An articulated skeletal analogy of the human upper-limb

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An Articulated Skeletal Analogy of the Human Upper-Limb

Graham Paul Whiteley

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Contents

ABSTRACT

An Articulated Skeletal Analogy of the Human Upper-Limb

Currently available upper-limb prostheses do not meet the needs or aspirations of the amputee.

Many technical challenges have been given as the limiting factors on the further development of these prostheses. Generally developments have occurred as incremental developments on three existing moderately successful archetypes; the cosmetic, body-powered and myoelectric prostheses.

Continued development on these archetypes appears to be further separating prostheses into those primarily considered cosmetic and those primarily considered functional. However, amputees have a need both for function and cosmesis from their prostheses.

Technology currently being developed for actuation and control in other laboratories indicates that the previous limitations placed on prosthesis design may be challenged. Therefore, it is appropriate to look for new design archetypes.

This thesis describes the development, implementation and evaluation of mechanical analogies of the skeletal components of the human hand and arm which have the potential to inform the design of a new generation of upper-limb prostheses integrating cosmesis and function in a single device.

The research has been undertaken using a form of practice led design research methodology. This iterative methodology uses physical models for both evaluation and also as a means of encouraging end-user involvement in the design process. These evaluations are then used in subsequent cycles of research activity.

The research has concentrated on developing mechanical analogies of the joints of the hand, wrist, forearm and elbow. The joints of the hand are shown to have a simple and similar structure. Therefore, a modular mechanical archetype has been elucidated that results in a hand configuration made from multiple similar modules positioned at different points throughout the hand. However, the wrist and forearm contain more complex joints which have been found to be unique to their anatomical position. The selection of appropriate prototyping techniques has been an integral part of the research.

Problems have arisen in assessing the degree of analogy achieved because the intact joints of the human skeleton are covered by soft tissue that has not been part of the skeletal analogy implemented. Additionally, it is postulated that there are subtleties to human movement which are not reflected in standard anthropometric measures. Therefore, a two stage evaluation has been undertaken that assesses the quality of the analogy realised in the models. This consists of goniometric measures to quantify basic angular rotations whilst qualitative evaluations by professionals with a good anatomical knowledge have been used to assess the more subtle movements within the joints.

The skeletal mechanical analogy developed through this research has been shown through evaluation to simulate the articulations of the human upper-limb. The model embodies design principles that appear to have short and long term significance to the field of prosthetics. The production of a tangible model has not only aided evaluation but has also stimulated research in other centres into ways of actuating and controlling a future upper-limb prosthesis. Additionally, the mechanical analogy may have applications in the field of tele-presence robotics, aerospace and the entertainment industry.

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I would also like to thank my father for his encouragement and support.

1. Introduction

As part of the rehabilitation for those with congenital upper-limb loss or limb amputation a prosthesis can be prescribed (Barsby et al 1995). Whether amputees' lose one arm (unilateral amputation) or both arms (bilateral amputation) they have a need to appear 'normal'. Additionally, bilateral amputees, and those with high level amputations have a particular need for prosthetic devices that will restore some of the functions of the lost limb.

Current prostheses available to the amputee have developed in small steps from a limited number of moderately successful initial archetypes. The continued development of prostheses from these archetypes has resulted in the separation of prostheses into those that offer the outward appearance of the lost limb and those that offer some functionality.

From reference to previous research (Kejlaa 1993, Burger and Marincek 1993) as well as both formal and informal discussions with amputees over a long period it is apparent that current prostheses do not meet the needs or aspirations that amputees have for a future prosthesis.

This chapter reviews the situation of the amputee; the reasons for limb loss, how this effects the amputee and what prostheses are commercially available to help the amputee. A history of the different prosthetic devices then given, followed by a description of the technological limitations that have been cited as reasons for previous research in this field being discontinued.

Additionally, complementary research into the fields of robotics is reported that demonstrates some of the design problems faced in prosthetics are not unique to this field.

Diagrams have been included to explain the terminology associated with these fields which will continue to be used throughout the main body of work.

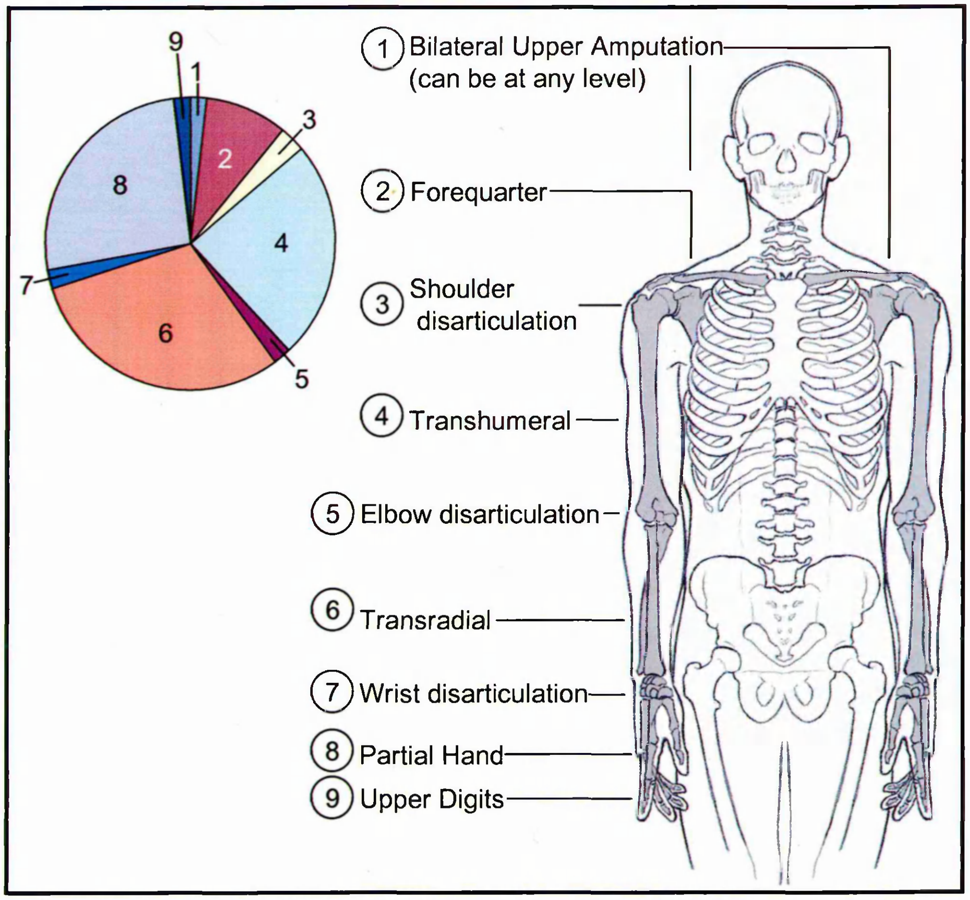

Fig 1.1 The Levels of Recorded Limb Loss in 1998 (NASDAB 1999)

There are records on approximately nine thousand upper-limb amputees held by Mobility and Specialised Rehabilitation Centres in the UK (Barsby *et al* 1995). The pie chart above shows how the total number of the 253 recorded referrals made to prosthetic service centres in the UK for 1998, splits into levels of amputation . The total number upper-limb amputees represents approximately 5% of the total number of amputations in this period. The majority of referrals are male 71.5%, with traumatic amputations accounting for 56% of the cases of limb loss (NASDAB 1999).

Loss of the upper-limb can be traumatic (through accident, injury or disease) or congenital (missing or imperfectly formed from birth).

Congenital absences are classified according to the missing bony segments which may be longitudinal or transverse (Barsby *et al* 1995).

An example of a longitudinal absence might be the absence of a finger of the hand or an absent humerus within an otherwise complete limb.

Transverse absences are more akin to traumatic amputations (Barsby et al 1995) and refer to the deficiency of all bony segments beyond a certain transverse level.

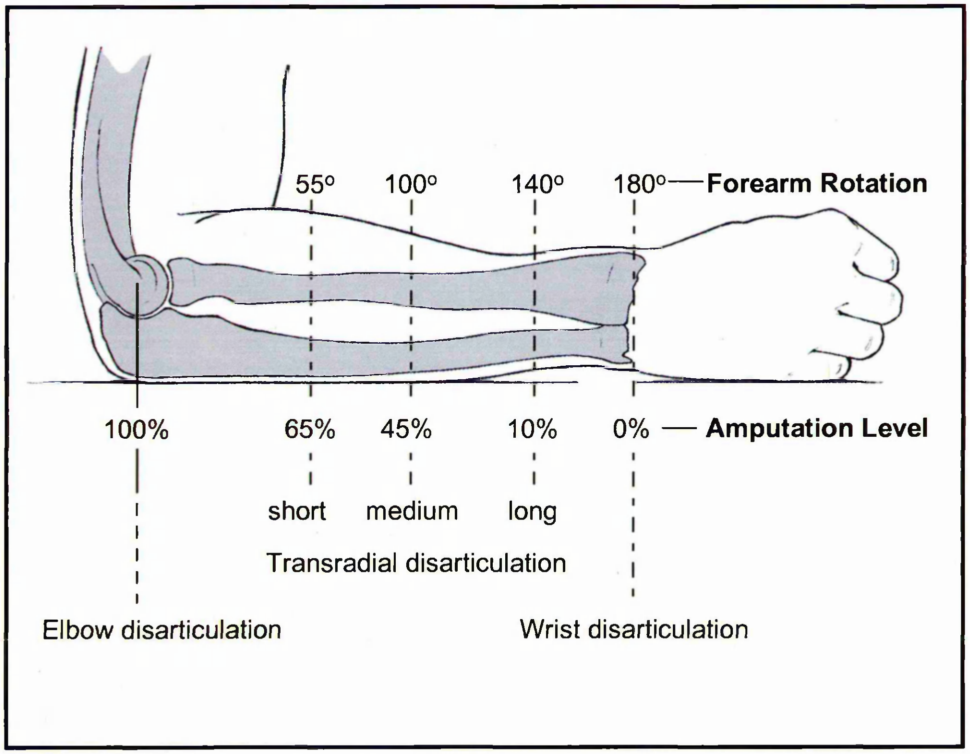

Fig 1.2 Levels of Forearm Amputation (Bennett Wilson 1989)

The general surgical procedure for traumatic amputation is to leave as much of the length of the limb as possible, taking account of the size and type of prosthesis that may be subsequently fitted (Kostuik 1980).

The chief cause of the most proximal amputation, the forequarter amputation is for conditions such as osteosarcoma of the shoulder girdle. This amputation includes removal of the whole arm including the scapula and clavicle (Kostuik 1980). Road traffic accidents, industrial accidents and burns are the main cause of the remaining levels of amputation (Barsby *et al* 1995).

Activities of daily living (ADL) become increasing difficult for the amputee as the level of amputation progresses upwards (Robertson 1978). Figure 1.2 shows how the range of forearm rotation diminishes as the level of amputation progresses up the limb, demonstrating that the functionality of the remaining limb is effected by the position of amputation (Bennett Wilson 1989).

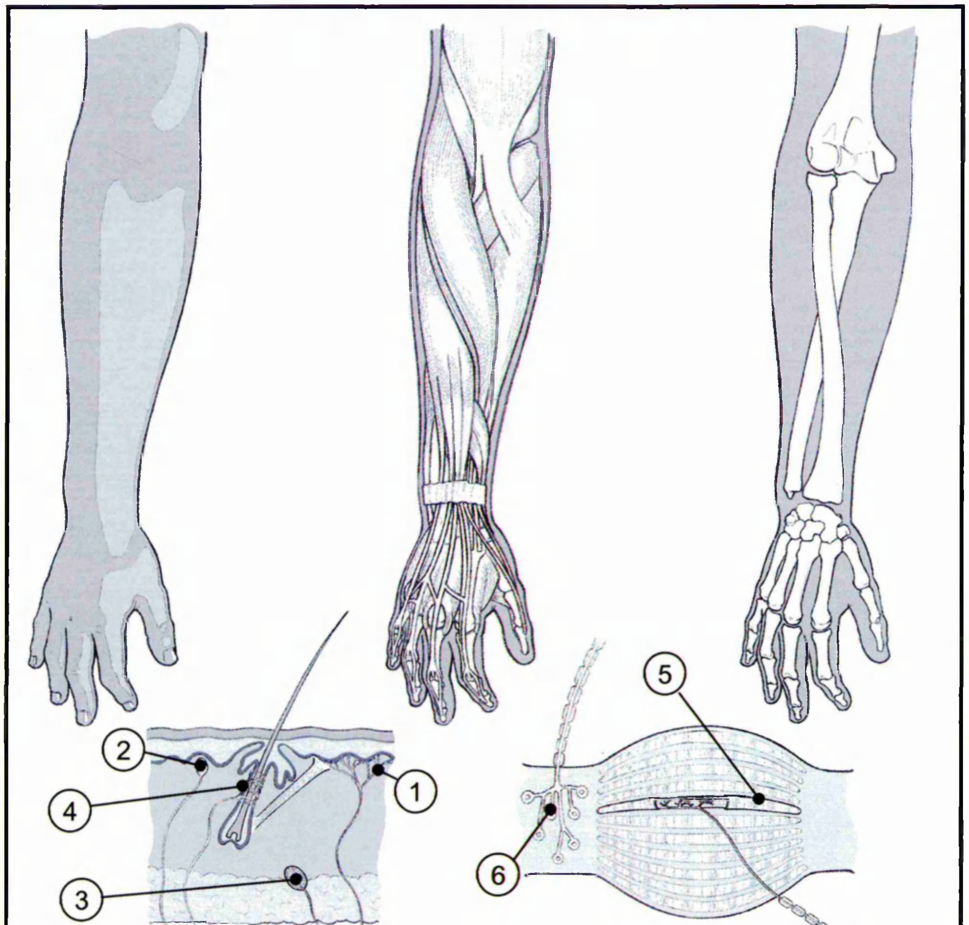

Fig 1.3 The Human Upper-Limb

To understand the disabling nature of losing a limb it is important know a little of the anatomy and physiology of the human upper-limb.
The human upper-limb contains 36 bones, linked to muscular tissue that results in an highly dextrous manipulator with approximately 42 degrees of freedom (Reichardt 1978).
The skin of the upper-limb has many types or sensory receptors (sensors). Free dendritic (branched) nerve endings (1) sense temperature, providing the sensations of hot and cold. Other dendritic nerve endings are encapsulated within various bulbous structures, such as Meissner (2) and Pacinian corpuscles (3). These provide the sensations of touch and pressure. Whilst free nerve endings wrapped around the root of hair follicles, provide further touch sensations (4) (Fox 1993).
The musculature of the limb, along with providing actuation for the limb, contains receptors that enable the human to known where the limb is in space without looking, and how much pressure the limb is exerting; known as proprioception (Harbres et al 1974 (a)). Proprioceptive receptors that convey muscular length information are named spindle cells (5), those that detect tension applied by the muscle are Golgi tendon organs (6).
Therefore, when an upper-limb has been lost not only are the appearance and manipulative functions of the limb lost but also a major means of gathering sensory information (Kyberd 1990).

