached to the subject with two-sided tape or Velcro straps to setup virtual references on the body. Two sizes of markers 16 and 25 mm in diameter were used in these experiments. Given a calibrated origin the VICON system tracks and reconstructs the positions of the markers balls in 3D space. The calibrated origin is determined at the start of each session with the use of calibration objects from the manufacturer which have multiple reflective markers on them at known positions to with respects to each other. The Vicon has to see the marker balls with at least two of the eight cameras to reconstruct its 3D position. The system's data capturing frequency was set at 60 Hz for the duration of these experiments, but can be adjusted from 1 Hz all the way up to 250 Hz if needed. From the data

captured in a trial the position of each marker relative to time can be reconstructed in a virtual representation of the motion lab with the help of the Vicon Workstation software. Figure 4.2 shows a typical marker set reconstructed in the workstation. The marker can then be pieced together with body segments with a user written text file program specifying how the markers connect relative to each other. The markers have to be labelled manually by the user first so that the software knows which marker is which before it proceeds to connect them. The acronyms in the figure represent landmarks on the upper body and are described in Table --.

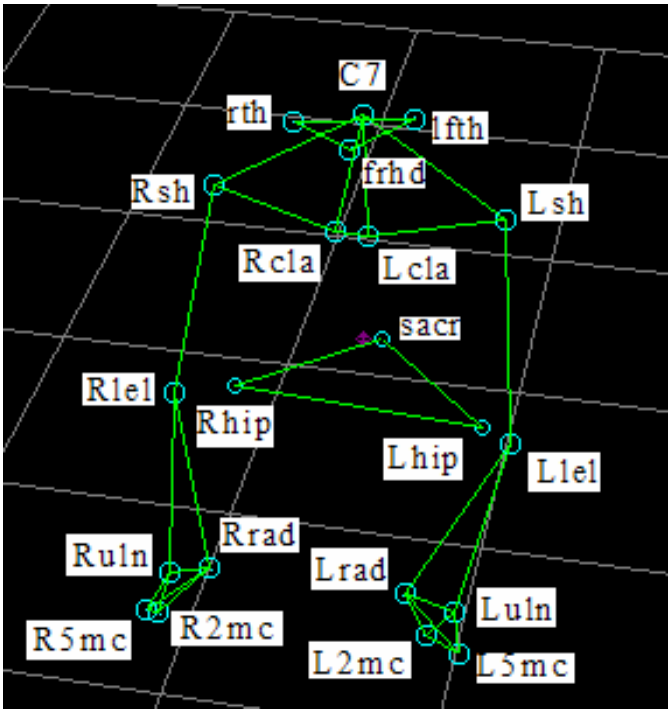


Figure 4.2: A labelled VICON marker set and data reconstruction

Once a successful data capture has been the markers are labelled according to a pre programmed marker set has stored in a text file. This text file lists all the markers according to there landmarks on the body and describes how they are to interact with one another. Once the marker set has been labelled a figure similar to the marker set in figure 4.2 will be displayed o the screen. After the marker set has been labelled the marker trajectories are then stored in binary files (**.c3d*) with resects to time. Before the files are ready to be analyzed, there are several steps to prepare the data. Please refer to Appendix B for specific settings and steps to facilitate data collection.

4.3.2 Accuracy and Reliability of the VICON M-Cam System

The VICON M-Cam (8 cameras) system's performance is dependant on the camera configuration and volume of the workspace. The accuracy of the currently used system's predecessor, VICON 512 (6 cameras), was tested for a known distance of 500 mm in three different ways: static, linear translation, and rotation (Chester, 2004). The volume used for the NRWD experiments is less than that of the study done by Chester (2004). The mean error and standard deviation of VICON 512, VICON M-Cam's predecessor, is shown in Table 4.3.

Table 4.1 - Measured error of VICON 512 system (Chester, 2004)

Test	Mean Absolute Error ± SD (mm)	Max absolute error (mm)
Static	0.106±0.048	0.230
Translational	0.305±0.219	0.937
Rotation	0.775±0.639	3.620

To understand what significance the error has on the joint angle measurements an example using the anthropometric data from a seven year old was used. The largest maximum absolute error shown in Table 3.3 is 3.620 mm for a rotating marker at a slow unknown angular velocity. Figure 3.4 represents the top view of the forearm of a child. The solid markers represent where actual markers are located on the forearm. The distance between them is 90 mm, the approximate length of the seven year old subject's forearm. Larger framed children would have less error and smaller framed children would have more error. The dashed markers indicate how the maximum error of 3.620 mm could change the marker position by 3.62 mm in either the X or Y direction. The vector between marker A and B would change its orientation by an angle θ equal to 2.3°. Therefore, the angle between two vectors with a maximum absolute error would combine to a total of 4.6°. This value represents the worst case for the error in angle calculations between two vectors.

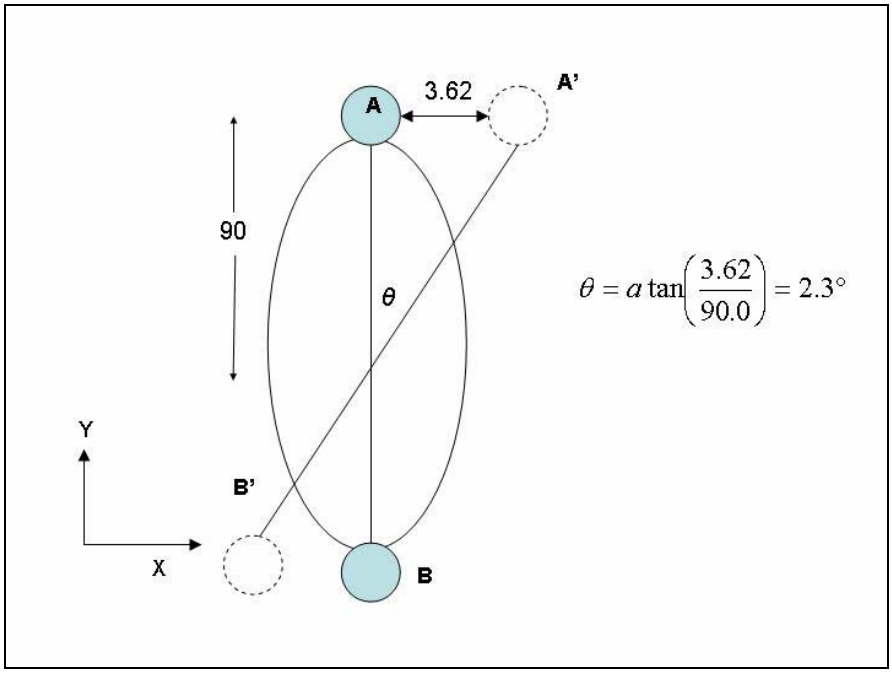


Figure 3.3: Model of top view of child's forearm for maximum angle error

4.3.3 Camera Location

The cameras in the motion lab are setup in eight positions on the walls as a starting point for any data capture. The position of each camera is important and is dependant on the marker set and activity to be captured. To establish the optimal camera setup several test sessions were performed doing the six ADLs that will be used throughout these experiments. The desired setup from the test trails was determined based on the ease of

setup with the tracking of the marker balls without losing them being the main deciding factor. The cameras were setup around the tasks with the largest needed area.

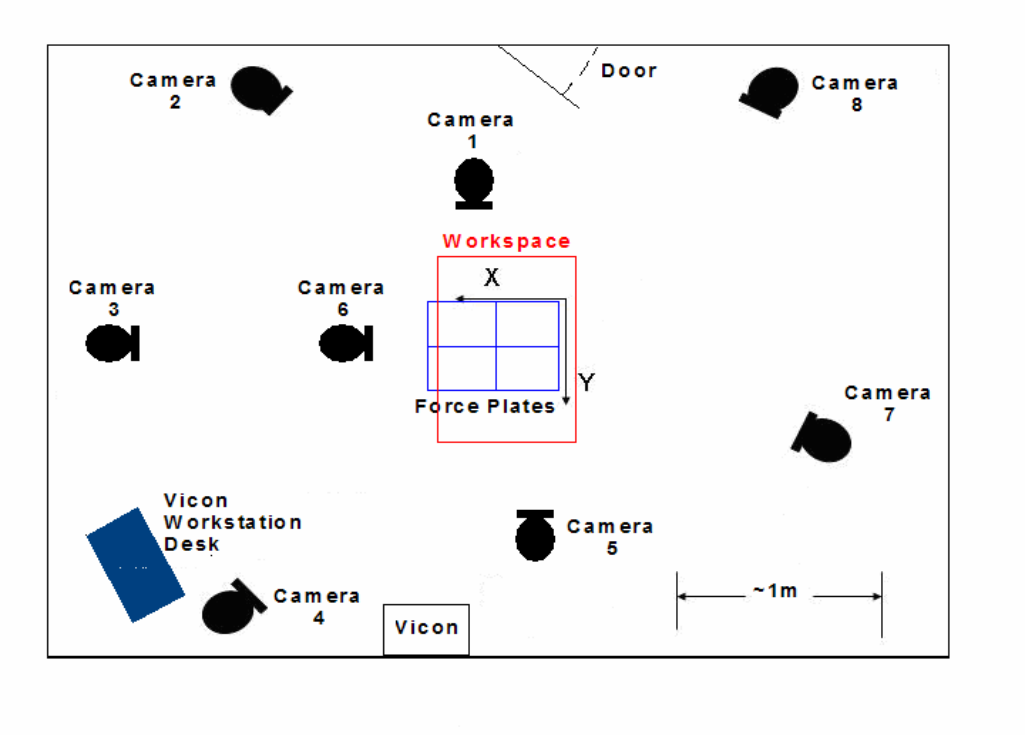


Figure 4.1: Overhead view of motion lab camera setup.

This allowed four of the eight cameras to be put on tripods and moved in closer to the desired capture area. From figure 4.1 it can be seen that cameras 1, 5, 6 and 7 are on tripods and cameras 2, 3, 4 and 8 and left on the wall mounts. Figure 4.1 shows the desire workspace and its position in the room relative the force plates. Once the optimal setup was determine the camera positions were recorded for reproducibility. The tripod positions were marked with tape on the floor, the height and general positions were

recorded as well. Finally the L-shaped calibration bar was placed in the force plate grooves so each of the eight cameras positions could be recorded. The positions of the four marker balls on the calibration bar were recorded on a transparent sheet placed over the Vicon computer screen for each of the eight cameras individually. For any future work a copy of the transparency can be found in Appendix -.

4.3.4 Marker Setup

There are a total of twenty-two marker balls which are described in Table 4.4, secured to the upper body of the subject using double sided tape or elastic straps. The markers are attached on bony landmarks such as the styloid process of radial bone at the wrist joint as shown in figure 4.2. To try to standardize marker setups used at the Institute of Biomedical Engineering, the present setup was copied from Ross (2005) which was a copy of Pick (2004) and Losier (2004) with the addition of the three pelvis markers. Depending on the distance between the markers, two sizes of markers were used, 16 mm for smaller distances and 25 mm for larger ones. The markers will be placed on bony landmarks to allow for repeatability between subjects.

Table 4.4 - Locations and sizes of the 22 markers.

Llel	left lateral epicondyle	25
Lrad	near left styloid process of radial	25
Lulna	near left styloid process of ulna	25
L2mc	left 2nd metacarpal head	16
L5mc	left 5th metacarpal head	16
Rsho	right shoulder	25
Rlel	right medial epicondyle	25
Rrad	near right styloid process of radial	25
Ruln	near right styloid process of ulna	25

R2mc	right 2nd metacarpal head	16
R5mc	right 5th metacarpal head	16
Lhip	front of left ASIS	25
Rhip	front of right ASIS	25
Sacr	flat part of the sacrum	25

The markers will be attached to the subject using Velcro straps and two sided tape. The location of the markers can be viewed in figure 4.5. The head will have three markers attached to it using Velcro strap. The waist will also have three markers attached around it using a second Velcro strap. The rest of the markers will be attached to the torso and arms using two sided tape.

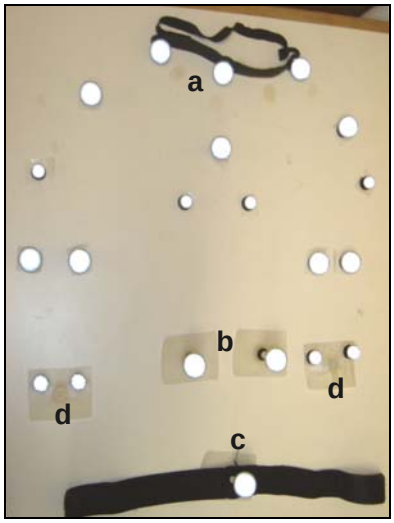


Figure 4.5 - Shows the marker balls and where they are placed on the subjects in relation to each other. [Ross 2005]

4.3.5 Fitting the Subject

Whether the subject is part of the normally limbed group or the NRWD users group they all have to be fitted and adjusted with the supervision of Greg Bush (the Prosthetist) or Wendy Hill (the OT Nurse).

4.3.5.1 Prosthetic Users

When a prosthetic user arrives for testing they will have to be fitting on the first visit by Greg Bush and Wendy Hill with a new socket including the NRWD wrist and a Trans carpal hand. There will be a minimum of three testing sessions for them so they will see Greg and Wendy before and after each testing session for adjustments and concerns. The new socket will be the same as there current socket with a shortened overall length to accommodate the wrist and hand without increasing the overall length of the arm. This may mean a visit before any testing is done to gather the information needed for the new socket construction. Once the fittings are completed the subject can return to the lab to be tested. There will be multiple days of testing with the participant being allowed to use the prosthesis at home during the study. The prosthesis has to be returned after the study has been completed.

4.3.5.2 Normally Limbed Subjects

When a normally limbed person comes in to be tested they will be asked which hand is there dominate arm. The non-dominate arm will then be splinted to limit undesired motions. The hand will be splinted to reduce it motion to a straight one DOF prosthesis

hand motion without limiting the wrist motion. The elbow will be splinted as well to mimic the socket of a below elbow limb deficiency. Therefore a reduction in the amount of flexion and extension in the elbow will be introduced. All the splinting will be done by the author with the supervision of the OT here in the Biomedical Building. The splinting will be done using a plaster casting material. The casts will be applied with the hand in the proper position (position will mimic a one DOF power prosthetic hand) and allowed to set. The same visit the subject will be tested after the casts are set. At the end of the testing in the same session the casts will be removed and discarded. This allows for the participant to only need one visit.

4.4 Experimental Procedure

When a subject arrives at the Motion Lab to be tested the first thing is to go over the information sheet and the Informed Consent form. Once all questions and concerns have been address and the consent form has been signed the testing can begin. The person will be fitted as per the explanation in section 4.2.4. Next the person is asked to change into a tank top to allow better access to the bony landmark ob the upper body where the markers will be attached with double sided tape. The person will be told in advance of the tank top requirements so they can bring their own if they feel more comfortable. The Informed Consent and Information sheet can be found in Appendix B. Before the person arrives at the lab the camera setup, the calibration and retrieval of the proper materials for the experiments will be all ready completed to reduce the time they are needed. There are procedures for both normally limbed subjects and prosthetics users.

4.4.1 Prosthetic Users

The first visit will include running through the six ADLs with the user's current prosthesis. The first visit will also include measurements and a casting of the residual limb. The final position of the electros will be found using the myo-boy. To find the best position the user will have the electros taped to the control areas they usually us and will be connected to the myo-boy. Then the OT nurse will get them to perform muscle contractions as they would when using their prosthesis. Once that optimal position is found the construction of the socket can begin. From the first visit to the second there needs to be ample time for the prosthetics clinical team to construct a socket and mount the NRWD, the hand, the battery and the required electronics including the electrodes. This should be completed in a two week period.

The second visit the will start with the user being fitted with the new NRWD equipped prosthesis. There will be checks for fit and electro signal performed by the clinical team. The wrist will then be set in the NRWD or the prosupinate configuration before training can begin. The positioning of the wrist will be decided in advance with a coin toss. Out of the two users if heads on the coin is the result the first user will get the NRWD position and the second user will get the prosupination configuration. Once all adjustments are completed the user will be allowed to practice (train) with it for awhile at the institute (awhile being one to two hours). After ample training the user will be asked to perform the six ADLs again with this configuration. Once the ADLs are completed then the user will be allowed to go home with their normal prosthesis and the

experimental one. They will be asked to use the experimental prosthesis at home when ever they fell comfortable to do so.

Two weeks after the second visit the user will come back in and go through the ADLs with the experimental prosthesis in the configuration that they first received it in. The prosthesis will then be taken and the configuration will be changed to the one that they didn't have the first time. While the adjustments are going on they will be asked about their time at home with it. They will also be asked if there were any problems or concerns with it. After the configuration has been changed they will be give the same amount of practice (training) time they got on the second visit and then be asked to perform the six ADLs again. After the testing they will be sent home again with their regular prosthesis and the experimental one and they can use it the same as they for the last two week.

Two weeks after the third visit the user will return again. Once again they will be asked if there were any problems or concerns with the prosthesis. They will be asked to perform the six ADLs for one last time with the second configuration. Once the ADLs are completed the experimental prosthesis will be returned to the me and the user is free to go with their regular prosthesis. The user can not keep the experimental prosthesis because the NRWD won't have continued support if broken or damaged and the prosthetic hands were borrowed and must be returned.

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As stated earlier when the study is completed the new prosthesis must be returned, regrettably they cannot keep the new prosthesis.

4.4.2 Normally Limbed Subjects

The normally limbed subject will come to the IBME only once for their test session. First they will need to have their non-dominate arm splinted to reduce motion of the hand. While performing activities the motion will be recorded using the Vicon motion capture system. The marker balls, coated with reflective tape will be attached to the skin on your upper torso and arms using two-sided tape. The markers are what the Vicon tracks. The subject(s) will be asked to stand or sit in a chair, depending on the task and perform activities of daily living. These activities will be the same tasks as the Prosthetic users have.

Before the subject(s) perform the activities, they will have the opportunity to practice. They will be required to wear a tank shirt, to ensure visibility of markers placed on the shoulders. You will be video taped for reference alone with the motion capture so that data collection can be referenced with this video. The subject may decline to be video taped for the experiment. The entire test will take two to three hours in one test session. No subsequent visits are required unless there is a problem with the date that can be tracked back to a technical problem.

Data collected will focus on the characteristics of the natural side as compared to the splinted side. During the test session, the subject will be asked to complete three trials of each activity note above. They will be asked to answer a questionnaire. They may decline to answer any of the questions if you choose.

4.4.3 The ADLs

Activities of Daily Living (ADL) are tasks used to assess a person's ability. They are task that everyone does on a daily basis such as washing dishes, feeding themselves, dressing, etc. We take these things for grant it but when faced with a limb loss these tasks can become very hard if not impossible. This is were prosthetic devices and specially designed tools for specific tasks comes in to play. A person with a limb loss will benefit greatly from the ability to perform these tasks by themselves; it allows them to regain their independence. The ADLs allow the assessment of these devises and tools to see the functionality if any of

4.4.3.1 Selection of Activities

The original work consisted of 16 tasks of daily living, from these ADLs the most appropriate six were chosen for this testing. [Stavdahl] The decision to reduce the number of ADLs was based on the fact that some of the 16 show identical information, secondly for the subjects being tested with the NRWD there was concern that the testing sessions would be too long, and finally some of them would be too hard if not impossible to perform with a limb deficiency. To reduce the number of ADLs to six and justify the decision, it was decided that a discussion with the OT would be sufficient. The discussion included Krista Fraser (OT), Colleen Dewis (master's student), Dr. Kyberd (advisor), Dr, Biden (advisor), Dr. Stavdahl and I. From the discussion the final six ADLs were chosen to be:

1. **Hanging clothes on a clothesline and then removing them from the line.** With the person stand on his/ her feet, they will be instructed to take various clothes from a clothes basket and attach them to the line using clothes pins. When done they will be asked to remove the pins and place the clothes back in the basket. The clothes line will be approximately 1.7 m from the floor and set in pervious experiments, while the clothes basket will be places on a near by table while the task it is performed.

2. **Slicing bread.** The person will be instructed to cut a loft of bread into 2 cm slice using a bread knife. This task will be performed on a table of kitchen counter height.

3. **Eating with a knife and a fork.** The person will be instructed to cut up a slice of bread and eat it with a fork. This task will be performed setting at a table.

4. **Sweeping the floor with a broom.** The person will be instructed to stand and collect up debris spread onto the floor into a pile. This will be done with the use of a domestic size broom.

5. **Stirring in a pot.** Person standing by a table, freely selects the proper cooking utensil and proceeds to stir in the pot as if to prepare a meal (e.g. Kraft Dinner)

6. **Cutting with scissors.** With the person sitting at a table with a pair of appropriate scissors (e.g. Left or right handed) and a piece of paper. The person will start with both hands on the table and then will proceed to cut the paper when instructed. The person will stop when commanded.

4.5 The Results

The resulting raw data from each of the test sessions was put through a series of Matlab functions that was developed originally by Laura Brown, Martha Ross and Yves Losier. There are changes that are being made to this code to allow it to be used by Ben MacPhee in continued work on the project that Martha Ross started. The changes although starting out small are becoming a large revision of the code. This revision was started by Ben and was carried on by myself.

4.6 Analysis

The analysis has been discussed with Dr. Maureen Tingley. The experimental method is based on the analysis. When the design was getting close to being completed there were discussions of how to test the wrist, Dr. Tingley was included in these discussions. By involving her, the entire experimental part of the project was developed around the analysis. The numbers of each group was chosen to give a supportive analysis. The types of ADL and the number of them were chosen to give a complete representation of the wrist without doing useless and redundant tasks. With the experimental methods discussed above a complete statistical analysis should be possible. The actual analysis

still needs some more discuss. Once some of the subjects have been tested and the data has been processed then the results can be used to finalize the statical analysis.

Data Analysis

The first part of the data analysis was preformed in Matlab. The raw data was collected and stored for each subject using the Vicon motion capture system. This data was processed using Matlab code developed by colleges in earlier work at the Institute of Biomedical Engineering at the University of New Brunswick (Losier, 2002, Ross and Brown, 2004). The code has gone though extensive change with a large part of new code being added by Ben MacPhee (UNB Masters student) to allow proper analysis of our data. Ben is using this update code is his research as well and deserves a lot of credit for the revisions. The All Vicon data was reviewed and processed in Vicon Workstation. This was done to find all the good trials. From the Matlab code result were derived in the form of relative joint angles.