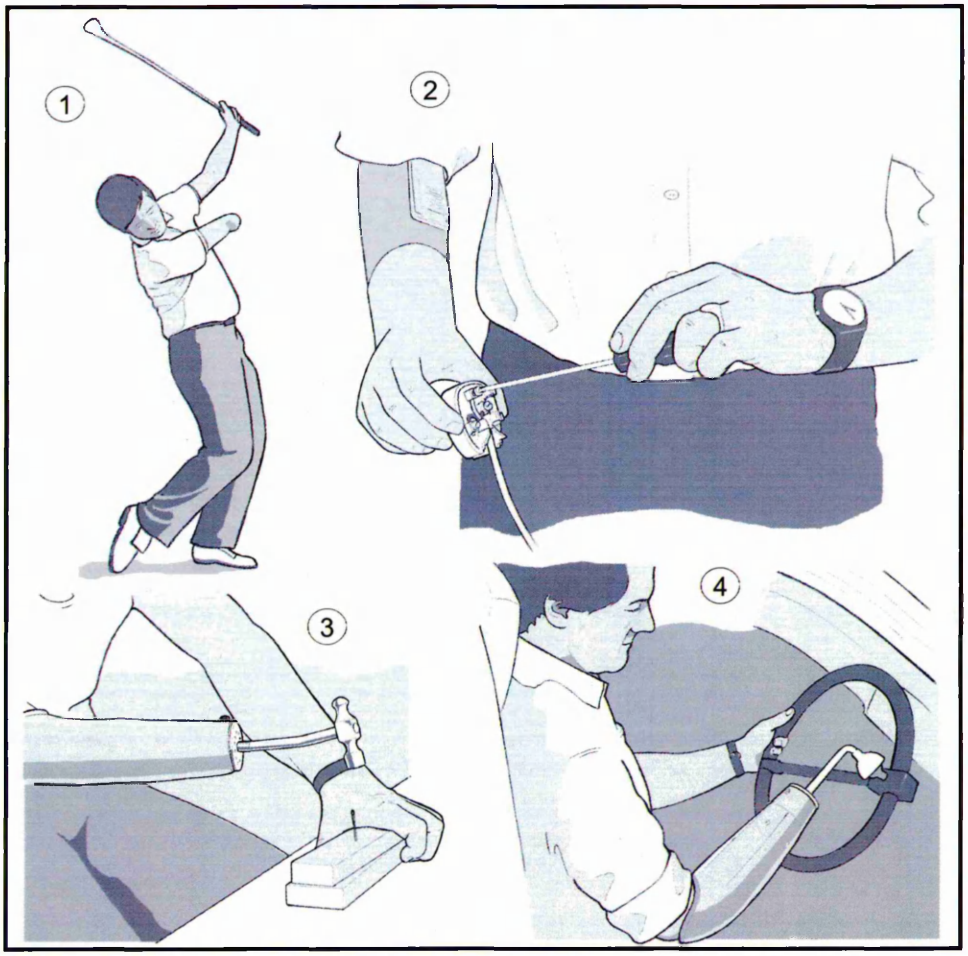

Fig 1.4 The Need for a Prosthesis

Amputees losing a single arm (unilateral) can adapt and function in the short-term without the aid of prosthesis (Scott and Parker 1988). Indeed figure 1.4(1) outlined from a photograph, demonstrates that, with adaptation of their golf swing, talented unilateral amputees can be competitive golfers. However, general dependence on the remaining upper-limb can lead to serious overuse syndromes (Jones and Davidson 1999).

The use of a prosthesis can assist the amputee in performing activities associated with daily living (ADL) (Kejlaa 1993). Unfortunately, whether the unilateral amputee loses their dominant or subdominant hands, the current functionality of prostheses dictate that the remaining limb will become the dominant limb and the prosthesis will only serve as an assistive device (Scott and Parker 1988). Figure 1.4.(2), again outlined from a photograph, demonstrates how unilateral amputees utilise their prostheses in an assistive manner to hold objects whilst the dextrous manipulations are performed with the remaining natural limb.

To perform certain tasks amputees often find that purpose designed tool-like terminal devices are more functional than hand shaped devices. (Banerjee 1982). Figures 1.4 (3) shows how a hammer is more easily used when connected directly to the socket of a prosthesis than via a prosthetic hand. Figure 1.4 (4) displays that how a ball and socket joint is commonly used as a device for steering a car. Bayonet fittings at the end of the socket provide a quick change facility for such tool-like terminal-devices.

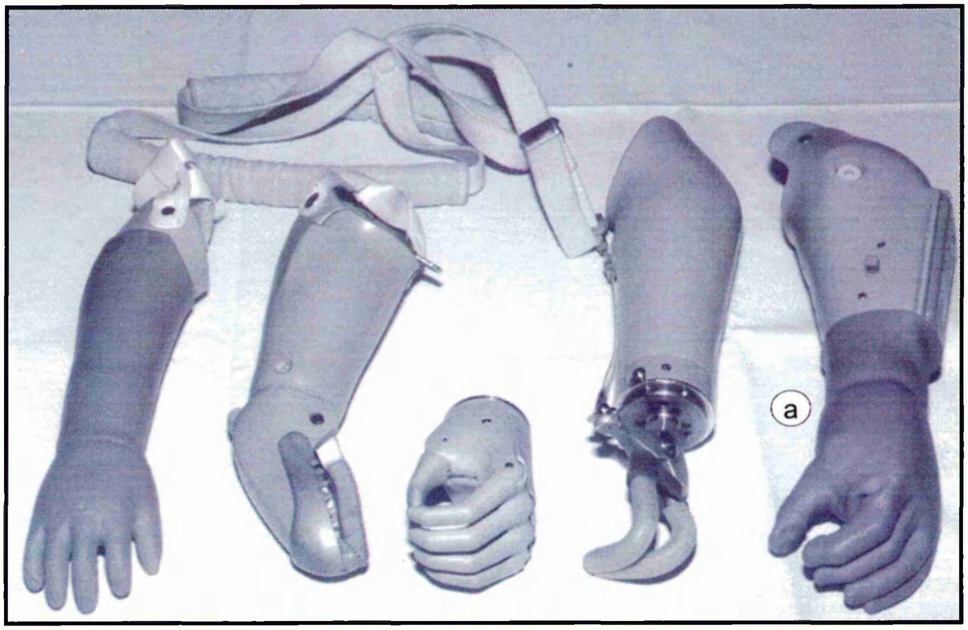

Fig 1.5 Prostheses Currently available to Amputees

The separation of prostheses into those that are tool-like and those that only give the appearance of a human limb has resulted in prostheses being categorised cosmetic or functional.

Amputees require both the appearance of the lost limb (cosmesis) and its functionality; however, due to the limitations of current devices amputees are required to choose which attribute they prioritise. Although some amputees own an additional device that complements some attributes of their main prosthetic choice.

Current commercial designs that aim to combine both attributes of cosmesis and function provide the amputee with a compromise solution. Commonly, the dexterity of the human hand is reduced to a single degree of freedom, a prehensile (gripping) action. This action is activated by mechanisms unlike those of the human limb resulting in an unsightly bulky hand form (a).

It has been stated that functional limitations of current prosthesis designs can lead the amputee to reject the prosthesis (Scott and Parker 1988). Additionally, this is compounded by false reporting in the popular media raising amputees expectations of the performance of prostheses to an unrealistic level (Curran and Hambrey 1991).

The following pages outline the history of each type of upper-limb prosthesis up to the current state of the art.

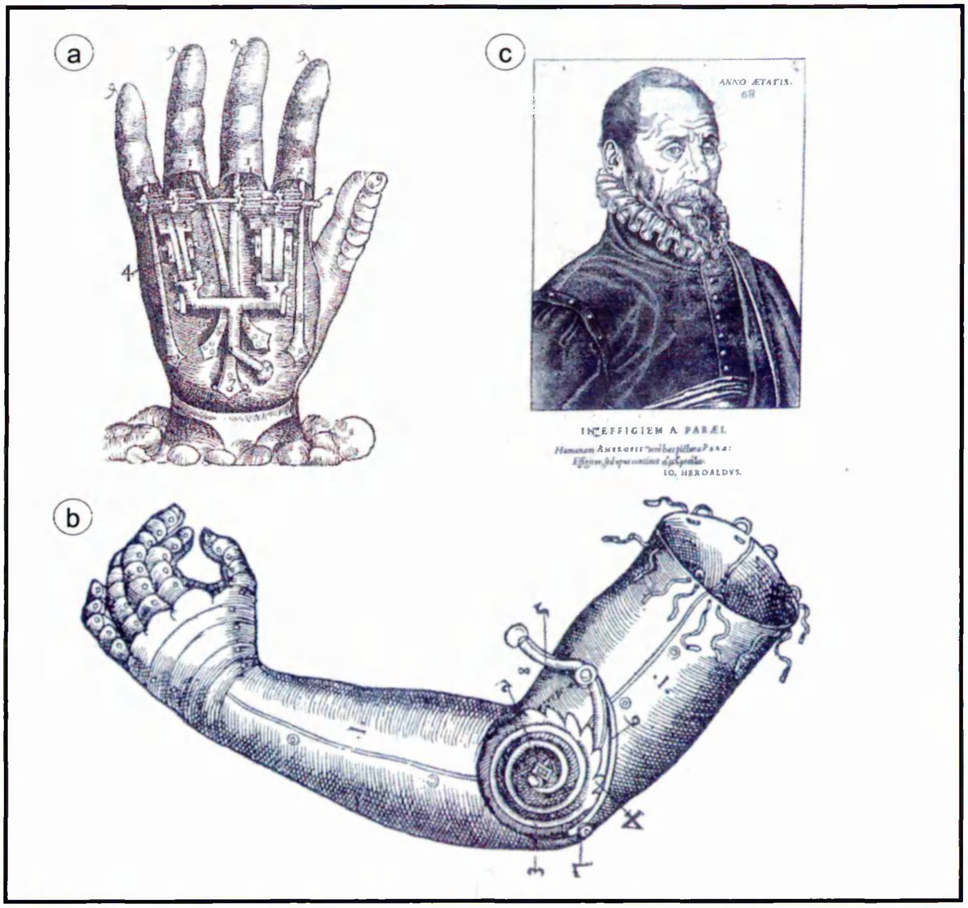

Fig 1.6 'Le Petit Lorraine' Passive Prosthesis

Passive prostheses have the static appearance of a human arm and hand; consequently they are referred to as cosmetic devices. They are the oldest type of upper-limb prosthesis; the first recorded being an iron hand worn by Marcus Sergius, a Roman General who lost his right hand in the Punic War (218-201 B.C.) (Banerjee 1982).

Few records remain of prostheses until the 15th century. During the 15th and 16th centuries knights who had lost limbs in battle were fitted with armour to disguise their limb loss, as limb loss was considered a sign of weakness (Kostuik 1980). Consequently, during this period prostheses were made by armourers and the needs of the civilian population were considered secondary. Figures 2.6 (a & b) show 'Le Petit Lorraine' a passive prosthesis designed by the famous military surgeon Ambrose Pare (1510-90) (c) (Reichardt 1978). Le Petit Lorraine comprises spring and ratchet systems so that the fingers and elbow could be flexed by the amputee's contralateral arm and released by levers (Reichardt 1978). It was not until detailed designs were produced by Pare, which were subsequently manufactured from moulded leather and paper by locksmiths or clockmakers, that prostheses were proposed that had the appearance of the naked human hand (Kostuik 1980).

Currently the most effective passive prostheses are individually made using silicone moulding techniques to appear very close to the appearance of the static human limb. These detail of these techniques are described later in this chapter.

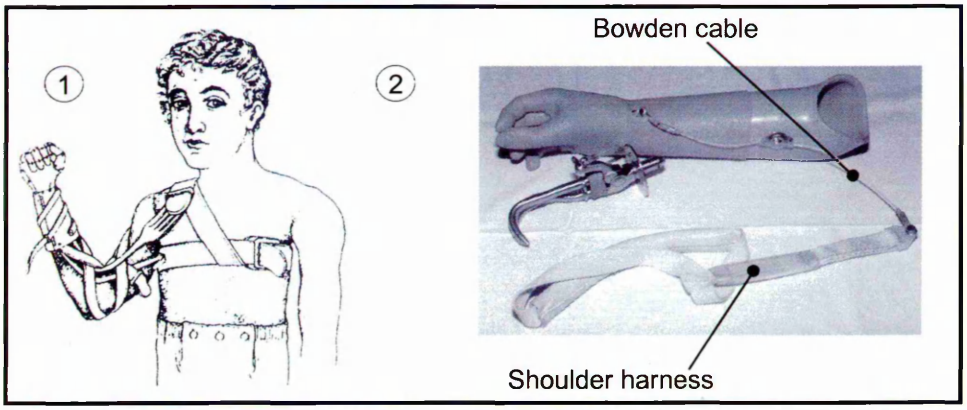

Fig 1.7 Body-Powered Prostheses

Although many of the 15th century passive prostheses included articulations so that the prosthetic fingers could be flexed into place using the amputee's contralateral hand, it was not until 19th century that movements of the amputees body were intimately linked to those of the prosthesis.

In 1812, Peter Baliff, a Berlin Dentist used leather thongs to connect the movement of an amputees shoulder and trunk to the movements of the fingers of a prosthesis shown in (1). In this way Baliff attempted to provide the amputee a means of using body-power to control and actuate the prosthesis. Baliff's design remained largely unchanged until 1944 (Banerjee 1982).

In 1944 Northrop Aviation introduced the Bowden cable which replaced connections to the amputees body made from leather thongs or linen cords (Banerjee 1982). The Bowden cable system is still in current use. For example, for the below elbow amputee; the amputees body-power is usually harnessed from biscapula abduction (rounding of the back) which produces cable excursion at one end of the Bowden cable that is transmitted to open the terminal device. Initially, body-powered prostheses used this force and movement to close the terminal device (hand or other prosthetic end effector) against the restoring force of a spring. These are referred to as "voluntary closing" devices. However, "voluntary opening" devices are more common, as voluntary closing devices are more complex and expensive (Banjeree 1982). However voluntary opening devices may also be favoured by amputees due to problems encountered by the amputee maintaining scapula abduction for grip whilst also manipulating the object (Vitali et al 1978).

The advantages of body powered devices are that they offer the amputee a mechanical link between the terminal device and their body, so that the amputee can know, without looking, where the terminal device is and (for the voluntary closing device) how much force is being applied. Additionally, body-power gained from biscapula abduction can yield large fast acting forces at the terminal device (Dalsey et al 1989). Weight has been indicated as a factor for both the comfort and function of the a prosthesis (Burger and Marincek 1994) Therefore, utilising body power requires no external power source resulting in a relatively lightweight prosthesis.

The disadvantages of the body powered prosthesis include the necessity for the amputee to wear an extensive harness to operate the device shown in figure 1.7 (2). Additionally, operation of the prosthesis requires unnatural movements that can make some tasks difficult (Kyberd 1990), as well as appearing unusual to the observer, therefore having a negative cosmetic effect.