4.5 Trial Selection

In the data collection stage of the experiment there were six ADL tasks preformed. There were three complete trials captured for each of the tasks, meaning there were some subjects that would have had four or five trials taken because of mistakes, missing markers or technical difficulties. The trials from the Vicon data were each reviewed and had a marker set attached to them. All extra markers due to reflection

and seeing other cameras were removed as well. The trials were selected for each activity based on whether or not they were acceptable. There were trials that were deemed un acceptable because of missing markers (markers may have fallen off or could of went missing during a task), subject making mistakes, being distracted during the capture or malfunction with the capture equipment. Only one good trial for each activity for each subject was required. If more then one trial was acceptable based on the above criteria, then other aspects were reviewed to determine the best trial.

4.6 Matlab Code

As previously mentioned, Matlab programming language was written to convert, process, store and analysis the raw Vicon data. The code was broken down into three parts; the first part read the data in and converted it to a format that was compatible with Matlab. After the data was converted then local coordinate systems were created to represent the mechanical model of the subject in that trial. Finally the data was analyzed and relative angles were determined between the body segments using the created coordinate systems. A complete copy of the Matlab code can be seen in Appendix C.

4.6.1 File Conversion

To keep track of the data and to reduce the amount of typing required to analysis a trial the subjects were given a code name (Ross 2004). This code is very similar to other students that are using this Matlab code. This is done to reduce the amount of

information that is required to be entered in to the computer when analyzing a trail. The file ***converter.m*** is the main file in the program that carries out the all the task by calling numerous functions to complete the analysis. Figure 4.14 show the code and how it is made up. The code contains a lot of the major information about that subject including:

- Whether the subject is a non – prosthesis user (N) or a prosthesis user (P)
- The sex of the subject, (F)emale or (M)ale
- Which is the subjects dominant hand (for prosthesis users the dominant hand refers to their Condi lateral hand
- The two digit number is just a reference to the order in which they were tested (one being the first and two being the second and so on)
- The last letter is there as an index if needed

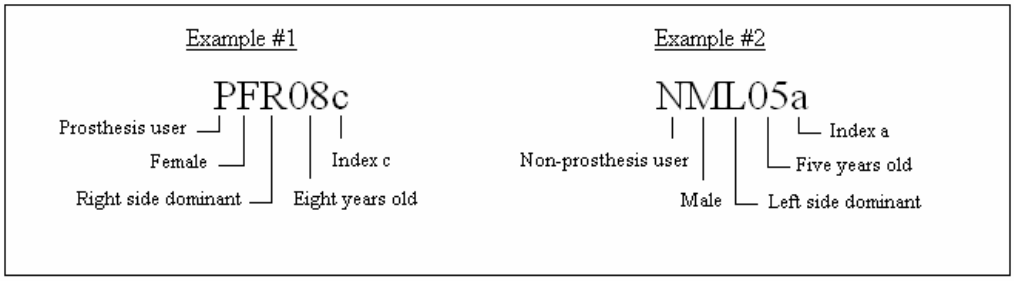

Figure 4.14: Example of the subject code. (Ross, 2004)

The Matlab code uses this subject code to know initial information about the subject data being analyzed. The Matlab code will ask for addition information to know which function to call and what way to proceed with the analysis. The program will ask for addition information such as:

- The type of wrist: NRWD or Prosupination

- The type of activity and the specific trial being processed
- The start and finish frames of a trial that is being analyzed
- The distance measured between the medial and lateral epicondyle
- The static file and frame (used to calculate C7)

Once all this information has been input the ***converter.m*** then calls the function ***getvicondata.m*** to go and retrieve the data in *.cd3 format from the static file. Then the C7_adjustment is call to calculate the angle needed to adjust C7 to a usable value.

The data from the specified trial was retrieved and converted into 2-D file (75 x the number of frames) that contains the x, y, z, coordinates of each marker using the ***getvicondata.m*** function. The ***converter.m*** function then calls a series of other function to process the data and come up with the relative angles at each of the joints for each of the six tasks. Once this is done the angle data will be stored as *.mat files.

Coordinate Systems

To analysis the motion of the body, the body was given eleven local coordinate systems that represent the different segments of the body. The three dimensional, orthogonal axes coordinate systems were created to help represent a mechanical model of the human upper body. The function labeled ***coordinate_system_creator.m*** was created to produce the local coordinate systems when called by ***converter.m***. Figure 4.2 shows how the program defines the individual coordinate systems in a schematic. The next section will explain how each coordinate system is derived.

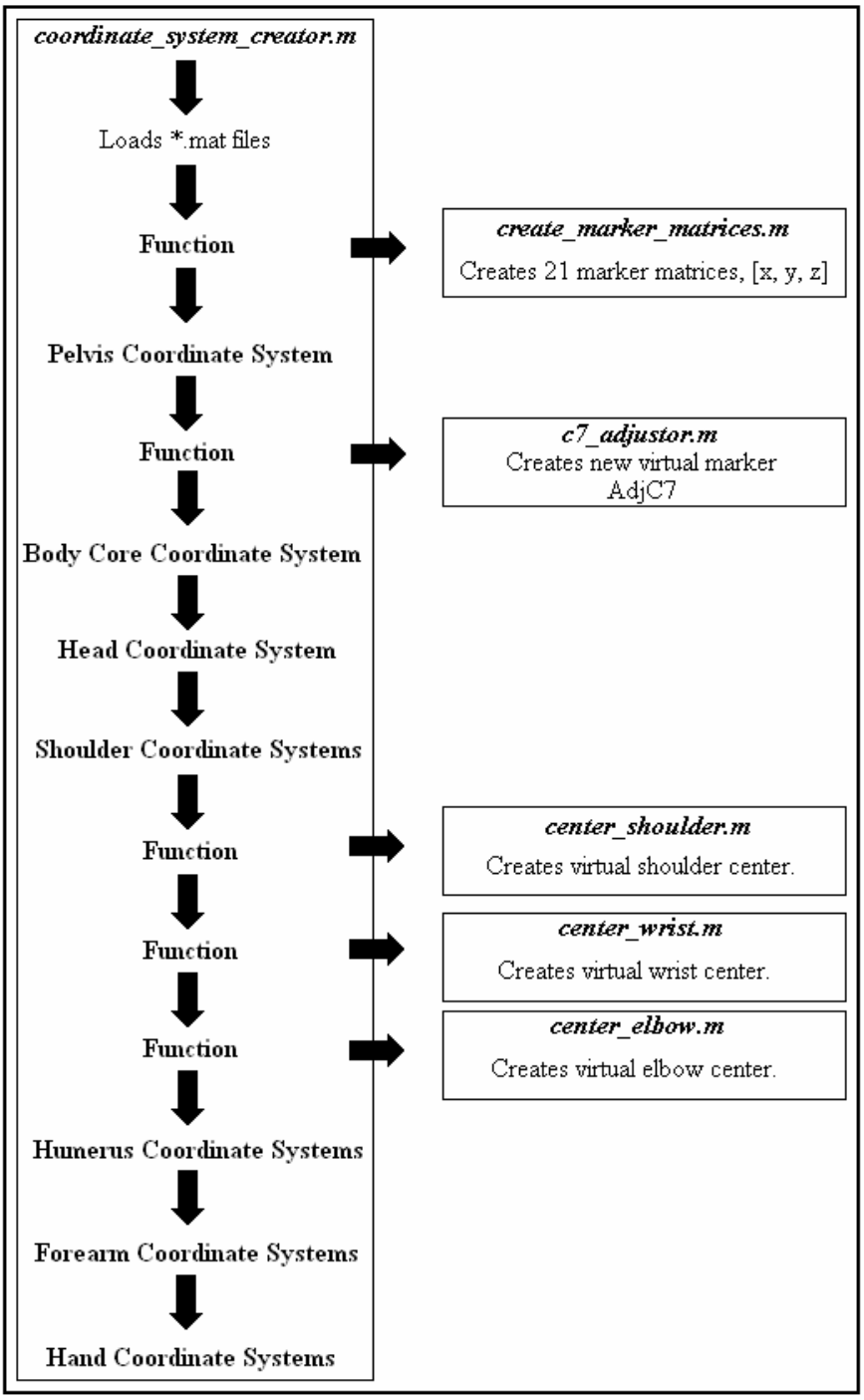

Figure 4.2 Schematic of coordinate systems creation. (MacPhee, 2007)

Hips

The coordinate system for the hips is constructed by first taking the vector that starts at the right hip marker and passes through the left marker as the y-axis. The z-axis was created by crossing the y-axis with a vector from the right hip marker to the sacrum marker. The x-axis is the result of crossing the y-axis and the z-axis.

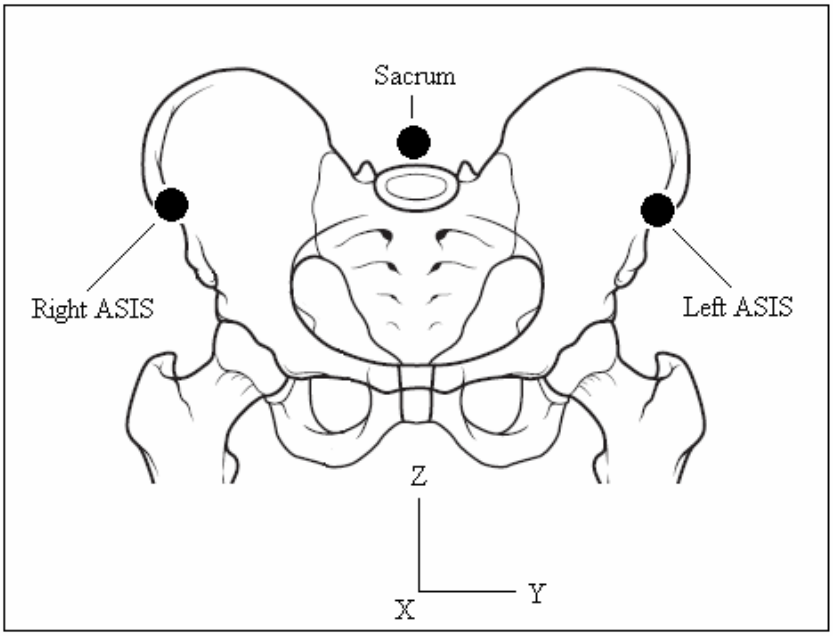

Figure 4.3 Diagram of pelvis, markers and coordinate system. (www.medscape.com, modified)

Trunk

The trunk was defined using the NECK marker at C7 and the clavicle markers. The NECK marker was adjusted using a function called ***c7adjustment.m*** to be perpendicular with the vertical of the subject standing. The NECK marker is used to create a new virtual C7 marker by rotating about the y-axis created by the two clavicle markers. The angle that the C7 had to be rotated was calculated earlier in ***converter.m*** program. Next within the ***coordinate_system_creator.m*** function the ***c7_adjustor.m*** function was called

to rotate C7 to the proper location and create the virtual marker AdjC7. The trunk coordinate system was then created. The y-axis was created by a vector that starts at the RCLA (right clavicle marker) and projects though the LCLA (left clavicle marker). The z-axis was created by crossing the y-axis with a vector from the RCLA through the adjusted C7. The x-axis was found by crossing the y-axis and the z-axis.

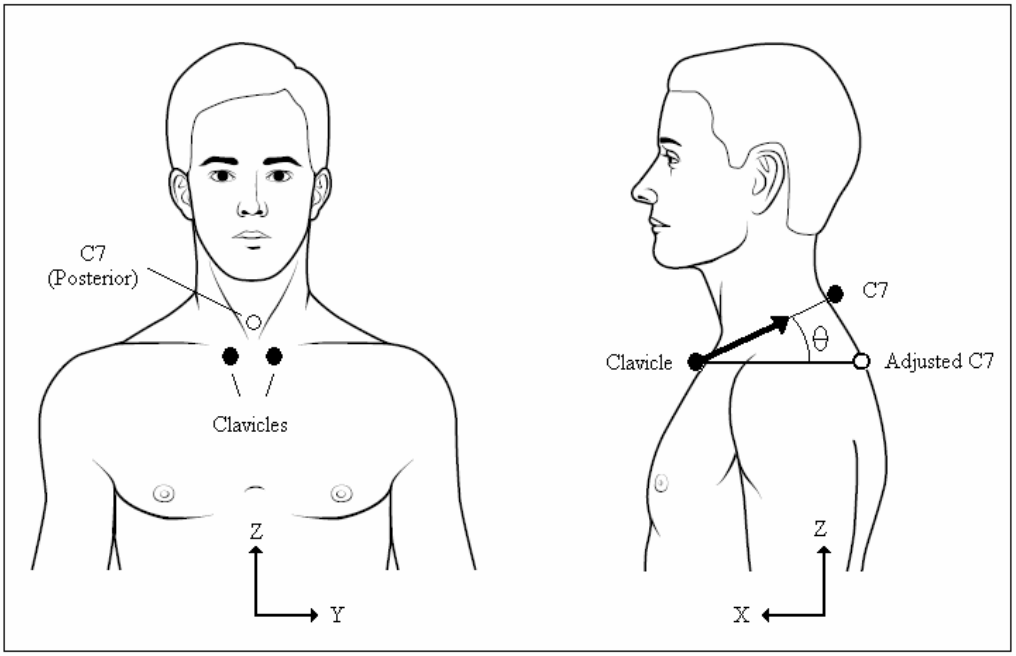

Figure 4.4 Trunk coordinate system. (www.medscape.com, modified)

The Head

The coordinate system for the head was derived from the three head markers. The y-axis was based on a vector starting at the right side head marker that intersected the left side head marker. The z-axis is the found by crossing the y-axis vector with a vector from the right side head marker that intersects the front of head marker. The x-axis is the cross of the y-axis and the z-axis.

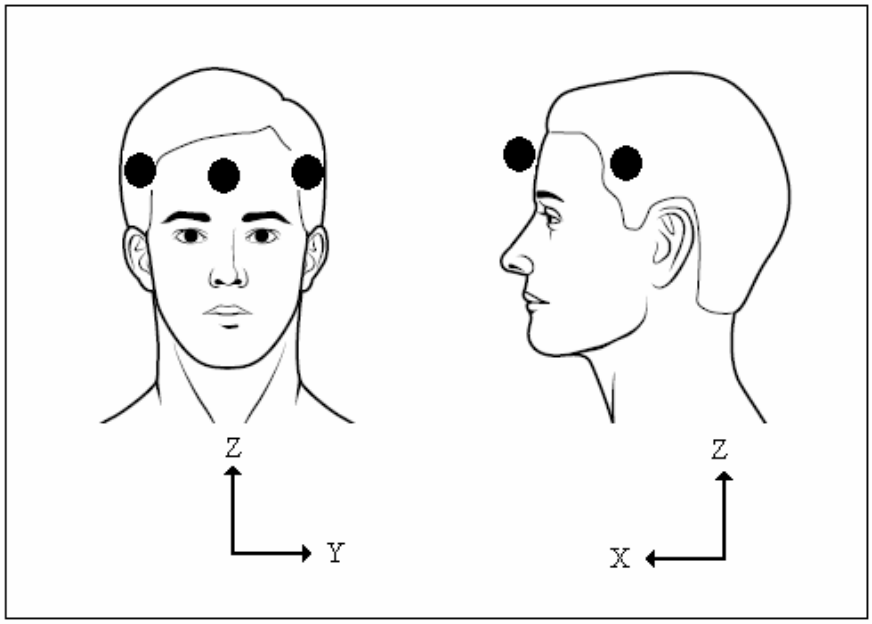

Figure 4.5 Markers and coordinate system of the head. (www.medscape.com, modified)

Shoulders

The shoulder coordinate system is made up of the adjusted C7, the clavicle maker and the shoulder acromion marker. There are local coordinate systems found for both the left and the right sides of the body. A vector from the midpoint between the clavicle markers and the adjusted C7, intersecting the right or the left acromion (depending on the left or right side of the body) was found to be the y-axis. The z-axis is the cross of the y-axis vector and the vector that is formed by taking a vector from the midpoint between the clavicle markers that intersects the adjusted C7 marker. The x-axis is the cross of the y-axis and the z-axis.

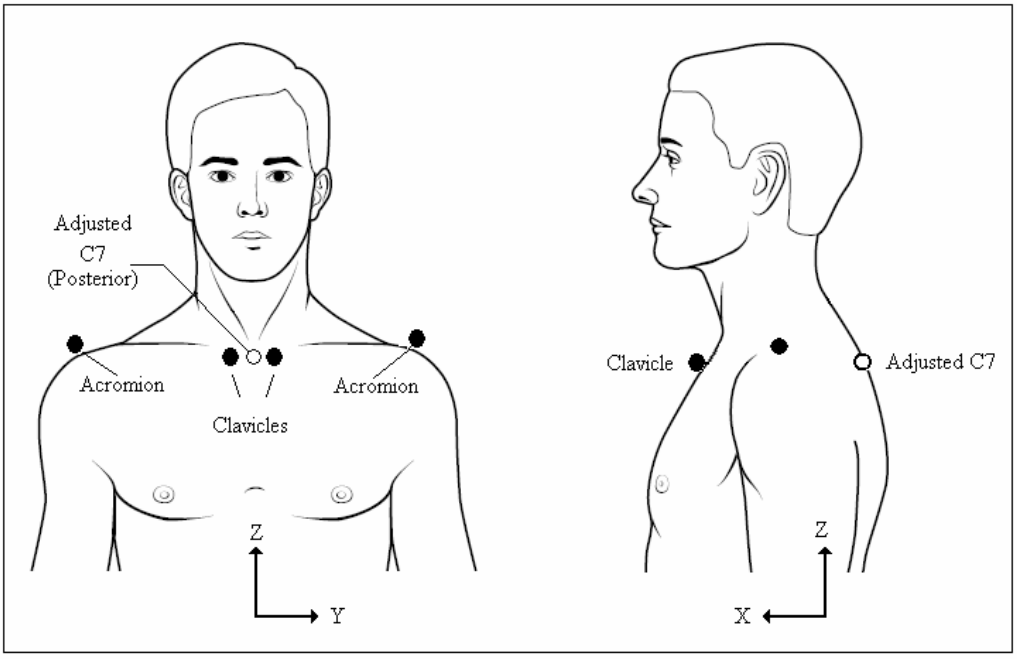

Figure 4.6 Markers and coordinate systems for the shoulders. (www.medscape.com, modified)

The Upper Arm

The upper arm was more involved to model. There was only one real marker at the acromion so virtual markers had to be developed to model the humerus. The first virtual marker represents the center of rotation of the shoulder as shown in figure 4.7. This marker is created by defining the lateral epicondyle marker relative to the newly created coordinate system for the shoulder.

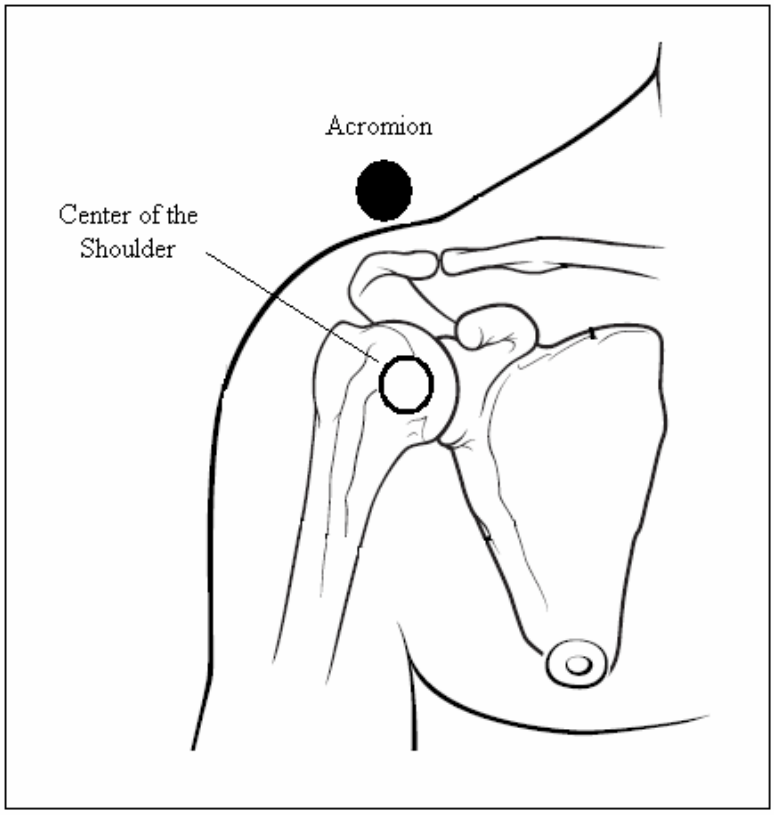

Figure 4.7 Representation of the virtual shoulder center marker. (www.medscape.com, modified)

The center of rotation of the lateral epicondyle relative to the shoulder coordinate system was found using a function called ***center_shoulder.m***. This function examines the data points provided by the lateral epicondyle marker during a task relative to the shoulder coordinate system for that side of the body. The lateral epicondyle shoulder marker always rotates about one point theoretically. This means that the lateral epicondyle marker should always lie on the spherical surface of the radius equal to the distance between the center of the virtual and lateral epicondyle markers. However there is some error due to the positioning of the lateral epicondyle marker by visual inspection for each subject. These errors make it almost impossible to fit the marker to a smooth

curve. To accommodate for this, a point cloud was employed instead, as seen in figure 4.8

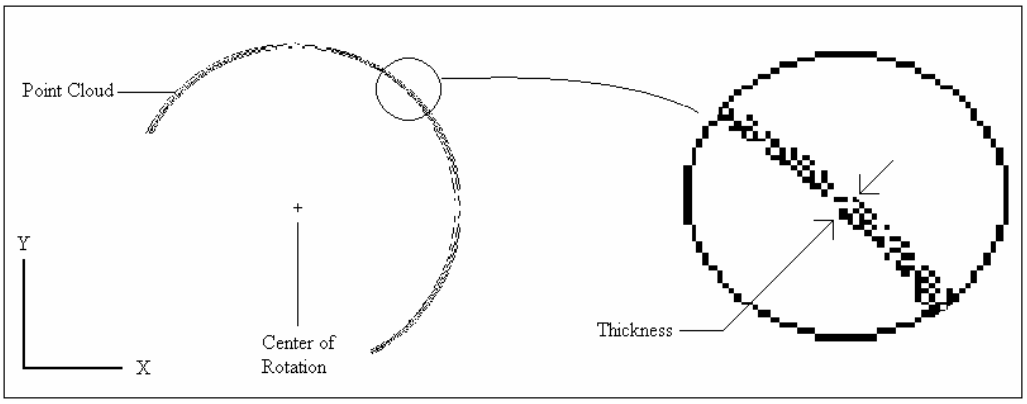

Figure 4.8 Point cloud about a center of rotation caused by marker location error.