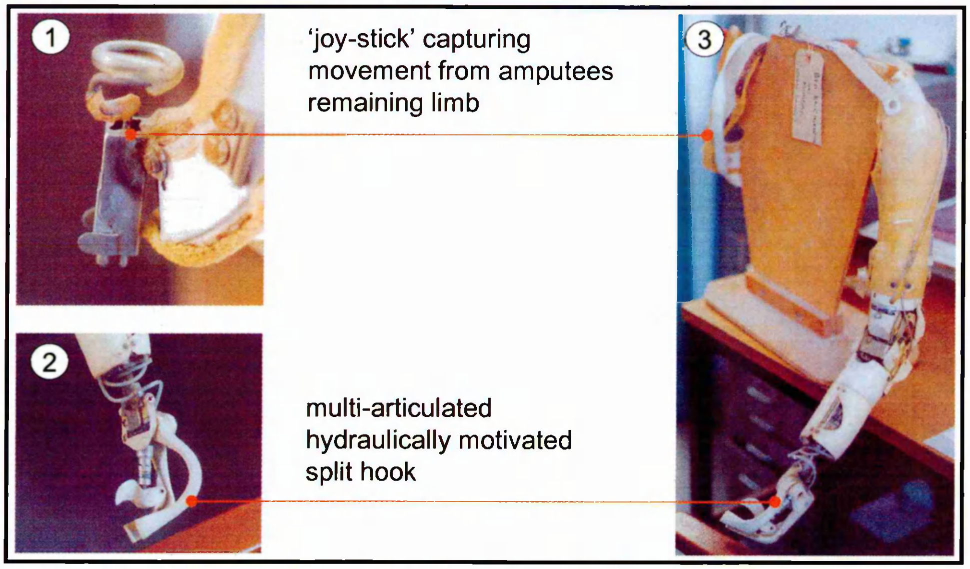

Fig 1.8 The Hendon Hydropneumatic Prosthesis

In the late 1940's in both Germany and the UK externally powered prostheses were being developed from aeronautical technology. These used compressed carbon dioxide as a power source (Sheridan and Mann 1978). These prostheses were developed for the needs of high level amputees who were not able to operate conventional body-powered prostheses with sufficient force (Marquardt 1965). In practice these prostheses comprised lightweight compressed carbon dioxide (CO_2) canisters connected to pneumatic actuators via specially developed valve gear which was often operated by movements of the amputees trunk (Marquardt 1965).

Both this work and development on powered splints for patients suffering poliomyelitis, resulted in many novel actuator and valve designs, such as the 'Pneumatic Muscle Actuator' by McKibben (Kinnier 1965) and the joy stick valve by Hendon shown in figure 1.8 (1). The Hendon prosthesis shown uses small powerful hydraulic cylinders to actuate many degrees of freedom controlled from the joy-stick. However, hydraulic oil was considered unsuitable for prosthetic use so water was used in the cylinders. This meant that the prosthesis required regular maintenance, which ultimately led to its disuse (Kyberd 2000).

The thalidomide tragedy (1958-62) presented another great need for a successful externally powered prosthesis. The effects of the drug meant that many people were born with symmetrical abnormally short arms but highly articulate hands (Kyberd 1990), again unsuited for operating body-powered prostheses. Consequently, more research was funded into pneumatically powered arms but this was discontinued because of problems of control (Banerjee 1982). However, during this period many of the fundamental control problems were tackled by Simpson in Edinburgh - detailed later in this chapter. Therefore, discontinuation of the development may be more accurately attributed to problems associated with the unsuitability of pneumatic power to prostheses (Kyberd 1990). Such problems included the inconvenience of recharging of the CO_2 canisters requiring a return to a central station. The replacement of gas canisters requiring two normal hands, and in additional, in operation the pneumatic actuators produced unwanted exhaust noises (Kyberd 1990).

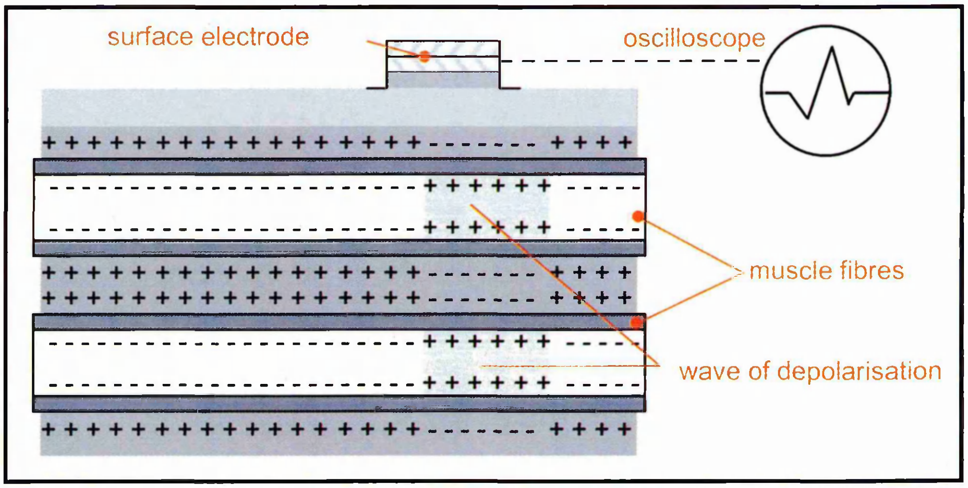

Fig 1.9 Diagram of Origins of Electromyographic (EMG) Signal

The earliest reference to an electrically powered prosthesis comes from experiments in Germany in 1918 in which the fingers of a prosthesis were flexed using electromagnets (Banerjee 1982). Further research efforts towards electrically powered prostheses commenced in the US in 1946, supported by IBM and the Veterans Association. However, after reporting impressive initial results the devices were reviewed as too complex for amputees to control (Banerjee 1982).

At the International Exhibition in Hannover in 1948 Reinhold Reiner introduced the first prosthesis to be controlled using electromyographic signals from the amputee. The control for this device was the size of a shoe box due to the technology available at the time, which is perhaps one reason why this work was overlooked until eleven years later. In 1961 Kobrinsky reported the use of newly introduced transistor components to produce a similarly controlled arm with a much smaller control package that could be worn on a belt (Kostuik 1980).

Kobrinsky's design aroused considerable international interest as at the time many children born with birth defects and could not use conventional body powered prostheses, and this offered a new, non-mechanical, means of control. Additionally, the Korean and Vietnam wars resulted in many US veterans demanding more technologically advanced prostheses. This led to many research programs being formed which exploited advances in micro-electronics and control system components of the early 1960's (Dalsey et al 1989).

The current generation of electrically powered prostheses utilise Reiner's electromyographic control method and are referred to as 'myoelectric' prostheses. Figure 1.9. shows the origin of the electromyographic signal and how this is detected using a surface electrode.

Each time a muscle is contracted an EMG signal is produced. The EMG signal originates from the depolarisation and repolarisation of the individual muscle cell membranes during muscular activity, this process produces measurable potential differences in the surrounding tissues which can be monitored using surface electrodes (Kostuik 1980).

The force of muscular contraction is determined by both the number of muscle fibres recruited, and by the rate at which they are activated, which is reflected in the amplitude of the EMG signal (Scott 1990).

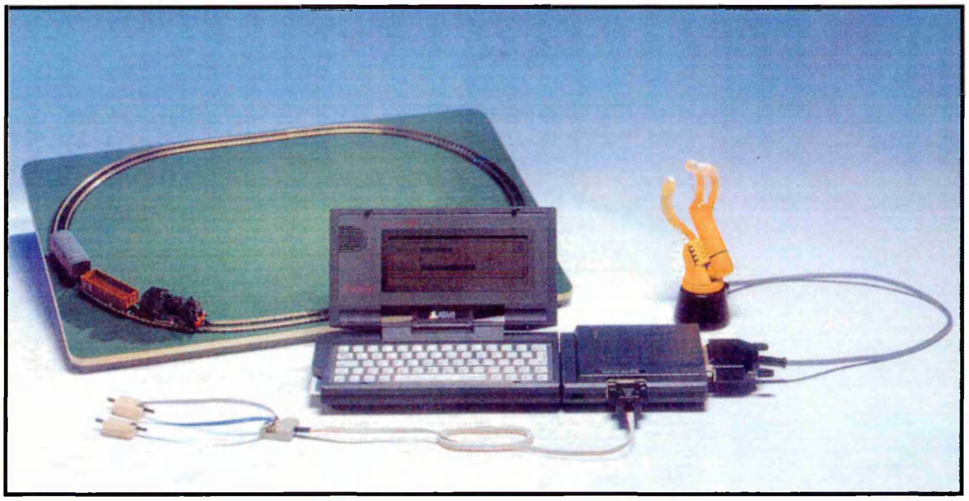

Fig 1.10 An Otto Bock 'Myotrainer'

Initially, it was thought that using control signals from appropriate vestigial muscle sites would form a natural link between desired action, and action completed under external power by the prosthesis (Banerjee 1982).

For a below elbow amputee the EMG may be obtained from electrodes placed over the extrinsic finger flexor and extensor muscles to switch on and off a motor to close and open the prosthetic terminal device. Early systems employed this 'two-site, two-state' control system in which the signals detected from two electrodes acted as switches with two states, off and on. However, the contraction of individual muscles is not 'natural' as muscles contract in synergies to produce joint movement (Harbres et al 1974 (1)). Therefore, amputees have to learn to control their prostheses in this way (Scott and Parker 1988). Currently, amputees are taught to produce these contractions using devices called 'myotrainers'. Early myotraining systems merely used the deflections of the needle of a sensitive volt meter to indicate levels of muscular activity (Kostuik 1980). However, figure 1.10 shows a modern Otto Bock myotrainer system suitable for both children and adults. This comprises a microcomputer screen that can be used to display a pictorial display of the actions of the proposed prosthesis as well as a depiction of the raw signal. Additionally, for children, the desired levels of muscular activity can be used to start and stop a train set, providing both a fun and emotionally more neutral means of training (Kyberd 1990).

The failure of the concept of the myoelectric prosthesis to provide a control method suitable for more proximal amputations such as those above elbow is because it is unusual to find more than one reliable EMG electrode site to control the prosthesis (Sauter 1991). This has led to systems that require a sequence of muscle contractions to produce codes to operate the prosthesis.

Such 'coded' systems include both single-site three-state controls and single-site two-state controls. The three-state system utilises a small muscular contraction to close the terminal device, and a large contraction to open it and no contraction to stop movement (Parker and Scott 1988).

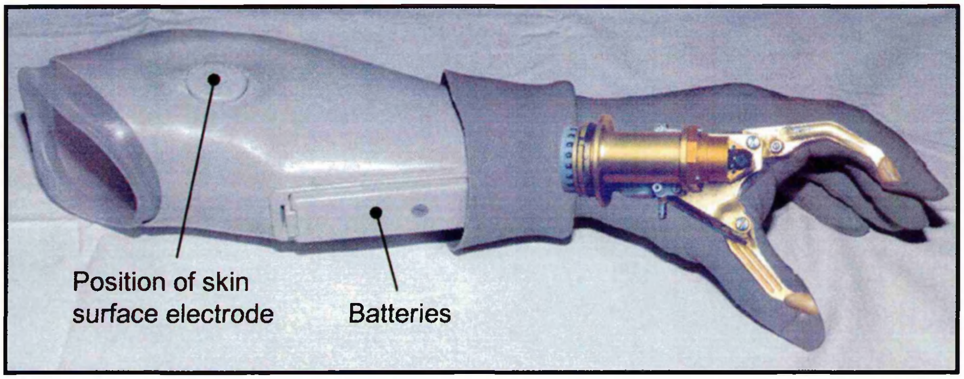

Fig 1.11 A Modern Myoelectric Prosthesis

Single-site five-state controls have been developed to control the function of both the terminal device and a prosthetic wrist, however, this system has been found to require an excessive level of concentration from the user (otherwise known as cognitive load) that cannot justify the benefits of its multifunctionality (Scott 1990).

More recent clinical developments to extend the amputee's voluntary control of the prosthesis have included proportional EMG controls that estimate the level of muscle cell activity and reflect this in the rate at which the terminal device of the prosthesis is driven (Scott 1990). However, these have been criticised again as'unnatural' as the level of muscular activity is not directly linked to the rate of contracture of the muscle (Kyberd 1994).

Using the relatively simple EMG switching control strategies described above to control more than two degrees of freedom becomes problematic for the amputee (Harbres et al 1974 (1)). However, to accomplish many of the activities of daily life, control of multiple degrees of freedom would be beneficial (Harbres et al 1974 (1), Kuribayashi 1994, Gibbons et al 1987).

Researchers addressing the need for multifunctionality have investigated both how to gain more EMG data from the amputee and how to extract more information from the EMG signal. The former studies used multiple electrodes placed on the amputee to detect patterns of synergistic muscular activity and then used these patterns to control a multiple degree of freedom prosthesis (Harbres et al 1974 (1)). Later studies looked to differences within the EMG signal from the 'cross-talk' produced when a single electrode pair was placed over two different muscles (Graupe et al 1982, Hudgins et al 1993). These systems proved relatively successful in producing volitional multifunctionality.

The principle advantages of current myoelectric prostheses are both that the remainder of the user's body is relatively unconstrained as an elaborate harness is no longer required to control the prosthesis; and that myoelectric prostheses generally possess a better cosmetic appearance than the body powered device (Datta and Ibbotson 1998). However, myoelectric prostheses are both heavier and more complex than body powered prostheses, which can result in both discomfort to the amputee and require more frequent maintenance (Datta and Ibbotson 1998).

The research discussed above on using myoelectric control principles does not address the primary problem of myoelectric control that there is an absence of sensory feed back from the prosthesis to the amputee (Banerjee 1982).

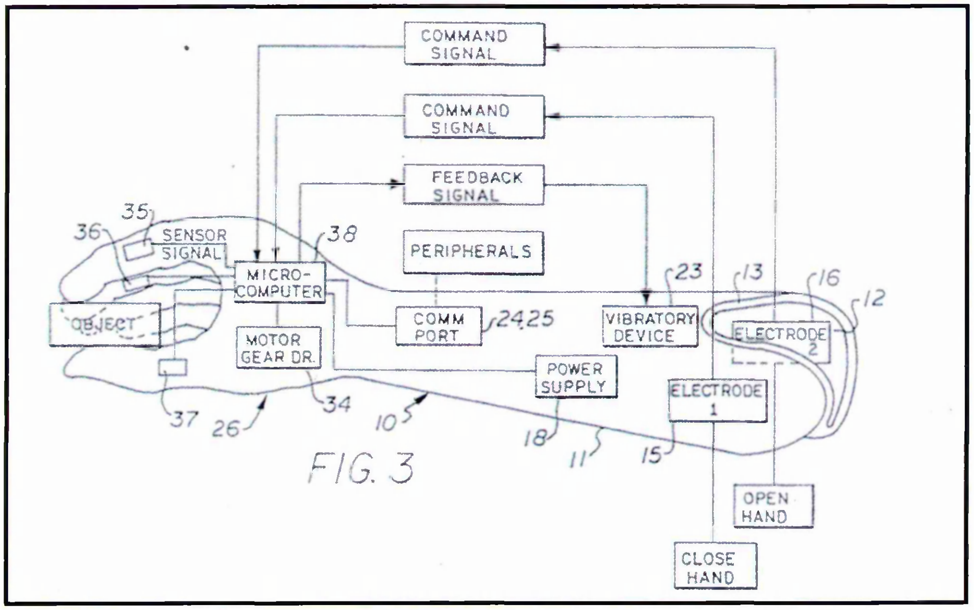

Fig 1.12 Vibrotactile Feedback Patent Drawing (Haslam et al 1995)

The dextrous ability of the human to control their natural upper limb effectively arises not only from multiple degrees of freedom but also from the return of afferent sensations to the nervous system and brain arising from proprioceptors in the hand and within the joints (Harbres et al 1974 (2), Banejee 1982). This sensory feedback is critical to the user in effectively controlling a prosthesis (Tura 1998). EMG signals can only provide efferent control signals to the prosthesis; that is, the control of the prosthesis is 'open-loop' (Gibbons et al 1987). Using a conventional myoelectric prosthesis the amputee has no direct means, other than visual, of knowing how much grip force is being applied or what the position of the terminal device is (Phillips 1988). Additionally, most myoelectric prostheses have a rigid socket that covers some of the amputees limb, depriving the amputee of further cutaneous (skin level) sensations (Scott and Parker 1988).