To get a good representation a trial of the subject was chosen based on good range of should motion in that trial. The acromion marker becomes the starting point for the center of rotation; from this the distances of all lateral epicondyle marker positions were calculated. Then from this two vectors were created. One vector was in in the direction of the farthest epicondyle position and the second is in the direction of the closest epicondyle position. The ***center_shoulder.m*** function moves the center of rotation 1 mm in the direction of the farthest position and 1 mm away from the closest position, using the two vectors. This process is repeated in a loop 15000 cycles to average the center of the point cloud (Figure 4.9).

`

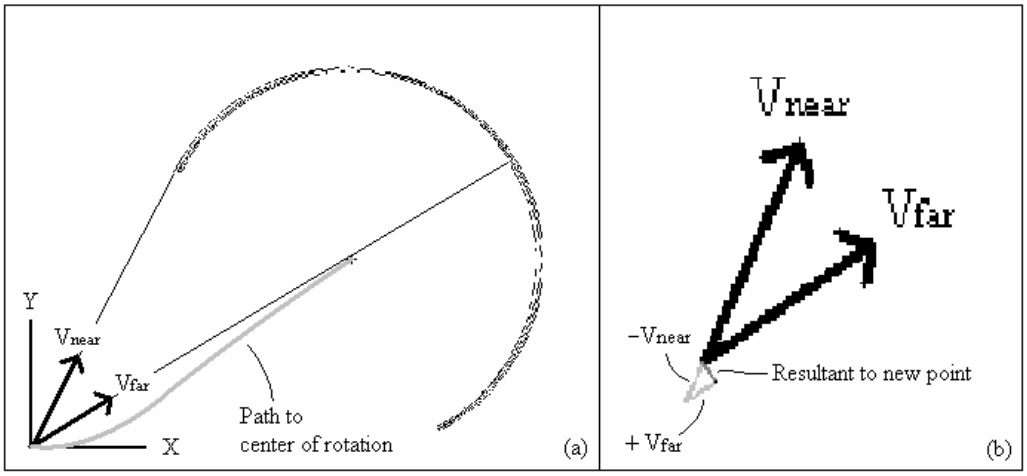

Figure 4.9 (a) Diagram of the creation of the near and far vectors, and (b) graphical representation for moving towards the center of the point cloud.

When looking at the accuracy of the point cloud method for finding the center of the shoulder, the thickness of the cloud was observed. Half the thickness of the cloud was considered to be the absolute error or the radius of the point cloud surface. The error varied between subjects from --- mm to --- mm with the average being --- mm.

A second virtual marker was created to define the humerus in the center of the elbow joint. The center of the wrist was defined first by the RWC and the LWC markers and the other two markers (the distal markers for the Ulna and radial conidials) at the wrist for the left and right sides of the body. The calculations for the wrist center marker were done with a function called ***center_wrist.m***. Half the distance between the ulna and radial condials markers was found and then the wrist marker RWC/LWC were lowered down perpendicular to the top of the hand to the center of the ulna and radial bone.

Comment [øs19]: This is very hard to follow, especially without any accompanying figure.
Do you mean that the RWC and LWC "markers" are defined as the midpoint between the radial and the ulnar styloids…? And "the top of the hand" is not a defined term, use "anterior/posterior" or "ventral/dorsal" instead..

Next the center of the elbow was located using the function called ***center_elbow.m***. A vector was created from the center of the shoulder to the center of the wrist, to find the center of the elbow. The elbow was considered to act like a hinge

joint; the center of the shoulder, the elbow and wrist all lie on the same plane relative to the humerus and the epicondyle marker to be perpendicular to that plane at the center of the elbow. A diagram of the virtual marker in the arm as well as a graphical representation of how the elbow center was located can be seen in figure 4.10.

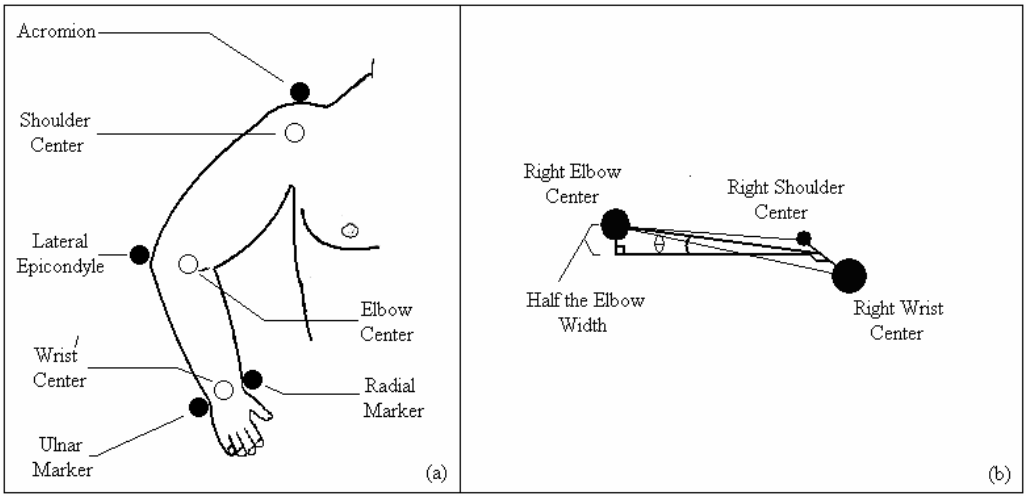

Figure 4.10 (a) Diagram of the arm, including real and virtual markers, and (b) graphical representation for locating the center of the elbow.

Next the coordinate system was then defined for the arm. The z-axis was defined by a vector from the center of the elbow to the center of the shoulder. Then a vector from the elbow center to the wrist center was crossed with the z-axis to deliver the y-axis. The x-axis was found by crossing the y-axis and the z-axis. If the forearm becomes fully extended this method does not work (ei. when the vector from the elbow center to the shoulder center and the vector from the elbow center to wrist center were not co-linear). Figure 4.11 shows a graphical representation of the humeral coordinate system created.

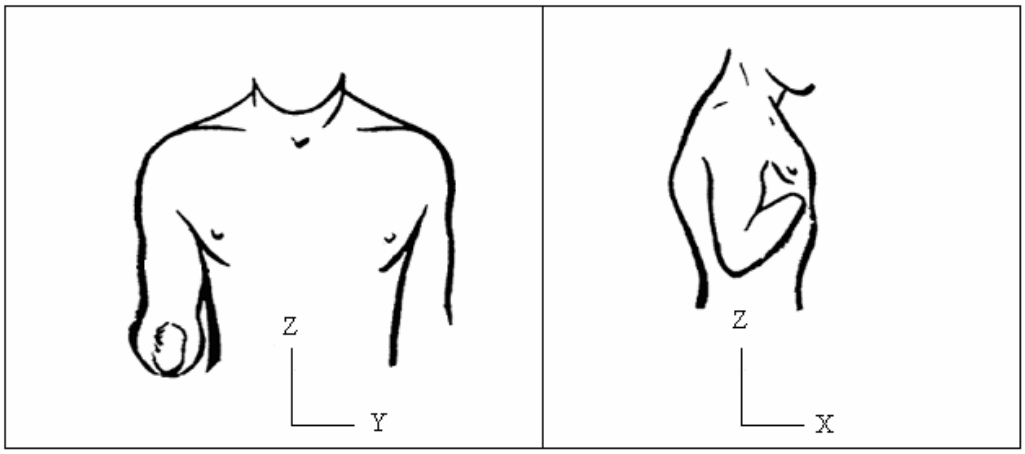

Figure 4.11 Coordinate system as created for the humerus.
(www.oandp.com/news/jmcorner/library/uclamanual/, modified).

Forearm

Two markers at the distal end of the ulna and radial bones, the center of the wrist and the center of the shoulder were used to define the forearm. The z-axis was defined by a vector from the center of the wrist to the center of the elbow. Next the y-axis was defined by crossing a vector from the ulna marker to the radial marker with the z-axis. The x-axis was found by crossing the y-axis and the z-axis. A graphical representation of this is shown in figure 4.12.

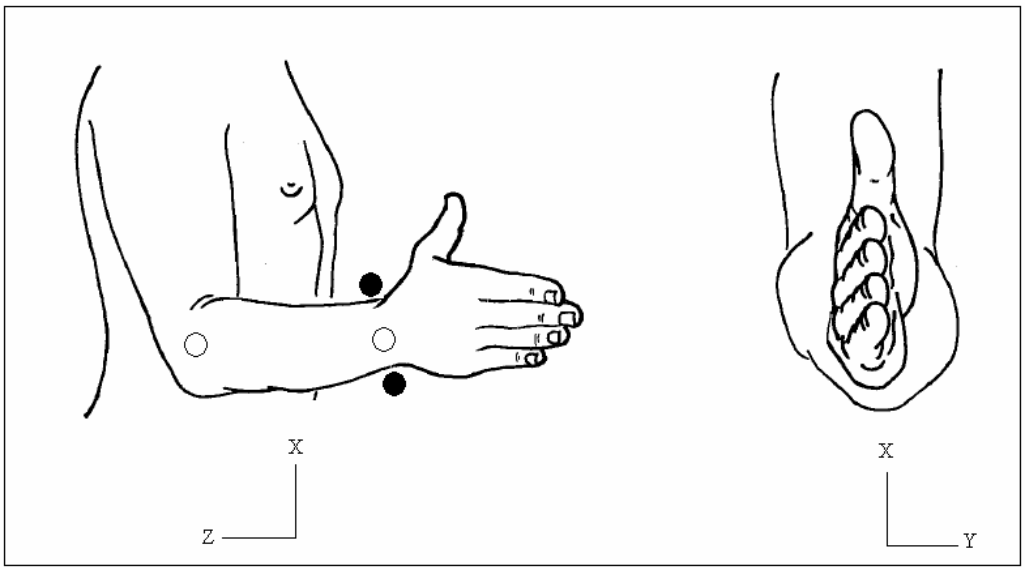

Figure 4.12 Marker locations and associated coordinate system for the forearm. (Kapandji, 1980)

The Hand

The coordinate system for the center of the hand was found using the wrist marker along with the 2nd and 5th metacarpal markers. The z-axis was represented by a vector from a point 1/3 of the way from the 2nd to the 5th metacarpal marker through the wrist marker. The y-axis was defined second vector from the 2nd metacarpal marker through the 5th metacarpal marker that was crossed with the z-axis. The x-axis was found by crossing the y-axis and the z-axis. A graphical representation of this is shown in figure 4.13.

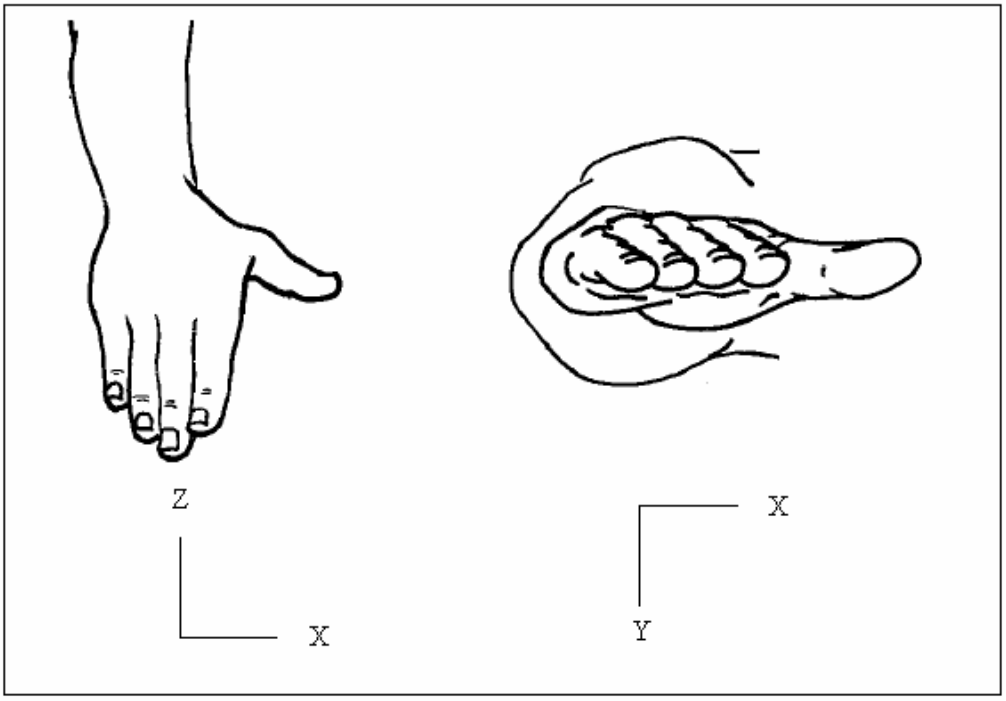

Figure 4.13 Associated coordinate system for the hands. (Kapandji, 1980)

Summary

Table 4.5 outlines each of the body segments, the anatomical markers and their associated coordinate system. Each segment is further described in detail in the following sections.

Comment [øs20]: I'd moved this towards the start of the chapter. The marker abbreviations are used extensively in the description of the coordinate frames, and it would be nice to be aware of the existence of this table when reading that description.

Table 4.5 Embedded Coordinate Systems

Coordinate System	Markers	Axes Definition
Pelvis (Section 4.2.2.1)	- Right Hip (Rhip) - Left Hip (Lhip) - Sacrum (sacr)	- 3 marker plane, X-Y plane - Rhip to Lhip, Y-axis - X-axis direction is forward
Trunk (Section 4.2.2.2)	- Right Clavicle (Rcla) - Left Clavicle (Lcla) - Adjusted C7 (AdjC7)*	- 3 marker plane, X-Y plane - Rcla to Lcla, Y-axis - X-axis direction is forward
Head (Section 4.2.2.3)	- Right Side Head (rth) - Left Side Head (lfth) - Forehead (frhd	- 3 marker plane, X-Y plane - rth to lfth, Y-axis - X-axis direction is forward
Right Shoulder (Section 4.2.2.4)	- Right Clavicle (Rcla) - Adjusted C7 (AdjC7)*	- 3 marker plane, X-Y plane - RCC to Rsh, Y-Axis

	- Right Core Center (RCC)* - Right Acromion (RSHO)	- X-axis direction is forward - Origin at RSHO
Left Shoulder (Section 4.2.2.4)	- Left Clavicle (LCLA) - Adjusted C7 (AdjC7)* - Left Acromion (LSHO)	- 3 marker plane, X-Y plane - RCC to RSHO, Y-Axis - X-axis direction is forward - Origin at RSHO
Right Humerus (Section 4.2.2.5)	- Center of Right Shoulder Rotation (RshCOR)* - Center of Right Elbow (RelCOR)* - Center of Right Wrist (RWC)*	- 3 marker plane, X-Z plane - RelCOR to RshCOR, Z-axis - X-axis direction is forward
Left Humerus (Section 4.2.2.5)	- Center of Left Shoulder Rotation (LshCOR)* - Center of Left Elbow (LelCOR)* - Center of Left Wrist (LWC)*	- 3 marker plane, X-Z plane - LelCOR to LshCOR, Z-axis - X-axis direction is forward
Right Forearm (Section 4.2.2.6)	- Center of Right Elbow (RelCOR)* - Center of Right Wrist (RWC)* - Right Ulna (RULNA) - Right Radius (RRAD)	- 3 marker plane, X-Z plane - RWC to RelCOR, Z-axis - RULNA to RRAD, X-axis - Y-axis direction is medial
Left Forearm (Section 4.2.2.6)	- Center of Left Elbow (LelCOR)* - Center of Left Wrist (LWC)* - Left Ulna (LULNA) - Left Radius (LRAD)	- 4 marker plane, X-Z plane - LwrC to LelCOR, Z-axis - LULNA to LRAD, X-axis - Y-axis direction is lateral
Right Hand (Section 4.2.2.7)	- Center of Right Wrist (RWC)* - 2nd Metacarpophalangeal Joint, Right (R2MC) - 5th Metacarpophalangeal Joint, Right (R5MC) - Right Center Hand (RCH)*	- 3 marker plane, X-Z plane - RCH to RWC, Z-axis - Y-axis, out palm of hand
Left Hand (Section 4.2.2.7)	- Center of Left Wrist (LWC)* - 2nd Metacarpophalangeal Joint, Left (L2MC) - 5th Metacarpophalangeal Joint, Left (L5MC)	- 3 marker plane, X-Z plane - LCH to LWC, Z-axis - Y-axis, out back of hand

* Virtual markers based upon positions of real marker locations (see respective coordinate system sections for mathematical method for determining virtual marker locations.) (Modified from MacPhee, 2007)

4.7 Analysis

The data was finally analyzed in terms of relative angles using MATLAB code. A function called ***relative_angles.m*** was called by ***converter.m***, to calculate the relative angles between body segments. See Appendix C for all Matlab code.

4.7.1 Relative Body Mechanics

The relative motions of the body, as described by the mechanical model for this study, were examined through the relative angles between the body segments. Euler rotations and Cardan rotations are typically used to describe three dimensional rotations. Euler rotations consist of three rotations of a coordinate system, of which two are about the same axis, and Cardan rotations consist of three rotations where each axis is rotated about only once. Great consideration was put into deciding the order of rotations for the body segments in this study. After examining various different orders of rotation it was determined that the use of Euler and Cardan rotations did not provide a true representation of the desired angles, as described in clinical terms. For this reason new methods were considered. Each coordinate system was examined independently and relative angles calculated based on their range of motion and the clinical terms used to describe them.

Trunk Relative to Pelvis

The trunk relative to the pelvis was analyzed first. The coordinate system of the trunk was considered to be distal to the pelvis coordinate system. The rotations which were examined, in clinical terms, were abdominal flexion/extension, lateral tilt, and trunk rotation.

Lateral tilt was defined using a 'planar intersect' method. The line of intersection between the X-Y plane of the distal coordinate system (trunk) and the Y-Z plane of the proximal coordinate system (pelvis) was determined by taking the cross product of the their respective normal vectors (Distal – Z coordinate system vector; proximal – X

coordinate system vector). The rotation about the X-axis was defined as the angle between the line of intersection and the Y-axis of the proximal coordinate system. Figure 4.14 shows a graphical representation of 'planar intersect' method.

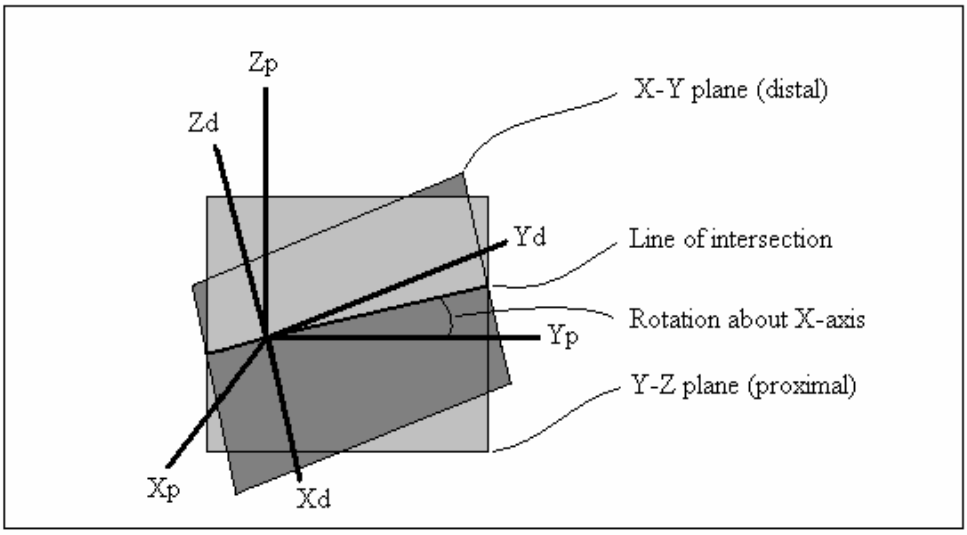

Figure 4.14 Graphical representation of the 'planar intersect' method. (MacPhee, 2007)

The abdominal flexion/extension was determined in the same manner as lateral tilt. The line intersection between the X-Y plane of the distal coordinate system and the X-Z plane of the proximal coordinate system was determined by taking the cross product of their respective normal vectors (Distal – Z coordinate system vector; proximal – Y coordinate system vector). The rotation about the Y-axis was defined as the angle between the line of intersection and the X-axis of the proximal coordinate system.

Trunk rotation was found using an 'imaginary axis' method. In this method an imaginary axis was created along the line of intersection of both the proximal and distal X-Y planes. The imaginary vector was created by taking the cross product of the two Z coordinate system vectors. The distal coordinate system was then rotated about the imaginary axis such that the two Z coordinate system axes were aligned. The X-Y plane

of the proximal system was then co-planar with the X-Y plane of the distal coordinate system. The rotation about the Z-axis was then determined by the angle between the two X-axes. Figure 4.15 shows a graphical representation of the 'imaginary axis' method.