Electrotactile and vibrotactile systems have been developed to provide the user with feed-back from the prosthesis such as the one shown in figure 1.12 (Phillips 1988). Electrotactile systems return a tiny electric signal back to the skin of the remaining arm (Phillips 1988). In a similar way vibrotactile devices return a small vibration back to the amputees limb. In the example in the figure this is modulated in amplitude with reference to the force exerted by the prosthetic terminal device (Haslam et al 1995).

Both electrotactile and vibrotactile systems have been criticised as placing an unacceptable cognitive load on the amputee. That is, they require too much conscious thought on the part of the user in interpreting what the sensations mean in terms of position and force exerted by the terminal device (Harbres et al 1974 (2)). Consequently, although these devices have been patented as novel, they have not been widely implemented into commercial prostheses (Datta and Brain 1992).

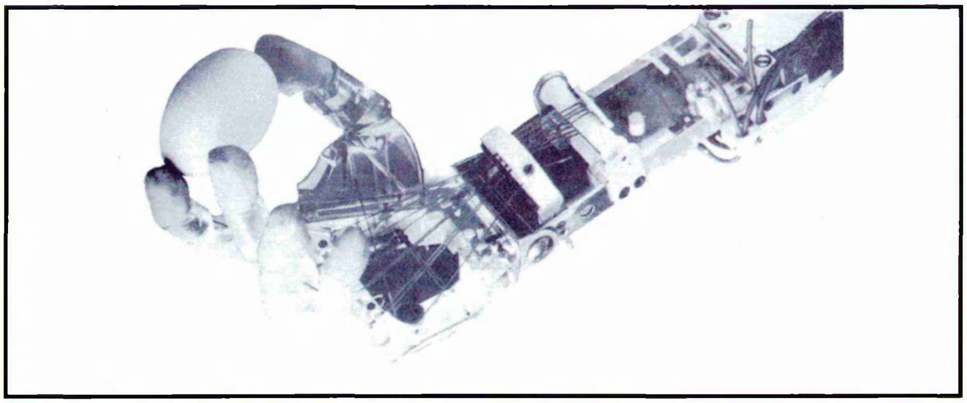

Fig 1.13 The Collins Hand

Adoption of the electromyographic control method into clinical practice meant that terminal devices were designed around the limitations on the number of control inputs to the prosthesis (Crossley and Umholz 1977). Using these conventional control methods amputees' can usually only reliably control a single degree of freedom at the terminal device (Aghili and Haghpanahi 1995).

However, certain activities of daily living (ADL) require the simultaneous control of multiple degrees of freedom (Harbres et al 1974 (2), Barker et al 1996). Therefore, some prostheses have been designed that employ mechanisms that couple many articulations together (Crossley and Umholz 1977). These have been labelled adaptable hands, due to their adapting grip (Bergman et al 1992).

Early hand-like prostheses linked the movements of multiple fingers together. This was done using spring and balance mechanisms, similar to those that apply even tension to either side brake shoes of a car's hand brake (Kyberd 1990). This enabled the fingers of the prosthetic hand to conform around objects. (Becker, 1968)

In the early designs, cords were used to couple the flexion of all the finger segments in synchrony (Banerjee 1982). The early designs consisted of a fixed thumb, however, a later design by Collins (figure 1.13) has an similarly motivated thumb that flexes towards the palm (Reichardt 1978).

Flexing all the finger segments has also been produced through solid interconnecting struts. The Belgrade Hand (Rosheim 1994), Southampton Hand (Kyberd 1990) and various hands developed in the early 70's in Japan use this mechanism to couple flexion of all the finger segments (Kato and Sadamoto 1982). This has been done as a single linear electric motor could then be used to drive the fingers both both in flexion and extension (Kyberd 1990). However, clinical trials which compared a commercially available adaptable hand (Protesindustri AB) against a conventional myoelectric hand (Otto Bock model 8E38=7) found that amputees were able to perform key ADL's significantly better with the conventional device. Subsequently, the amputees were given both types of prostheses for a year's trial, after which all the amputees still preferred the non-adaptable hand (Bergman et al 1992).

Although grasping is a key component of dexterity, manipulation is crucial, which is defined as movement of an object within the grasp requiring independent control of the the movement of the fingers (Pons et al 1999).

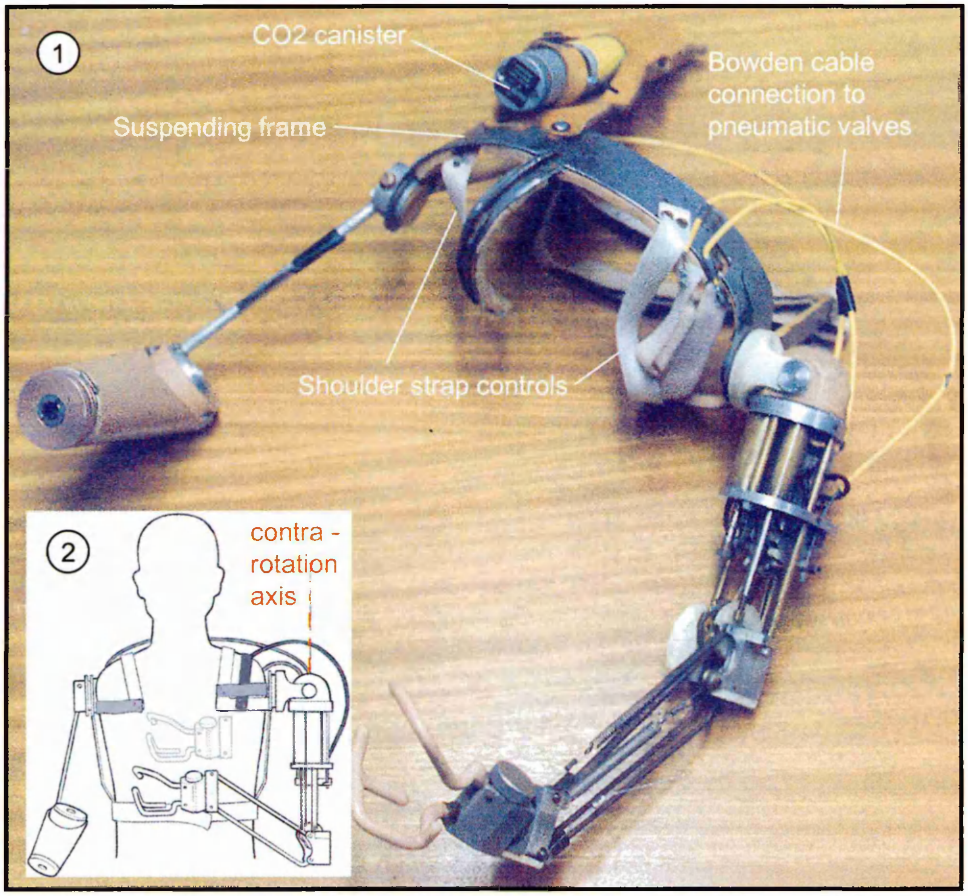

Fig 1.14 A Simpson Pneumatic EPP Prosthesis

The Bowden cable operated body-powered prosthesis provides a mechanical link to the amputee's body that conveys information about the position and force exerted by the terminal device (Frey and Carlson 1994). That is, one or more of the amputees intact joints is locked to the position of a joint in the prosthesis. In this way the control method utilises the proprioceptors of the intact joints, which reduces the cognitive load (mental burden) on the amputee (Harbres 1974(2), Doubler and Childress 1984). Using this control method is said to provide the amputee with Extended Physiological Proprioception (EPP) (Harbres 1974(2)).

Figure 1.14 (1) shows an EPP prosthesis developed at Princess Margaret Rose Orthopaedic Hospital by D. C. Simpson, who has been alluded to earlier. The pneumatically powered prosthesis shown was developed for the needs of a child missing both upper-limbs due to birth defects caused by the drug Thalidomide. The principle function of the prosthesis was to assist the child in feeding activities (Gow 2000). The child operates the device through shoulder straps, (figure 1.14 (2)). Relative rotation of the child's trunk within the suspending frame, pushes on the straps (shown in grey in (2)), which opens a light pneumatic value which causes a powered contra rotation of the prosthesis about the vertical axis shown. Elevation of the child's shoulder blades pushes on the black shoulder strap, this causes another light pneumatic valve to open to power flexion of the prosthetic elbow. Detail (2) shows how the prosthetic forearm provides a link between terminal device and elbow so that as the elbow is flexed the terminal device remains level to aid eating and drinking activities.

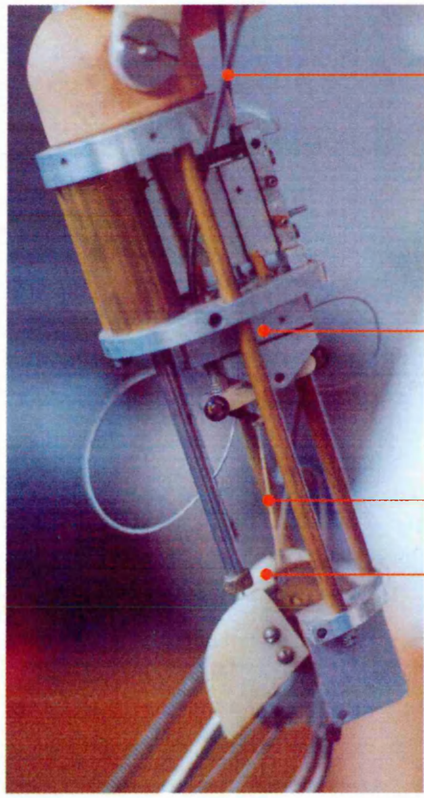

Fig 1.15 Detail of Simpson's EPP Pneumatic Valve Arrangement

Figure 1.15 shows of detail of the specially designed valve arrangement used in the previous prosthesis to control the flexion of the prosthetic elbow.

The pneumatic valve only requires a small displacement for operation, which is supplied from the Bowden cable link. However, the position of the whole valve is linked to that of the prosthetic elbow through the cord shown. Therefore, as the operators shoulder blade is raised so is the valve in a proportional manner. In this way the position of the amputees shoulder reflects that of the prosthetic elbow, even though the movement of the shoulder is significantly smaller and of less power.

Pneumatic power has a higher discharge rate when compared to electrical batteries (Datta and Brain 1992) . Therefore, using pneumatic technology, Simpson was able to build a powerful, fast acting and lightweight prosthesis. However, pneumatic prostheses have many drawbacks, as mentioned earlier. These drawbacks, in conjunction with laws limiting the transportation of pneumatic canisters in the U.S., have been cited as reasons why this type of prosthesis is not now in use (Kyberd 1990).

EPP systems have been developed using electrically powered components (Doubler and Childress 1984, Baer and Seliktar 1987). However, it has been shown in such a system the input signal could 'beat' the motors ability to match this with output positioning of the prosthesis (Gibbons et al 1987). Simpson found that the exact correspondence of input to powered output is an essential feature of a system possessing EPP (Harbres et al 1974 (2)).

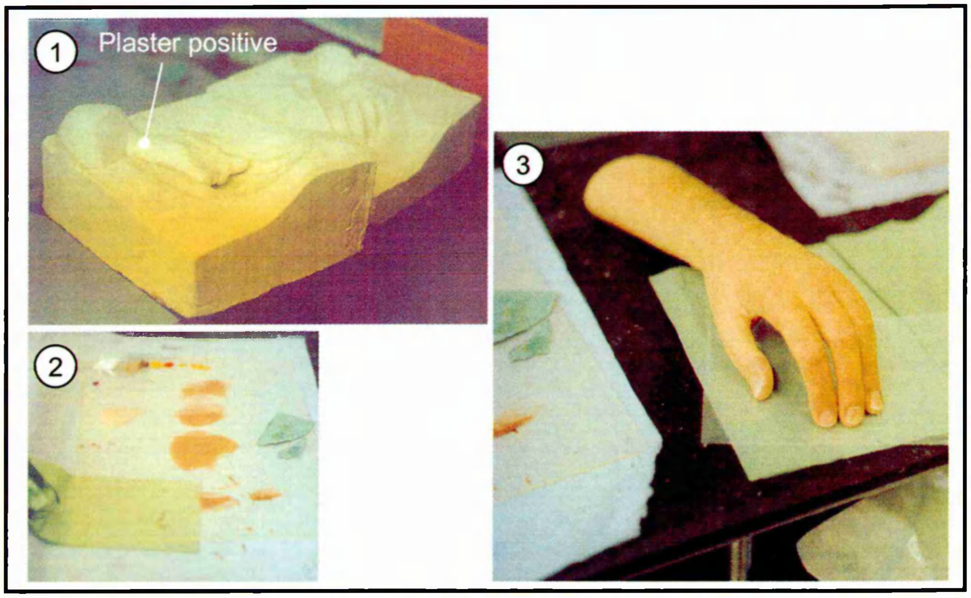

Fig 1.16 Maxillo Facial Techniques Used to Make a Cosmetic Glove

Alongside the functional considerations of the prosthesis, amputees have a requirement to appear 'normal' (Burger and Marincek 1994, Herder et al 1998)); and for the unilateral amputee a need for bilateral symmetry (Barsby 1995). Cosmesis is the aesthetic component of a prosthesis that aims to achieve the appearance of the normal limb. Rejection of many of the functional prostheses has been directly attributed to the lack of cosmesis (Sauter 1991). It has been found that amputees only accepted externally powered prostheses when cosmetic versions became available (Sauter 1991). The lack of an acceptable prosthetic appearance can be disadvantageous for the amputee in forming normal relations with others; such problems have been documented as especially acute in the case of child amputees where parental relationships are involved (Scott 1990, Datta and Ibbotson 1998).

Using labour intensive maxillo-facial layered silicone techniques, limbs can be created by skilled practitioners that are statically indistinguishable from real limbs (Leow et al 1997). Figures 1.16 (1-3) show this technique in practice. Firstly, a mould is made of the amputee's remaining limb, a plaster 'positive' of the amputees limb is then taken from this mould. The positive is then built up with wax and sculpted to appear the form of the amputees contralateral hand. Another mould is then made of the positive and wax part combined, then the wax is melted out to leaving a mould as shown in figure 1.16 (1). Whilst the mould is split silcone is pigmented and applied to areas such as the knuckles figure 1.16 (2). Subsequently, a large quantity of base pigmented silicone is mixed and poured into the mould. Once the silicone part has been taken out further appointments are made with the amputee to apply further pigment details (Watson 2000). Figure 1.16 (3) shows how visually convincing such prostheses can be.

However, such statically convincing replicas can lead to problems for the amputee in deciding when to inform a new acquaintance that they have a missing limb. Additionally, it is documented that movement is an essential part of cosmesis (Jacobsen et al 1982, Vitali et al 1978,), and the static prosthesis can promote feelings of unease in the observer due to its absence (Reichardt 1978).