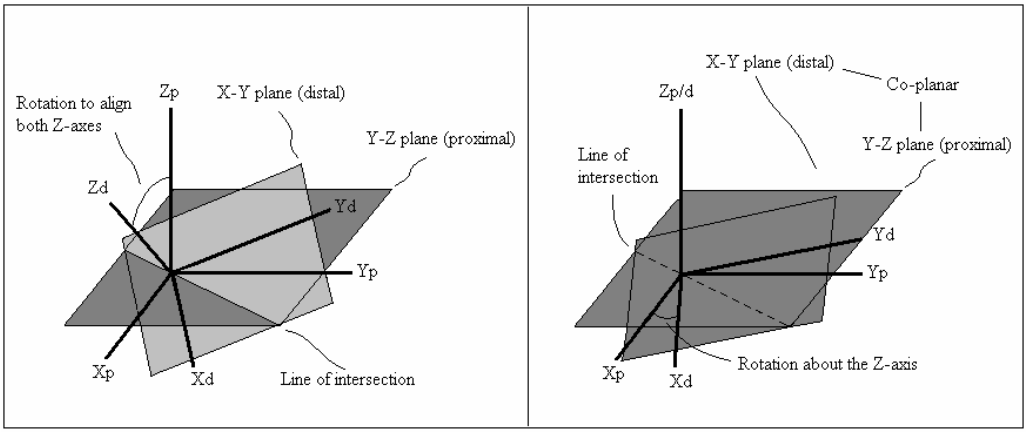

Figure 4.15 Graphical representation of the 'imaginary axis' method. (MacPhee, 2007)

Head Relative to Trunk

Similar to the previous systems, the coordinate system of the head was distal to that of the trunk for analysis. The rotations which were examined, in clinical terms, were abdominal flexion/extension, lateral tilt, and trunk rotation. All three rotations for the head were found using the same methods as used to determine the rotations of the trunk.

Shoulders Relative to Trunk

The shoulder coordinate systems were also analyzed (individually) as distal to the trunk coordinate system. The shoulder however, according to the mechanical model defined in Section 2.1, only exhibits two degrees of freedom; elevation/depression and flexion/extension.

The 'planar intersect' method was used to calculate both shoulder rotation angles. The line of intersect between the X-Y plane of the distal coordinate system and the Y-Z

plane of the proximal coordinate system was found by taking the cross product of the distal Z coordinate system vector and the proximal X coordinate system vector. The angle between the line of intersection and the proximal Y-axis provided the angle of shoulder elevation.

The line of intersect between the Y-Z plane of the distal coordinate system and the X-Y plane of the proximal coordinate system was found by taking the cross product of the distal X coordinate system vector and the proximal Z coordinate system vector. The angle between the line of intersection and the proximal Y-axis provided the angle of shoulder flexion.

Humerus Relative to Shoulder

The humeral coordinate systems were analyzed as distal to their respective shoulder coordinate systems. Humeral rotations in the shoulder joint have a large range of motion, which caused problems differentiating between flexion/extension and adduction/abduction. Figure 4.16 helps to explain the reasoning. As either flexion or abduction approached 90°, the other angle automatically approached 90° except in the case of pure flexion in the sagittal plane or pure abduction in the frontal plane. In the case of pure flexion in the sagittal plane, abduction remained 0° until flexion reached 90°. When flexion reached 90°, abduction became undefined. The situation was similar but reversed for pure abduction. For this reason, they were replaced with humeral elevation (combination of flexion and abduction) and medial/lateral rotation.

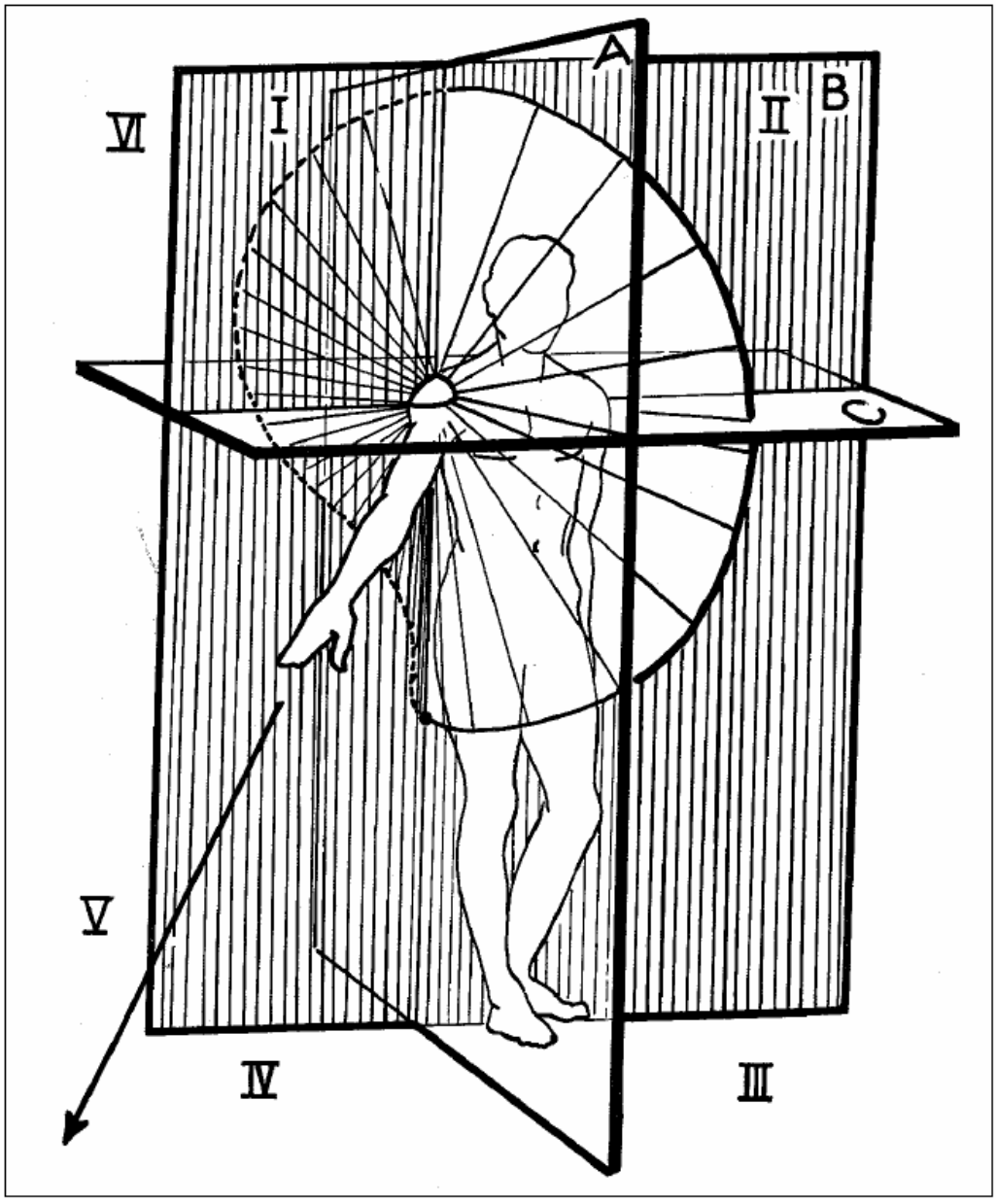

Figure 4.16 Graphical representation of the planar cross sections of the shoulder joint. A – sagittal plane, B – frontal plane, C - frontal plane. (Kapandji, 1980)

Humeral elevation was defined as the angle between the Z coordinate system vector of the shoulder and the Z coordinate system vector of the humerus. Medial/lateral rotation was defined as the angle between the frontal plane and the Z coordinate system

vector of the humerus, as projected onto the horizontal plane. Rotation of the humerus about its Z-axis was determined using the 'imaginary axis' method, as described in the rotations of the trunk.

Forearm Relative to Humerus

The forearm coordinate systems were analyzed as distal to the respective humeral coordinate system. A described earlier in the creation of the coordinate systems the elbow joint was considered to act as a hinge and therefore there's no rotation about the X-axis. Only two degrees of freedom were examined in the elbow, flexion/extension and pronation/supination (rotation about the forearm).

Elbow flexion was defined simply as the angle between the respective Z coordinate system vector of the humerus and the Z coordinate system vector of the forearm. Pronation/supination was defined using the 'imaginary axis' method, as previously described.

Hand Relative to Forearm

The hand coordinate system was analyzed distal to that of the forearm. Only two degrees of freedom were considered according to the mechanical model described in Section 2.1. Flexion/extension and adduction/abduction were the two rotations that were examined.

Flexion/extension of the hand was determined using the 'planar intersect' method in the same manner that was used to find the trunk abdominal flexion. The adduction/abduction of the hand was calculated using the 'planar intersect' method, in the same manner that was used to find the trunk lateral tilt.

Table 4.5 defines the angles of rotation for each segment in clinical terms.

Table 4.5: Relative angles of rotation (MacPhee, 2007)

Trunk relative to pelvis		
Symbol	**Rotation**	**Positive direction**
θ_x	Lateral Tilt	Towards dominant side
θ_y	Abdominal Flexion/Extension	Flexion
θ_z	Rotation	Towards dominant side
Head relative to trunk		
Symbol	**Rotation**	**Positive direction**
θ_x	Lateral Tilt	Towards dominant side
θ_y	Flexion/Extension	Head forward
θ_z	Rotation	Towards dominant side
Shoulders relative to trunk		
Symbol	**Rotation**	**Positive direction**
θ_x	Elevation/Depression	Upward
θ_y	None	N/A
θ_z	Flexion/Extension	Forward
Humerus relative to respective shoulder		
Symbol	**Rotation**	**Positive direction**
θ_i	Elevation(Flexion/Abduction)	Laterally
θ_z	Rotation	Anterior from frontal plane
θ_h	Humeral Rotation	Medially
Forearm relative to respective humerus		
Symbol	**Rotation**	**Positive direction**
θ_x	None	N/A
θ_y	Flexion/Extension	Flexion
θ_z	Pronation/Supination	Pronation
Hands relative to respective forearm		
Symbol	**Rotation**	**Positive direction**
θ_x	Adduction/Abduction	Adduction
θ_y	Flexion/Extension	Flexion
θ_z	None	None