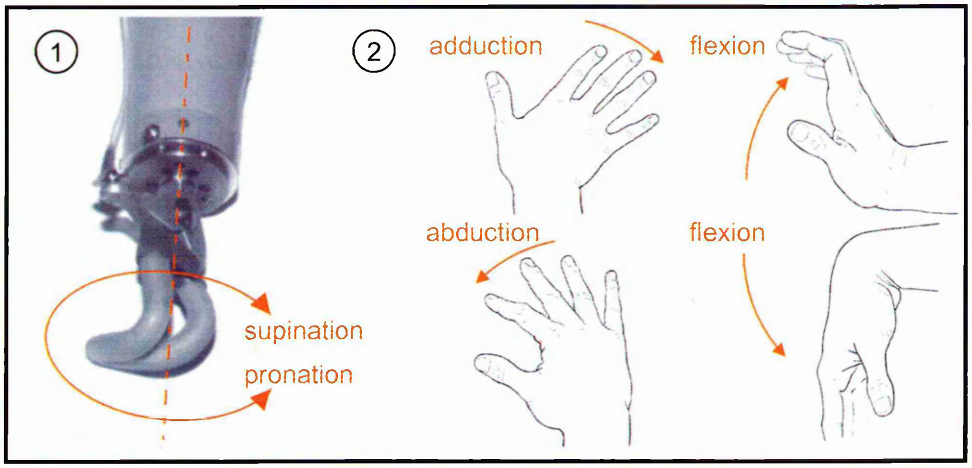

Fig 1.17 Human and Prosthetic Wrist Movements

There is a strong connection between, ‘static cosmesis' and what has become known in the prosthetics field as 'dynamic cosmesis' (Gow 2000). Not only do the limited articulations of existing prostheses prove to functionally limiting (Harbres et al 1974 (1)), from discussions at amputee support groups, amputees find the accessory movements they are forced to make to use their prostheses ugly. Commercially available prosthetic ‘wrists' such as the example shown in figure 1.17 (1) do not provide the range of movement of the human wrist (2) (Datta and Brain 1992). This is evident when observing a transradial amputee performing tasks with a prosthesis. Positioning of the terminal device is achieved by altering the angles of the intact joints of the elbow and shoulder. Due to the distance of these joints from the terminal device, what might have been achieved through small angular adjustments at the wrist, become amplified at the elbow and shoulder. Additionally, the presence of these accessory movements have been recorded in grasping activities. It has been found that a unilateral transradial amputee grasping a cylinder with the intact hand primarily used movement of the digits, however, grasping with the prosthesis was found to include accessory movements of forearm rotation (Venkataraman and Iberall 1990).

Movement, or animation of a prosthesis, is an essential part of both cosmesis and function (Jacobsen et al 1982). Simple robotic joints result in 'singularities' which mean extra rotations often have to be performed to place the robotic terminal device where it is required (Rosheim 1994). This contrasts to human movements which are characterised by articulated joints often with multiple degrees of freedom permitting complex co-ordinated movements (Knudson and Morrison 1997).

Human beings are very sensitive in observing the ‘quality' of human movement (Bruderlin 1996). Human movements can be characterised by both the speed at which they are performed as well as the gross positions of the segments of the body (Knudson and Morrison 1997). For example, Japanese robotics research developed a robotic face that can perform a set of facial gestures including a smile. It was been found that when the robotic smile is performed at one speed the gesture appears comforting to the observer, however, experiments with the smile at half this speed induce feelings of unease in the observer, and comments that the face is leering (Reichardt 1978). Currently, powered prostheses move much slower than the normal limb (Buckley et al 1996).

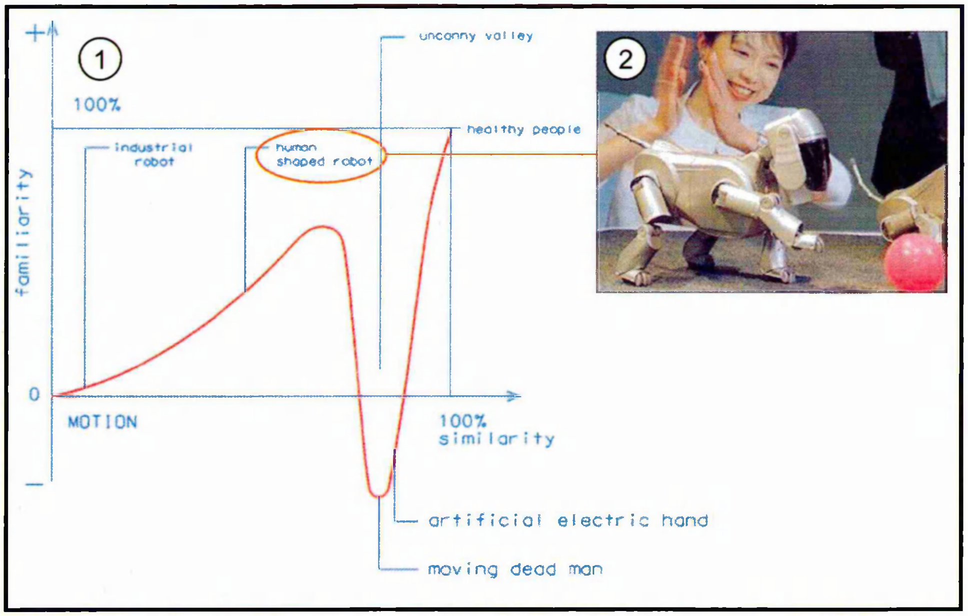

Fig 1.18 Professor Mori's Graph and 'AIBO' The Sony Robotic Dog

Outside the field of prosthetics the connection between static and dynamic cosmesis is also documented. The connection became evident to early motion picture animators. Animators found in the process of animating 'Snow White and the Seven Dwarfs' that the movement of the dwarfs could be conventionally animated through artistic 'inbetweening'; as these characters were clearly caricatures. However, in animating the more anthropomorphically proportioned characters such as Show White it was found that viewers' had much higher expectations for the character to move in a convincing human-like manner. Consequently, a solution was found by filming actors acting the scenes that were subsequently traced to produce the graceful movements of Snow White in the finished film (Disney 1933). This tradition persists, both in the film industry and in computer games. Currently, movements for anthropomorphically proportioned 'virtual figures' have their movements 'motion captured' from live actors using cameras trained on 'markers' attached to the actors body (Watt 2000).

The connection of static and dynamic cosmesis has been formalised by Professor Mori. Figure 1.18 (1) shows Professor Mori's qualitative graph depicting a non-linear relationship between an observers familiarity or acceptance of an object against the human-like movement and static appearance possessed by the observed object (Reichardt 1978). It demonstrates how the observers familiarity with the object gradually positively increases as the static and dynamic appearance increase up to point, which might today be occupied by the Sony Robotic Dog (Figure 1.18 (2)). An object possessing limited animal-like movement, however also possessing a similar level of static appearance to inform the observer of its artificiality. However the graph shows a large 'valley' which includes objects that although statically appearing human-like do not possess similar human-like movement. Indeed Professor Mori places electrically powered prostheses with the static appearance of the human arm at the bottom of the graph promoting feelings of unease in the observer as the static and dynamic qualities of the device are not those expected by the observer (Reichardt 1978).

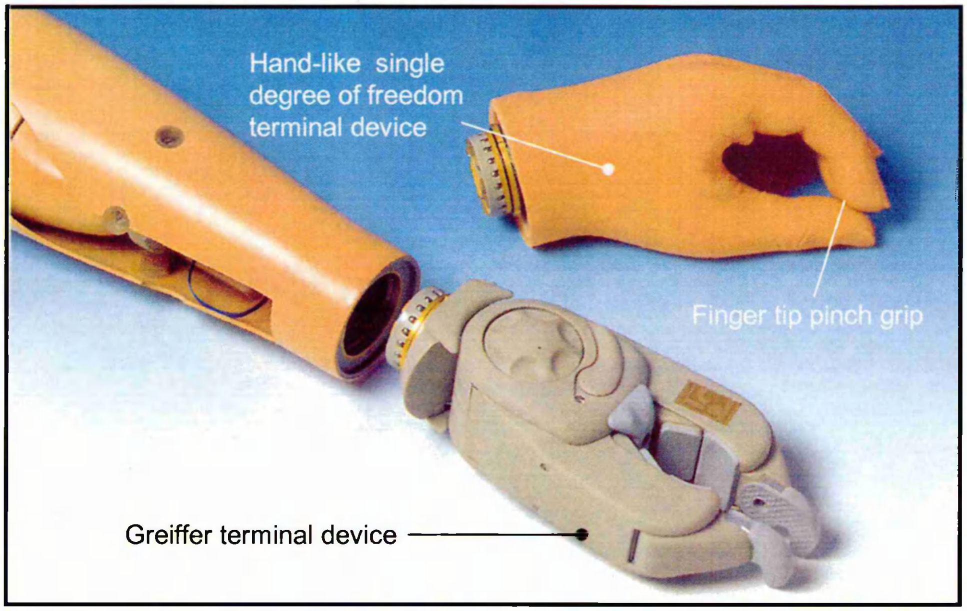

Fig 1.19 Two Otto Bock Myoelectric Terminal Devices

An essential feature of any active prosthesis is the functionality of the terminal device, which must replace the function of the lost hand (Scott and Parker 1988). Figure 1.19 shows two terminal devices available from the prosthetics manufacturer Otto Bock that will fit into the same socket. This starkly demonstrates the current separation of 'cosmetic' and functional devices. As described earlier, using conventional myoelectric control methods it has been found that usually only a single degree of freedom of the prosthetic device can be reliably controlled (Aghili and Haghpanahi 1995). Using the hand-like terminal device shown, the single degree of freedom relates to opening and closing of the hand in pinch grip form. The only powered movement is the motion between the thumb and first finger, the other fingers are there merely for cosmetic effect. Myoelectric control doesn't allow any direct afferent sensations from the terminal device to return to the amputee (Tura 1998). Therefore, in practice these fingers obscure the amputee's view of what is being gripped. Visual surveillance becomes vital to the amputee when other forms of feed-back have been severed (Phillips 1988); as it is often the only means available to determine the position and force applied by the terminal device (Tura 1998). Consequently, the Greiffer, above, has been specially designed to operate from a single degree of freedom control. The jaws open in a parallel motion similar to conventional robotic grippers (Crossley and Umholtz 1977). This permits a much larger grip than available from the pinch grip form of the hand-like device. Additionally, the Greiffer includes a 'wrist' that allows the device to be rotated along the axis of the forearm (pronation - supination movements), which permits greater visual surveillance of what is being gripped. The device also features distinct joints contrasting with the less durable silicone cover on the hand form which are prone to splitting (Herder et al 1998).

Alongside the multifunctional terminal devices there are many special devices that serve only to aid the amputee in particular activities (shown in figures 1.4 (3, 4)). The use of specialist devices has been advocated in UK, however, has found less favour in the USA (Banerjee 1982). This approach has obvious limitations, as the amputee must be prepared in advance with the devices needed perform the desired activities (Kyberd 1990).

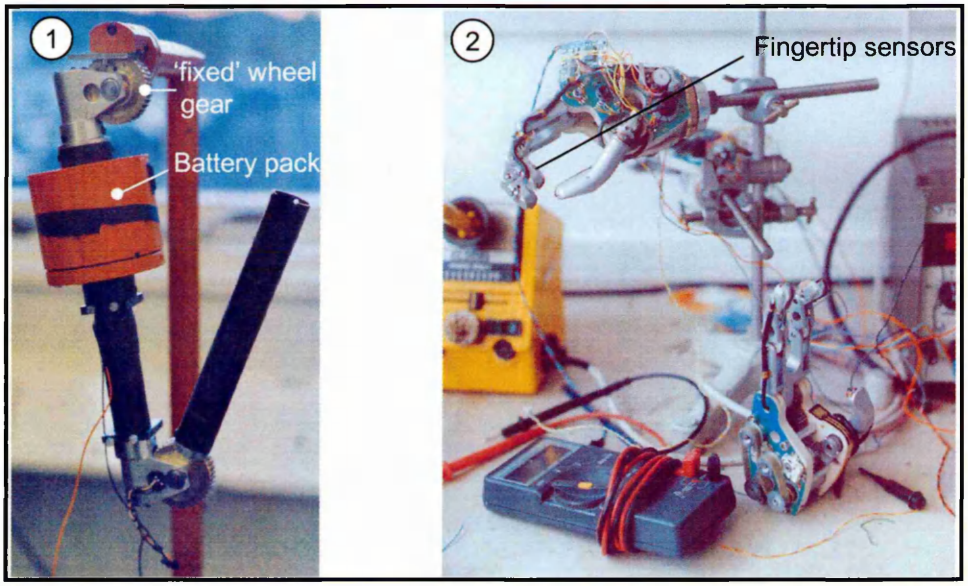

Fig 1.20 Current Laboratories Developments of Gow and Kyberd

Currently active research in upper-limb prostheses in the UK includes the work pursued by D. Gow in Edinburgh and Dr. Kyberd in Oxford. Gow's work builds both on the EPP work of Simpson but additionally looks to novel powered modules. The powered modules currently under development started from the need for powered digits for amputees with partial hands. Conventional myoelectric terminal device mechanisms (see figure 1.11) are inappropriate as the remaining hand occupies the space needed for the drive mechanism. Therefore, it was reasoned that the motivating device for the digit needed to be situated in the space of the prosthetic finger. It was found that, appropriately powerful motors could be integrated into the space of a normal finger. This design approach became known as 'ProDigits'. The powered modules comprise an electric motor connected through a gearbox to a 'worm' gear at the joint. When activated, the rotating worm gear propels the motor and gearbox around the fixed wheel gear. The approach proved powerful due its modularity, and so has been extended to larger modules for shoulder rotation and for elbow flexion shown in figure 1.20 (1). Currently trials are ongoing on a device that comprises powered digits, wrist elbow and shoulder movements (Gow 2000).

Research into novel control methods is being pursued by the Oxford Orthopaedic Engineering Centre under the direction of Dr. Kyberd. This research looks to embody 'intelligence' into the prosthesis to remedy some of the problems associated with using conventional electromyographic control. As the normal afferent feedback (except for vision) cannot be utilised using electromyographic control, Dr. Kyberd has integrated slip sensors into a specially designed terminal device. The terminal device design Figure 1.20 (2) comprises two 'fingers' each with three simple hinge-like joints, the last two joints being coupled together. The device possesses a powered 'thumb' that has a powered joint at its base permitting two degrees of freedom. Combined, the mechanical design, sensors and control technology result in device that on contact with an object 'choses' which grip is optimal and only grips with sufficient force to stop the object being gripped falling from its grasp. Currently, Dr. Kyberd is looking to exploit the opportunities embedded microcontroller chips may have for tailoring control strategies to the individual (Kyberd 2000).