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APPENDIX A

Data Sheets

Faulhaber 6 x 20 mm Brushless DC Motor

NEW

FAULHABER

Brushless DC-Servomotors

Electronic Commutation

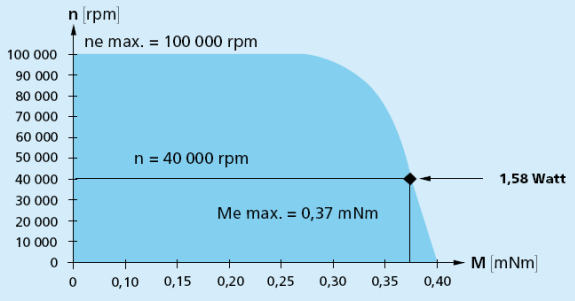
0,37 mNm

For combination with
Gearheads:
06/1
Drive Electronics:
BLD 2401

Series 0620 ... B

		0620 K		006 B	012 B	
1	Nominal voltage	U_N		6	12	Volt
2	Terminal resistance, phase-phase	R		9,1	59,0	Ω
3	Output power [1]	$P_{2\ max.}$		1,56	1,58	W
4	Efficiency	$\eta_{max.}$		57	55	%
5	No-load speed	n_0		47 000	36 400	rpm
6	No-load current (with shaft ø 1,0 mm)	I_0		0,047	0,016	A
7	Stall torque	M_H		0,73	0,58	mNm
8	Friction torque, static	C_0		0,016	0,016	mNm
9	Friction torque, dynamic	C_V		$8,0 \cdot 10^{-7}$	$8,0 \cdot 10^{-7}$	mNm/rpm
10	Speed constant	k_n		8 421	3 282	rpm/V
11	Back-EMF constant	k_E		0,119	0,305	mV/rpm
12	Torque constant	k_M		1,13	2,91	mNm/A
13	Current constant	k_I		0,882	0,344	A/mNm
14	Slope of n-M curve	$\Delta n/\Delta M$		67 575	66 533	rpm/mNm
15	Terminal inductance, phase-phase	L		26	187	µH
16	Mechanical time constant	τ_m		6	6	ms
17	Rotor inertia	J		0,0095	0,0095	gcm^2
18	Angular acceleration	$\alpha_{max.}$		772	607	$\cdot 10^3 rad/s^2$
19	Thermal resistance	R_{th1} / R_{th2}	14 / 88,0			K/W
20	Thermal time constant	τ_{w1} / τ_{w2}	1 / 149			s
21	Operating temperature range:					
	– motor		– 20 ... +100			°C
	– coil, max. permissible		+125			°C
22	Shaft bearings		ball bearings, preloaded			
23	Shaft load max.:					
	– radial at 10 000/50 000 rpm (3,7 mm from mounting flange)		2,0 / 1,5			N
	– axial at 10 000/50 000 rpm (push-on only)		0,6 / 0,2			N
	– axial at standstill (push-on only)		10			N
24	Shaft play:					
	– radial	≤	0,012			mm
	– axial	=	0			mm
25	Housing material		aluminium, black anodized			
26	Weight		2,5			g
27	Direction of rotation		electronically reversible			
Recommended values						
28	Speed up to [2]	$n_{e\ max.}$		100 000	100 000	rpm
29	Torque up to [1] [2]	$M_{e\ max.}$		0,373	0,377	mNm
30	Current up to [1] [2]	$I_{e\ max.}$		0,371	0,146	A

[1] at 40 000 rpm
[2] thermal resistance R_{th2} by 55% reduced



Recommended area for continuous operation

For notes on technical data and lifetime performance refer to "Technical Information".

Edition 15.03.2006

Specifications subject to change without notice.

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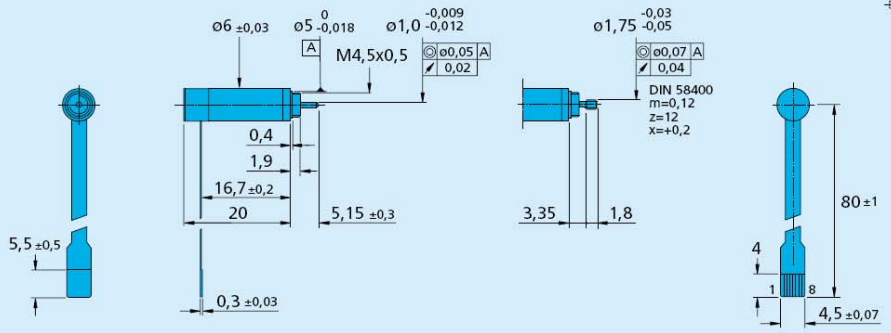
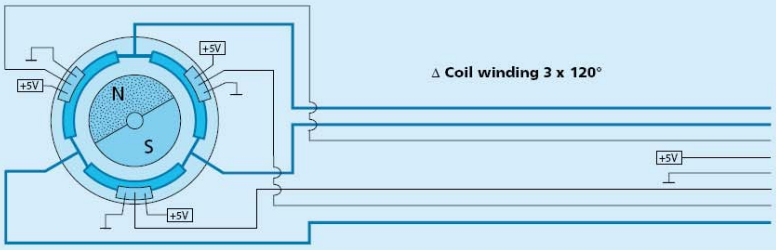
0620 ... B



0620 K

0620 C for Gearheads 06/1

Cable and connection information



Flex Print connector
Molex 52745-0890
FPC, 8 circuits, 0,5 mm Pitch
Top contact style

Connection

Pin	Function
1	Phase C
2	Phase B
3	Hall sensor C
4	+5V
5	GND
6	Hall sensor A
7	Hall sensor B
8	Phase A

For notes on technical data and lifetime performance refer to "Technical Information".

Edition 15.03.2006

Specifications subject to change without notice.

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Faulhaber 8 x 12.3 mm Planetary Gear head

FAULHABER

Planetary Gearheads — 60 mNm

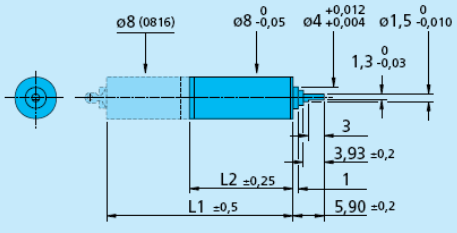
For combination with
DC-Micromotors:
0816

Series 08/1

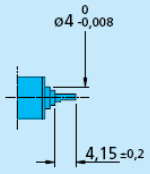
	08/1	08/1 K
Housing material	metal	metal
Geartrain material	all steel	all steel
Recommended max. input speed for:		
– continuous operation	8000 rpm	8000 rpm
Backlash, at no-load	≤ 3°	≤ 3°
Bearings on output shaft	sintered sleeve bearings	ball bearings
Shaft load, max.:		
– radial (4,5 mm from mounting face)	≤ 0,8 N	≤ 5 N
– axial	≤ 1 N	≤ 3 N
Shaft press fit force, max.	≤ 5 N	≤ 5 N
Shaft play (on bearing output):		
– radial	≤ 0,03 mm	≤ 0,02 mm
– axial	≤ 0,10 mm	≤ 0,05 mm
Operating temperature range	– 30 ... + 100 °C	– 30 ... + 100 °C

Specifications

reduction ratio	weight without motor g	length without motor L2 mm	length with motor 0816 P L1 mm	output torque continuous operation M max. mNm	output torque intermittent operation M max. mNm	direction of rotation (reversible)	efficiency %
4 : 1	2,9	9,6	25,6	60	120	=	90
16 : 1	3,8	12,3	28,3	60	120	=	80
64 : 1	4,6	15,0	31,0	60	120	=	70
256 : 1	5,4	17,7	33,7	60	120	=	60
1 024 : 1	6,3	20,4	36,4	60	120	=	55
4 096 : 1	7,1	23,1	39,1	60	120	=	48



08/1



08/1 K

For notes on technical data and lifetime performance refer to "Technical Information".

Specifications subject to change without notice.

120 TOOTH INTERNAL SPUR GEAR

Description for Part No. N96S2-120

96 Pitch

1/8" Face

AGMA Quality 10 Internal Gear

20° Pressure Angle

303 Stainless Steel with 2"

12 TOOTH SPUR GEAR PINION SHAFT

Description for Part No. PS96S3-12

48 to 120 Pitch

AGMA Quality 10 Pinion Shaft

20° Pressure Angle

303 Stainless Steel

45 TOOTH SPUR GEAR PIN HUB

Description for Part No. P96S19-45

96 Pitch

1/8" Face

AGMA Quality 10 Spur Gear

20° Pressure Angle

303 Stainless Steel

pin hub style, spot drilled with set screws supplied

stocked bore is 3/16"

APPENDIX B

Calculations

Faulhaber Motor Specifications:

Torque = T = 0.73 mNm
Velocity = V = 47000 rpm
RR = 5:1
Ks = 1.5
Nd = 1.1

Belt Choice

Belt Diameter = 1.7 mm (0.067 in)
d = 2 mm = 0.0787 in
D = 10 mm = 0.394 in
Belt Stretch = 10%
Max Power = 1.56 W (0.00209 hp)

O-ring belt diameter calculation:

$$W = 0.533\sqrt{\left[\frac{63000 - P}{d * 10\% * V}\right]}$$

$$W = 0.533\sqrt{\left[\frac{63000 - 0.00209}{0.0787 * 10\% * 47000}\right]}$$

$$W = 0.03180"(0.808mm)$$

Max Power possible to be transmitted (with one belt):

$$P = \frac{W^2 * d * e * n}{18000}$$

$$P = \frac{(0.067")^2 * 0.0787" * 10\% * 47000}{18000}$$

$$P = 0.00922hp(6.88W)$$

First Stage Specifications:

Belt Diameter = 1.7 mm (0.067 in)
d = 2 mm = 0.0787 in
D = 10 mm = 0.394 in

P = T(2)

P = (0.73mNm)(2)
P = 3.593 w ($4.818x10^{-3}$ hp)

$$\phi = \phi d = \pi - \sin^{-1}\left[\frac{0.393 - 0.0787}{2(0.8)}\right]$$

$$\phi = 2.746 rad$$

$$\exp(F\phi) = \exp[0.7(2.746)]$$

$$F\phi = 6.837$$

$$V = \pi\left[\frac{(0.0787)(47000)}{12}\right]$$

$$V = 308.2\, ft/\min$$

$$\omega = 12\gamma bt$$

$$\omega = 12(0.038)(0.0787)(0.0276)$$

$$\omega = 2.4x10^{-3}\, lbs.in$$

$$F_c = \frac{\omega}{g}\left(\frac{V}{60}\right)^2$$

$$F_c = \left(\frac{2.4x10^{-3}}{32.17}\right)\left(\frac{308.2}{60}\right)^2$$

$$F_c = 1.97x10^{-3}\, lbf$$

$$T = \frac{(63025)H_{nom}K_s n_d}{n}$$

$$T = \frac{(63025)(4.818*10^{-3})(1.25)(1.1)}{47000}$$

$$T = 8.884*10^{-3}\, lbf.in$$

$$(F_1)_a - F_2 = \frac{2T}{d}$$

$$(F_1)_a - F_2 = \frac{2(8.884*10^{-3})}{0.0787}$$

$$(F_1)_a - F_2 = 112.9*10^{-3}\, lbf$$

$$(F_1)_a = bF_aC_pC_v$$
$$(F_1)_a = 0.0787(7.389)(1.0)(0.7)$$
$$(F_1)_a = 0.407lbf$$

$$F_2 = (F_1)_a - [(F_1)_a - F_2]$$
$$F_2 = 0.407 - 0.1129$$
$$F_2 = 0.2942lbf$$

$$F_i = \frac{(F_1)_a + F_2}{2}$$
$$F_i = \frac{0.407 + 0.1129}{2}$$
$$F_i = 0.1462lbf$$

$$f' = \frac{1}{\phi}\left[\frac{(F_1)_a - F_c}{F_2 - Fc}\right]$$
$$f' = \frac{1}{2.746}\left[\frac{0.407 - 1.97 * 10^{-3}}{294.2 * 10_{-3} - 1.97 * 10^{-3}}\right]$$
$$f = 0.505$$

$$f' \le f$$
$$0.505 \le 0.70$$

This means that there is no danger of slipping.

$$n_{fs} = \frac{H}{H_{nom}K_s}$$
$$n_{fs} = \frac{6.625 * 10^{-3}}{(4.818 * 10^{-6})(1.25)}$$
$$n_{fs} = 1.1$$

These calculations are for one 014 O-ring belt. This system employees two belts which doubles the safety factor to 2.2.