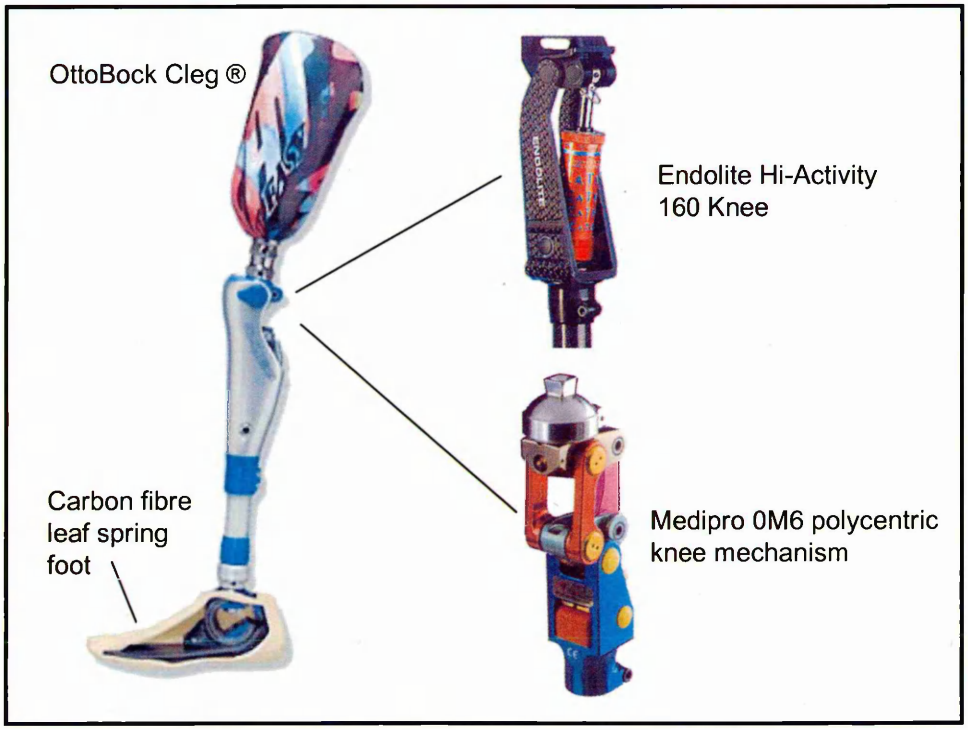

Fig 1.21 Lower-limb Prosthetic Components

It is often remarked by amputees' that prosthetic lower limbs appear more advanced than upper-limbs. Therefore, it is appropriate to be aware of contemporary prosthetic lower-limbs. The figures above show components available for the amputee with an above knee amputation. It can be seen from the figure that the constructional materials are much more evident; such as the carbon fibre braid in the Endolite products, and the highlighting of metallic components through high polish or anodisation.

However, the common functions of lower limb must be appreciated if a objective comparison is to be made between upper-limb and lower-limb prostheses.

Observing the figure; like the upper-limb the lower-limb featured has only a single degree of freedom, the movement at the knee. However, in conjunction with a sprung foot component, (C-Leg above) this single degree of freedom has been found to provide a convincing walking gait (Engerstrom and Van der Ven 1999). Western dress codes mean that the lower-limb can remain covered, whilst the upper-limb is usually uncovered (Robertson 1978). Consequently, the convincing gait can often disguise the absence of leg segments from observer although cosmetic covers are available should more of the leg be exposed, therefore providing a satisfactory cosmesis (Engstrom and Van der Ven 1999) . Mobility is the primary function of the lower limbs, therefore, current prostheses can be said to be functionally satisfactory.

By contrast the upper-limb amputee has not lost the functions of mobility but the functions of manipulation (Pons et al 1999) and a major means of sensing the world around them (Kyberd 1990). Additionally, upper-limbs are required to be far more adaptable; whilst lower limbs have to negotiate climbing man-made stairs, the upper-limb needs to be able to manipulate a vast array of man-made objects predominately designed around the anthropometrics of the intact human hand (Croney 1980).

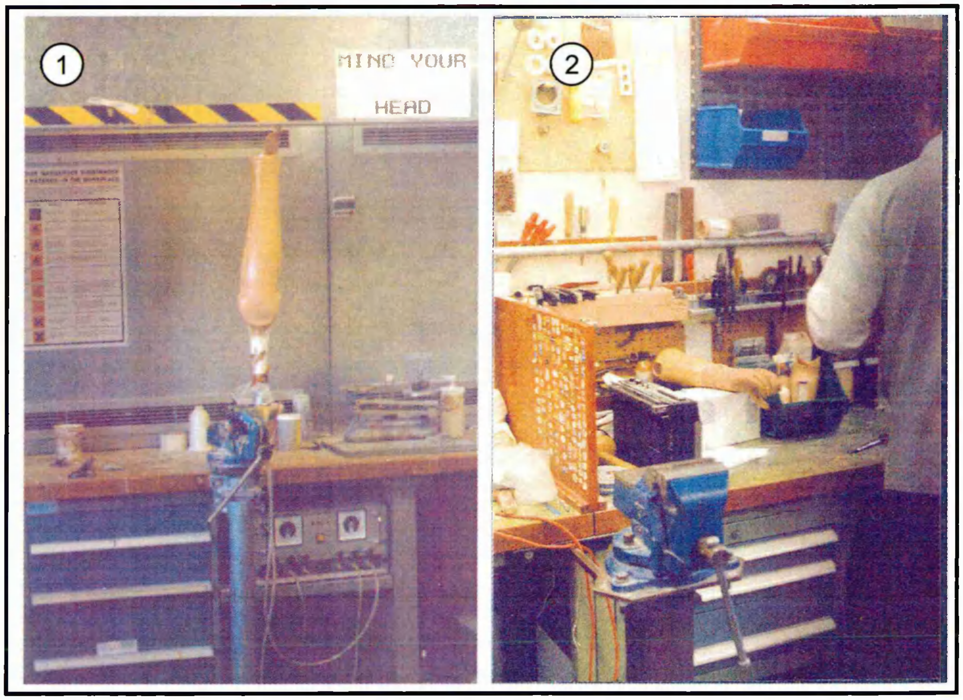

Fig 1.22 Nottingham Limb Centre Workshops

Figures 1.22 (1) and (2) show views of a typical workshop used by prosthetist's in the UK. Figure 1.22 (1) shows a socket being laminated from nylon stockingette and polyester resin using a vacuum method. Figure 1.22 (2) shows an array of hand tools used to finally shape the glass-fibre socket. Due to the complex individual form of the socket, craft techniques performed by skilled personnel have been chosen over machining techniques in the production of the sockets (Martin 2000); although automated production processes have been researched (Boone et al 1994). However, the individual manufacture of prostheses has been given as a reason for their expense (Aghili and Meghdari 1995).

Since the adoption of myoelectric prostheses, workshops have needed to support not only the mechanical structure but also the electrical and electronic components of the prosthesis. This has largely been achieved using large scale modularity of parts, where components such as the battery tray and electromyographic electrodes and bayonet socket for terminal device are standard and are incorporated later into the tailor-made prosthesis (Martin 2000) (figure 1.22(1,2)). Large scale modularity means that items such as the terminal device as a whole is considered a single module, as are the wrist and elbow. Consequently if standardised components malfunction they are either replaced or returned to the manufacturer for repair (Martin 2000).

In the UK amputees can be prescribed a prosthesis by the health service. This means that anyone entitled to UK health service care can be fitted with a prosthesis. However, it results in the anomaly that although the device will have been tailor made for the individual, they do not own the device. This can be problematic when the amputee experiences discomfort due to an ill fitting prosthesis. This occurs frequently, as socket discomfort has be cited as a chief problem for the amputee (Burger and Marincek 1994). Currently, minor changes to improve the comfort of an ill fitting prosthesis need to be performed by the health service. Which is not always acceptable to the amputee.

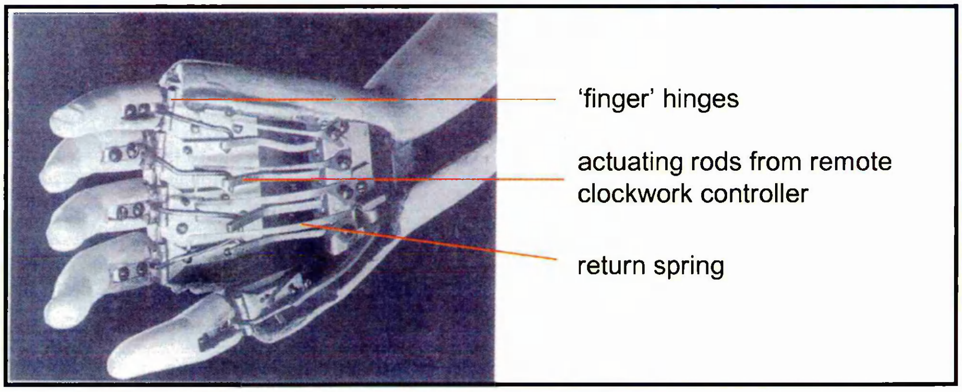

Fig 1.23 Hand of the Musician Clockwork by Jaquet-Droz (1721-90)

In addition to knowing the history and factors that have formed contemporary prostheses it is important to be aware of developments towards creating human-like robots known as 'Anthrobots' (Rosheim 1994). Such human-like robots have been developed for the needs to remotely manipulate either hazardous substances or to work in hazardous environments; a process known as telepresence or telemanipulation (Caldwell 1996). Human-like robotic devices are also used in the entertainment industry, referred to as animatrons (Iovine 1997). Whereas the prosthetics market is small and so research money limited, many of these robotic projects are high profile aerospace projects that command comparatively large research budgets (Rosheim 1994). However, such projects wrestle with similar problems to those faced in prosthetics, and are producing components (Herzinger 1996) and methodologies (Rosheim 1997) that may be appropriate to the field of prosthetics.

People have been interested in creating technological reproductions of the human back to the times of the ancient Greeks who used 'automata' operated by water power to re-enact significant liturgical scenes (Rosheim 1994). With the revival of interest in Greek art and culture in the Renaissance period came a refreshed interest in the production of automata. During this period Leonardo Da Vinci used his extensive knowledge of human anatomy (see methods, chapter 2) along with descriptions of the Greek automata to devise water powered clocks complete with figures that struck the hours, and designed an articulated armoured knight that could sit up, wave its arms, move its neck and open and close its jaw (Rosheim 1997). The next major development towards anthropomorphic mechanism came from the Swiss watch making industry. Inventor of the wrist watch, Jaquet-Droz (1721-90), produced three 'programmable' automata; The Scribe, The Draftsman and The Musician. Figure 1.23 shows the ingenious application of clock work technology to operate The Musician's digits (Reichardt 1978).

Whilst the above examples existed for entertainment, the advent of the industrial revolution and the consequent development of modern machine tools in the 19th century meant many tasks could be more cost effectively performed by robots than human labour. The term robot is in fact derived from the Czech 'robotnik' meaning compulsory labour (Scott 1984). The automotive industry is the chief user of robots, using robot arms to take hot, heavy castings from ovens, to spray body shells and to spot weld body panels together amongst many other tasks (Rosheim 1994). The early robots used prismatic joints, that is joints that permit translating movements similar to those found on conventional machine tools. These joints permit the accurate movement of comparatively large loads (Scott 1984).

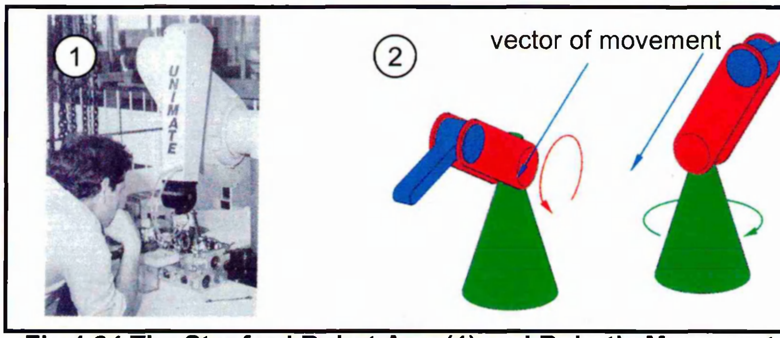

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Fig 1.24 The Stanford Robot Arm (1) and Robotic Movements (2)

In the mid seventies research was undertaken at Stanford University to develop a new robot arm as it was found that the majority of tasks on the automotive factory floor only required the robot arm to lift a comparatively light weight of 2.3 kg but required greater 'dexterity' of the arm (Rosheim 1994). The Stanford Arm developed consists of a series of 'revolute' joints. Revolute is the term used to describe a cylindrical rotation (Schilling 1990). The arrangement of joints in the Stanford Arm allows a large 'working envelope' (reach) for a relatively small 'footprint'. This revolute joint configuration has led such robot being labelled '*anthropomorphic robots'* (Scott 1984). Figure 1.24 (1) shows a commercial example of the Stanford Arm.

The 'arm' consists of three major joints, which might be thought of as two at the '*shoulder*' and one at the '*elbow*'. These joints enable the arm to position the terminal device anywhere in the arm's working envelope (Shilling 1990). The robot arm might then possess a further three minor joints at the 'wrist' permitting 'pitch' 'yaw' and 'roll' allowing the terminal device to placed at any angle (Scott 1984). Combined, the three major and three minor articulations then allow the terminal device to be placed at any position and angle within the working envelope of the robot arm (Schilling 1990). However, the 'anthrpomorphic' Stanford arm doesn't move in the same manner as a human arm. Figure 1.24 (2) shows some of the limitations of this joint configuration. Whereas the human shoulder (gleno-humeral) joint has three degrees of freedom (Kapandji 1982), the base joint of the Stanford arm only consists of two, therefore, to achieve movement in the direction of the vector indicated requires that the base joint to be rotated to align it with direction of movement (Rosheim 1994).

Although the combination of three major and three minor simple revolute joints permits the positioning and orientation of the terminal device, this may mean that the joints have to be in a placed in a unique 'singular' arrangment to achieve a given position and orientation of the terminal device. In contrast, the human arm has more degrees of freedom, therefore, is able to position the hand in the same position with a variety of postures of the arm. This proves important, as the human being, unlike conventional robots, does not operate in a structured environment, and commonly needs to manipulate objects that are obsured by other objects. This requires extra degrees of freedom, or redundant articulations, to reach around objects (Schilling 1990).

Simple revolute joints have been chosen as they are relatively simple to accurately and powerfully actuate, meeting the historical needs of the robotic market, load capacity and accuracy (Rosheim 1994). Commonly, robots work in structured environments (Schilling 1990), and providing these extra 'redundant' degrees of freedom to robotic joints increases mechanical complexity (Rosheim 1994) and programming sophistication (Okada 1982).

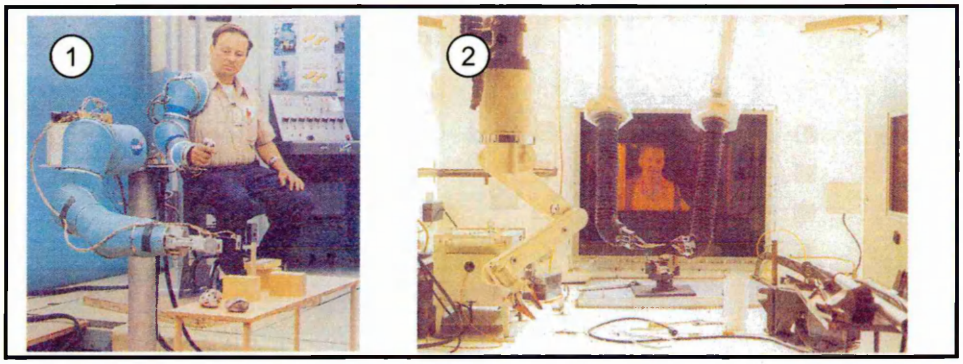


Fig 1.25 Telemanipulators for space (1) and (2) nuclear applications

One of the major factors that has driven the development of human-like robotic hands has been the needs of the nuclear and space industries for remote manipulation, or telemanipulation figures 1.25(1,2) (Caldwell 1995). Typical robotic terminal devices designed for manipulation consist of jaws that grip in a parallel motion (Schilling 1990). Although these devices have been shown to be very versatile, they encounter problems using tools designed around the anthropometrics of the human hand such as using a screw driver; which require a conformable grip (Crossley and Umholtz 1977).
Figure 1.26 (1), over page, shows a robot hand designed in the 1960's by General Electric to fit onto the end of a slave robotic arm for nuclear applications. This contrasts with conventional robotic parallel grippers as the series of revolute joints permits a conforming grip (Rosheim 1994).
The control of the robotic hand increases in sophistication as the degrees of freedom (D.O.F) allowed by the joints increase (Okada 1982). Therefore, early robotics research aimed to limit both the degrees of freedom of the joints and the number of digits of the hand (Crossley and Umholtz 1977). In the 70's a three-fingered hand robotic was designed (figure 1.26 (2)), on the basis that the hand would only be required to perform limited tasks. These researchers' concluded that three-fingers with simple single DOF revolute joints, were the least possible to perform such tasks as operating an electric drill with a trigger switch (Crossley and Umholtz 1977). Parallel research in Japan aimed to further increase robotic hand dexterity by including joints at the base of the fingers that permitted both simple revolution combined with side to side rotation (Okada 1979) (figure 1.26 (3)). It was found that these extra articulations permitted the robotic hand to achieve many more functions including fastening a nut to a bolt (Okada 1982).
Independent research at the Jet Propulsion Laboratory resulted in a similarly configured three-fingered hand (Mason and Salisbury 1985) (figure 1.26 (4)). The kinematic design of this robot hand came from optimising methods, where many joint configurations were considered and judged against how effectively they could both impart arbitrary forces and velocities to a grasped object and also how effectively the different grasps constrained an object (Mason and Salisbury 1985). The robotic hands of Okada and Salisbury are actuated by steel cables. In general using this method requires two opposing cables to control a single degree of freedom. Okada linked these cables together around a pulley. However, in the Salisbury hand separate motors are used on each cable to limit friction effects caused by pretensioning the system (Salisbury-Mason 1985). Both these three fingered hands have ranges of movement larger than those of the human hand (Salisbury and Mason 1985, Okada 1979). Salisbury's optimisation approach contrasts with design of the Utah/MIT hand which appears much more anthropomorphic, figure 1.26 (5).

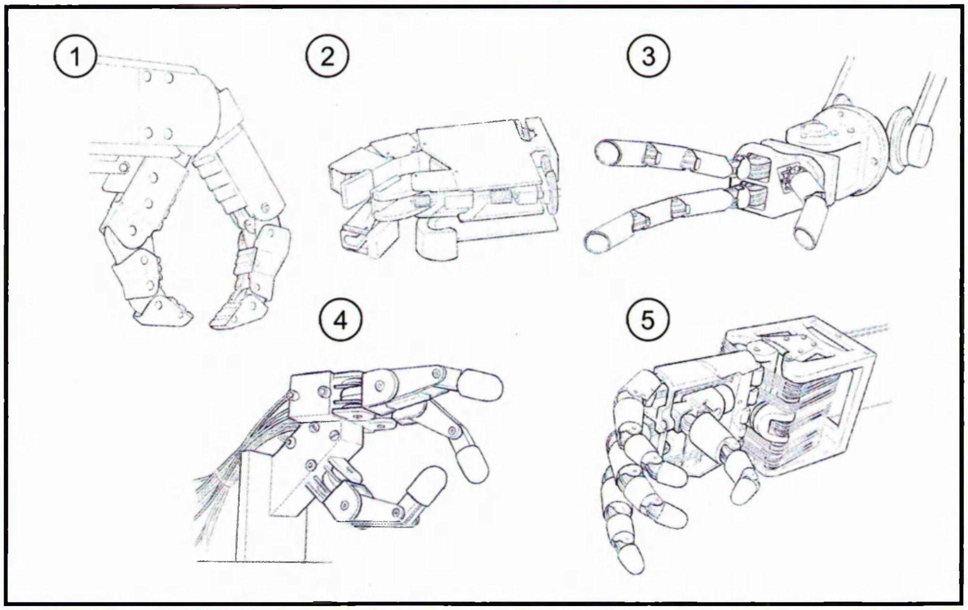


Fig 1.26 Robotic Hands of the 1970's and 1980's

The reasoning used for configuration of joints of the Utah/MIT hand was that the dexterity of the human hand proves the anthropomorphic arrangement of joints successful (Jacobsen et al 1984). The Utah/MIT hand has four fingers to provide a 'redundant' finger to add security to the grasp of an object. Like the previous three-fingered hands it is cable operated to limit it's weight and bulk and so reduce inertial effects when connected to a robot arm (Jacobsen et al 1984). It comprises similar modular digits, with three simple revolute joints and a side to side joint at the base. The base joint is non-anthropomorphic due to the difficulties of routing tendons around this joint (Jacobsen et al 1984). Unlike the previous three-fingered hands the tendons are not powered by DC electric motors (Okaka 1979, Mason and Salisbury 1984). Instead, specially developed glass pneumatic cylinders are used operated from novel two stage valves (Jacobsen et al 1984).

It has been found that the minimum number of fingers required for grasping is three, whilst for manipulation and regrasping four are needed (Pons et al 1999). Consequently, the Utah/MIT hand is the only hand shown above with the potential of manipulating an object within its grasp. Unlike the previous hands it also comprises an 'anthropomorhpic' three degree of freedom wrist to orientate the palm (Caldwell et al 1995).

Versions of the Utah/MIT hand have been made available to researchers in control, prompting criticisms of the hand where it departs from the configuration of the human hand (Perlin et al 1989). These deviations have become particularly noticeable when a human hand within a 'dataglove' is used for control. Additionally, problems have become apparent when the hand is required to use tools designed around the anthropometrics of the human hand (Perlin et al 1989). The early version of the Utah/MIT hand pictured has a oppositional 'thumb' in the middle of the palm, to enable the same components to be used as either left of right hands (Jacobsen et al 1982). However, this placement is problematic when the hand needs to grip a screw driver which requires the thumb to follow the long axis of the screw driver (Perlin et al 1989).

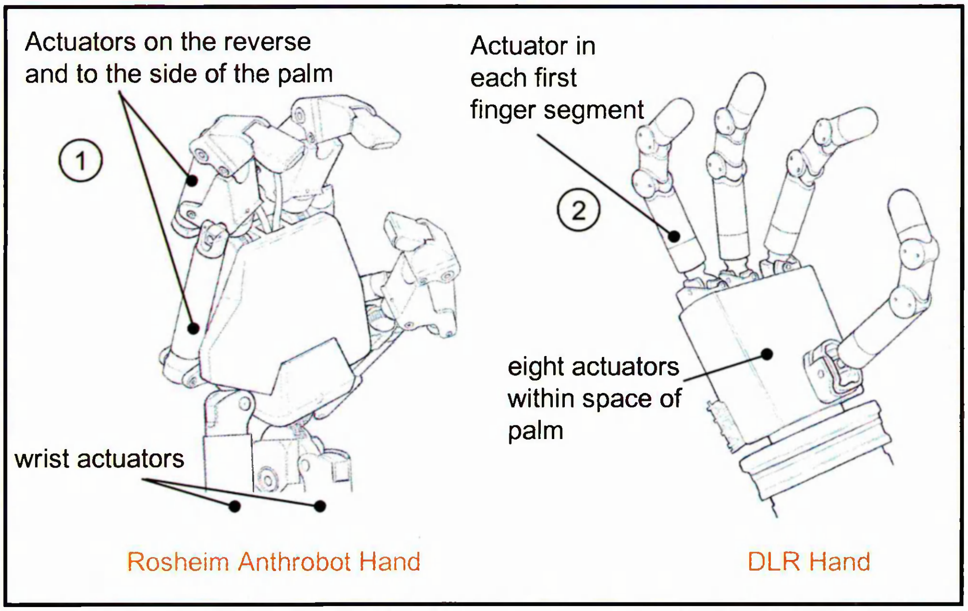


Fig 1.27 Robotic Hands of the 1990's

As a solution to this problem, control researchers using the human hand to control or instruct the Utah/MIT hand have developed software 'tools' that are able to 'map' the most appropriate grip configuration onto the robot hand from the controlling human hand (Bing Kang and Ikeuchi 1997).

The mechanical, and control complexity of the tendon driven hands have led to the design of hands which include local actuation (Lin and Huang 1996, Peiffer 1996). Due to limitations of conventional actuators, designers in the development of the two hands above have had to develop their own electrical actuators (Rosheim 1994, Herzinger 1995). Consequently, the resulting designs are largely based around their methods of actuation (Rosheim 1994, Liu et al 1999).

Figure 1.27 shows a robotic hand designed by Rosheim (Rosheim 1994). This uses a specially designed actuators, indicated on the figure, that can be used in thrust and tension, unlike human skeletal muscle which can only actuate joints in tension (Smith et al 1996). Two actuators are used to move the 'wrist' and these are situated in a forearm position. Actuators that move the fingers are placed on the reverse of the hand, whilst actuators for the side to side motions of the base joints of the fingers placed on either side of the palm (Rosheim 1994).

The DLR (translated acronym: German Aerospace Research Establishment) actuator uses a high efficiency motor linked through a novel 'planetary roller' gearbox to convert the revolutions of the motor to a linear motion. These units are placed both in finger segments and in the palm to move the fingers (Herzinger 1996). This has resulted in a roughly anthropomorphic geometry, however, it is 50 percentage larger than a human hand (Liu et al 1999).

Both the hands above use sophisticated actuators based on electromagnetic principles. However, currently there is research into actuators that convert electric energy more directly into mechanical energy, and may be closer to human muscle. Therefore, these actuators may be more appropriate for application to a future prosthesis (Pons et al 1999).

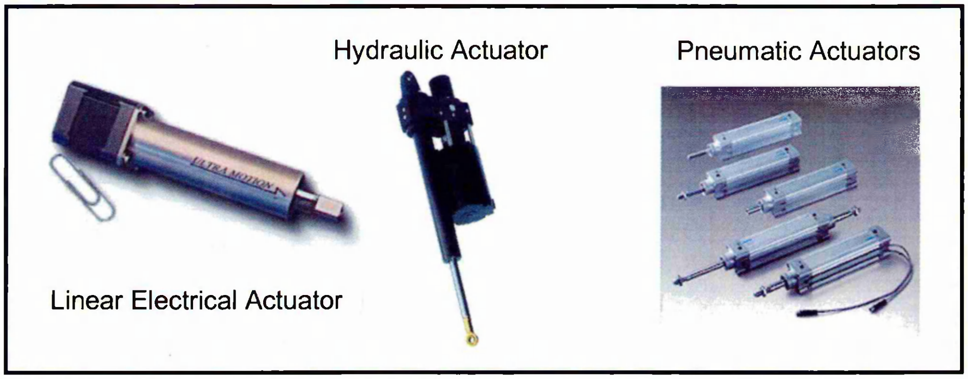


Fig 1.29 Commercially Available Actuators

Conventional actuators such as electrical motors, hydraulic and pneumatic cylinders are not ideal for prosthetic or robotic application (Pons 1999). Electric motors require gearing to convert the high speed revolutions of the motor armature into powerful linear or revolute motions suitable for prostheses. Unavoidably this gearing results in undesired added weight and bulk. Hydraulic cylinders require bulky control valves for electrical control, and pneumatics additionally present unwanted exhaust noise (Kyberd 1990). Consequently, developments towards ‘artificial muscle’ or electrochemomechanical (ECM) actuation technologies may be appropriate for future prosthetic devices (Baughman 1996, DeRossi et al 1992, Lawrence et al 1993).

In the 50’s a large volumetric change was observed in water swollen polymer gels in response to immersion in solutions of either acid (for contraction) or alkali (for dilation). Consequently these materials have become known as ‘pH muscles’ (Caldwell 1993). Typically experimental polymer gel actuators have been configured from either thin strips (Caldwell 1990) or bundles of thin fibres (30 microns - approximately the thickness of a human hair) (Brock et al l994) . Since chemical stimulation relies on diffusion into the fibres, thin fibres contract much more rapidly as the rate of contraction is inversely proportional to the square of the thickness of the contractile element (DeRossi et al 1992). However, chemical stimulation is not ideal. It requires hydraulic valves, electrical pumps and a supply of acid and alkali as the solutions cannot be fully recycled. Therefore when the chemicals combine a salt and water waste product is formed (Caldwell 1993).

Consequently, it is seen as preferable to directly convert electrical energy to mechanical work (DeRossi 1992). Early attempts were made at electrical stimulation by placing PAN (polyacrylonitrile) fibres in a strong electric field created between two metallic plates within an electrolyte solution (Salehpoor et al 1996). Unfortunately, the water within the polymer gels would easily electrolyse and generate gases that would spoil the actuator (Toshihiro et al 1994). Consequently, similar experiments have been devised using polymer gels swollen with other chemicals (dimethyl sulfoxide) that are not so easily electrolysed and therefore allow repeated activation in a strong electric field (2.5 kV DC) (Toshihiro et al 1994).

However, despite these modifications polymer gel type materials can only generate the forces and rates of contraction approaching those of skeletal muscle when stimulated chemically (DeRossi 1992). The polyelectrolyte gels have become known as the first generation of artificial muscle (Otero and Sansinera 1996).

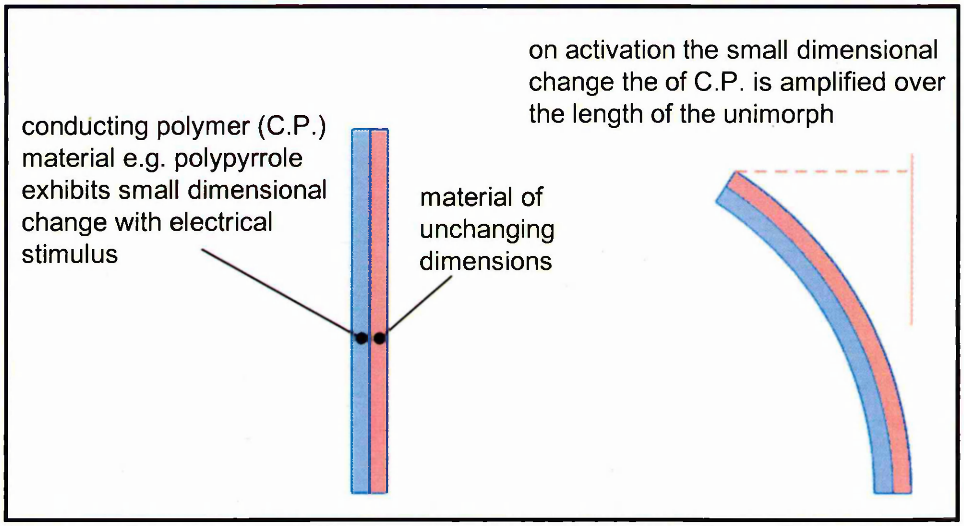


Fig 1.30 Unimorph Conducting Polymer Actuators

To be electrically stimulated the first generation materials required to be between two separate electrodes in an electrolyte bath, however, the second generation materials can be used as electrodes themselves (Baughman et al 1990 and Otero and Sansinena 1997) since they are electrically conducting. When used as electrodes conducting polymers have been shown to react much more rapidly than polyelectrolye gels - in the order of seconds rather than 10's of seconds (Della Santa et al 1997). However, the percentage dimensional changes (strains) are smaller than those of first generation materials (between 0.5 and 10 percent) (Della Santa et al 1997, Baughman et al 1990), but, the force per unit area (stress) produced is comparatively large (Smela et al 1995)
Consequently, mechanical configurations have been devised that can amplify these small strains and make use of the potentially high work capacity of these materials (Della Santa et al 1997).
Figure 1.30 shows the most common experimental configuration, termed the unimorph. The unimorph configuration uses a thin strip of material of unchanging dimensions connected to the conducting polymer strip. On activation the combination bends until an equilibrium of forces is reached. Conducting polymers appear particularly appropriate to prosthetics as their action is silent , and once in the given position no further energy is needed to maintain position (Kaneto et al 1995).

Shape memory alloy has also been put forward as a possible prosthetic actuator (Pons et al 1999, Kuribayashi et al 1994). Materials such as Nitinol (a nickel titanium alloy) change dimension with temperature. Drawn into thin wires these intrinsically conducting materials can be activated by the heating effect (I^{2*} R) of electrical current passing through the thin wire. The wire typically contracts by 5 percent with a temperature rise from 30 to 70 degrees (Delaey 1974). The drawback of these devices is that for a complete cycle the wire needs to cool, commonly a process much longer than that of heating. Additionally, the heat is usually dissipated to atmosphere so that although light and powerful the actuators are comparatively inefficient.

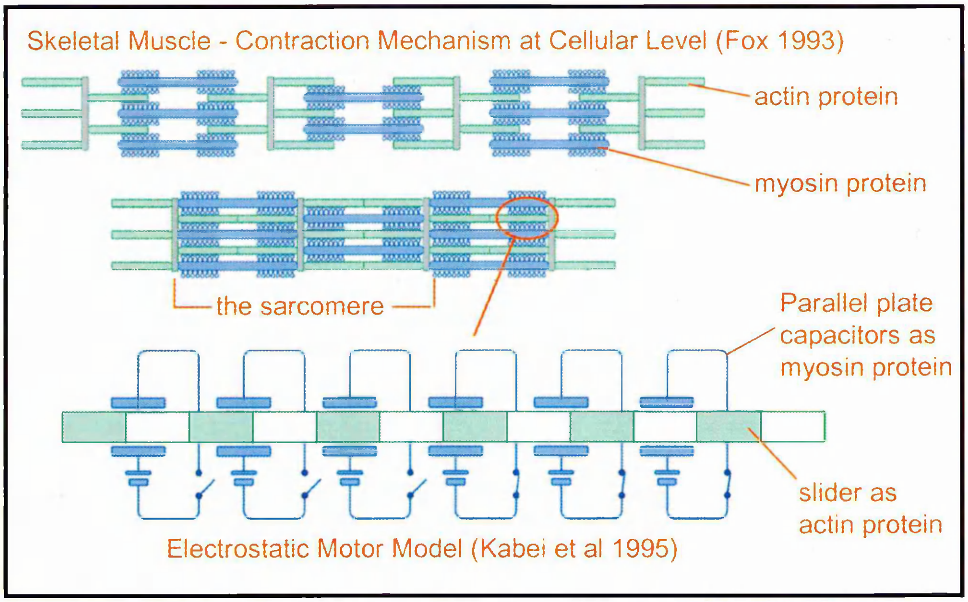


Fig 1.31 Electrostatic Linear Actuator (Kabei et al 1995)

Most of the actuators previously discussed operate much slower than human muscle, which typically can contract at rates of 500% per second (Caldwell 1993).
Searching for a fast response rate has made electrorheological fluids (ER fluids) attractive. Application of an strong electric field across an ER fluid increases the shear forces within the fluid (Stangroom 1999). Devices have been constructed that use ER fluid as a type of valve (Tanaka and Tsuboe 1994). The speed of such response is such that when connected to a speaker cone they can produce audible music (Stangroom 1999). Other researchers have combined the ER effect with electrodes fixed within a flexible material. Electrodes with a strong electrical field between them will be attracted to one another (Bohon and Krause 1998). An experimental test rig has been devised in which two electrodes are fixed within an elastic medium that is mixed with ER fluid. When a strong field is applied between the electrodes the electrodes move together until the ER fluid within the elastic material stiffens to stop them. On releasing the field the elastic nature of the material restores the electrodes to their initial position. This experiment has demonstrated electrode movements up to a frequency of 15 cycles per second (15 Hz) (Bohon and Krause 1998).
Although ER fluids are fast acting, high voltages are required for their operation (typically kV) which makes them inappropriate for prosthetic applications.
Other actuators that have been devised utilising dimensional change caused by piezoelectric or electrostrictive phenomena (Shinsei Kogyo 1985, Uchino 1986). However, commonly these produce this is less than 0.1% strain on activation and require relatively high operating voltages (100's volts) (Baughman et al 1990).
Other actuators have been developed that although not electrochemomechanical in their action have be liked to human muscle in their structure. Such actuators have been referred to as 'biomimicking' human muscle (Kabei et al 1995). Figure 1.31 shows an actuator developed by (Kabei et al 1995) working on a capacitive principle that is likened in its action to the 'sarcomere' of human skeletal muscle.

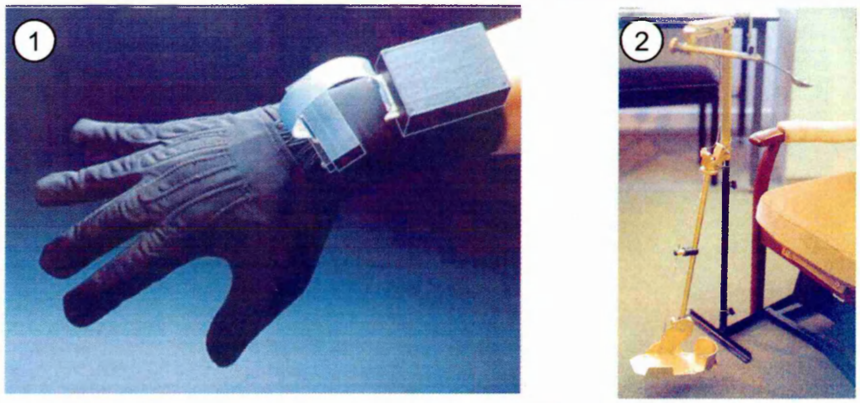


Fig 1.32 A Dataglove and The 'Magpie'

Whatever the actuation method used, multidegree of freedom robotic hands need an effective control method. Robotic hands can be programmed at many levels including through a commercial text based language. However, the most effective method is seen as by 'data glove' control (Speeter 1992). Data gloves fit over the operators hand and record the angles of the joints of the fingers. Outputs from the transducers within the glove are linked to a computer so that joint angles can be recorded against time. From this data joint velocities and accelerations can be determined (Speeter 1992).
Many data gloves have been designed and are now commercially available. These can be separated into those that purely provide data to the computer from the glove about joint position such as the VPL Research Data Glove and the Vitrex CyberGlove. However, 'powered' gloves such as Sarcos Exoskeletal Master not only record position but allow the fingers of the glove to be moved allowing closed loop control of a virtual hand (Pimentel and Teixeira 1993). Just as extended proprioception has been found to be important in the functionality of prosthetic devices (Harbres 1974(2)), such powered feedback has become an important goal in remote manipulation to enhance the operators efficency (Caldwell 1996). This has become an important concept, known as 'telepresence' (Caldwell 1996) and research into channelling further sensations to the operator are being investigated. These include peltier effect devices included in the finger tips of the glove to simulate temperature change experienced at the slave robotic manipulator, and vibratory transducers to simulate touch sensations (Caldwell 1996). However, problems have arisen in the data glove control of current multidegree of freedom dexterous robotic hands where these manipulators divert from the geometry of the human hand (Perlin et al 1989). Production of a slave robotic hand that is closer to the human anatomy should substantially reduce some of the control problems encountered controlling current robotic devices (Caldwell 1995).

Devices exist in the medical field that aim to control multiple degrees of freedom terminal devices using inputs from other parts of the body. Figure 1.32 shows a 'Magpie' designed for people afflicted by MS (Multiple Sclerosis). This degenerative condition means that for a short period of time whilst the motor control of the upper limbs is inoperable the lower limbs are relatively unaffected, the magpie uses motion of the lower limb to guide the motions of the spoon to enable the person to feed themselves (Kyberd 2000).

Development of Research Hypothesis

Research and clinical experience have shown that amputees have a need to both appear and function normally. However current prostheses can only satisfy either a functional or a cosmetic requirement in a single device.

Due to the comparatively small market for upper-limb prosthetics, commercial research and development has focussed on incremental change on moderately successful archetypal designs. The technology used in these archetypal designs means that the number of control inputs that the amputee has control over is very limited.

Continued development along these archetypes has lead to designs where the control limitations have dictated the form of the device. This has resulted in a separation of cosmesis (an acceptable aesthetic hand-like appearance) and functionality. However, it is clear that amputees require both cosmesis and functionality in a single device; and that movement is an essential part of cosmesis. Therefore prosthetic devices are required which offer both the form and function of the human hand.

Successful control strategies for multiple degree of freedom prostheses were reported in the early 1970's, however, this research was not pursued further due to inappropriate actuation methods.

Current actuation methods have been cited as a limiting factor on the design of more complex prostheses. As it has been found that current electrical actuators cannot achieve the performance necessary for effective closed loop control. Historical designs have endeavoured to bypass this limitation by coupling the movement of many fingers together using a single actuator. However, this has not been successful as amputees require manipulative functions in addition to the grasp function provided by such devices.

Advanced robotic hand research has not been bound by the same financial, control and weight restrictions as prosthetics. Therefore, other examples of electrically and pneumatically actuated hands have been developed. However, it has been demonstrated that problems arise both in control and functionality where these robotic hands divert from the anatomy of the human hand. In many, diversions from the original anatomy have been necessitated by the actuation strategies used.

Current research into novel actuators may, however, permit multiple actuators within structures much closer to those of the human hand. Additionally, technology developed from the needs to control of objects in virtual reality environments, or remotely in hazardous environments, may indicate new methods of multiple degree of freedom control.

There is need in both the fields of prosthetics and robotics for a hand which combines both form and function. This thesis examines the development of a skeletal analogy of the human upper limb which must form the basis of any device possessing both the form and functionality of the limb.

Hypothesis

Many design principles appropriate for a new generation of upper-limb prostheses combining cosmesis and functionality will develop from exploring a close analogy to the skeletal articulations of the human upper-limb. Additionally, using a research method based on the production of tangible models will serve an means of gaining useful evaluation from a wide range of interested parties.

Plan of thesis

This research was carried out largely through practical design work and the form of the thesis reflects this. Drawings and artefacts are an integral part of the material presented, and in some cases these provide the clearest means of communicating aspects of the research.

The process used in the preparation of this thesis began with the creation of a systematic archive of models and drawings created during the project. Once assembled this archive was catalogued. The work is described by a series of images extracted from this archive accompanied by narrative text. The full catalogue of material is given in appendix (iv).

The work described in this thesis falls naturally into two parts: the development of a model hand and its evaluation; and the development of a model arm and its evaluation. For convenience and to aid understanding the work in each section has been divided into chapters, each of which addresses a particular joint or joint area.

The chapters are arranged as far as possible in the order in which the work was carried out. However, the research was essentially iterative and where developments were carried out in parallel this is indicated in the text.

A system of annotation has been devised for images and this is described in full on the following page.

Plan of thesis

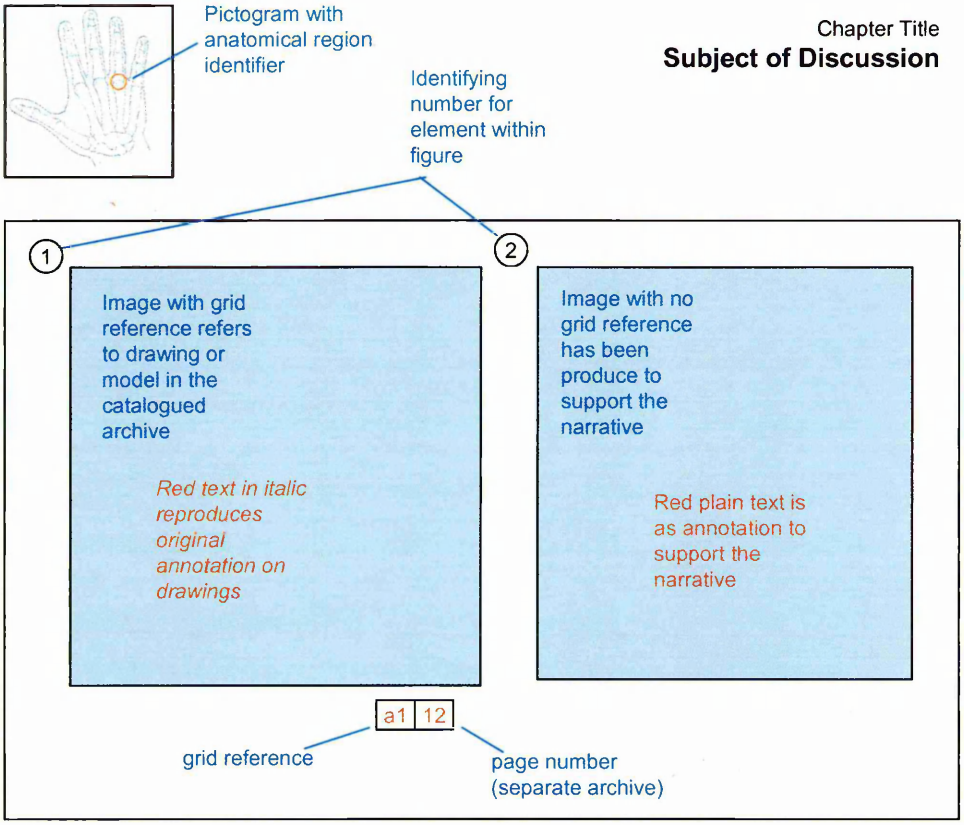


Fig x.y Annotation of figures

The page layout of the main body of original work of the thesis is laid out with figures from the development work serving to explain points made in the text. Where sketches or sub-diagrams are referred to in the text it is done thus (1).

This format has not been followed in both the methods and conclusions chapters.

Funding

This work has been supported by grants from the the National Hospitals Trust and the Arts and Humanities Research Board. This support is gratefully acknowledged.

Dissemination of Knowledge

During the course of this research the work has been reported through both papers in refereed journals and presentations at international conferences:

RUST, C., WHITELEY, G.P., and WILSON, A.J.. (1997) The Development of Upper-Body Prostheses Directly Analogous to Real Limbs, Proceedings of the Medical and Biological Engineering and Computing Conference September 14-19 Nice, France, Vol. 35, Supplement pt. 1, p 655.
(appendix (i))

RUST, C., WILSON, A.J., and WHITELEY, G.P. (1998) Using Practice Led Design Research to Develop an Articulated Mechanical Analogy of the Human Hand, Journal of Medical Engineering and Technology, Vol. 22, No. 5, pp226-232.
(appendix (ii))

WHITELEY, G.P., WILSON, A.J., EROL, R. and RUST, C. (1999) Development of Elbow and Forearm Joints for an Anatomically Analogous Upper-Limb Prosthesis, Proceedings of the European Medical & Biological Engineering Conference EMBEC '99 November 4-7 Vienna, Austria, Pt. 2, pp1376-1377.
(appendix (iii))

Research groups in several countries have expressed an interest in applying the work described in this thesis to both prosthetics and to more fundamental work on actuation and control. Currently, a model limb has been supplied to the University of Pisa who are investigating appropriate actuation and control strategies. A further copy of the model has been requested by the Jet Propulsion Laboratory in Pasadena. Further dissemination of model arms to other international research groups is planned.

Need for a Another Research Approach

The preceding chapter shows that current prostheses are either cosmetic or functional, evident in three prosthetic archetypes: myoelectric, body-powered and passive prostheses. The results of many previous research projects have improved on these archetypes but have not shown a successful means of combining cosmesis and functionality in a single device, which is desirable for the amputee (Fraser 1998, Sauter 1991).

New developments from research into actuation and control appear to provide key elements for a new generation of artificial limbs that might combine cosmesis and functionality (Della Santa et al 1997). What is missing, in these developments, is a mechanical 'platform' demonstrating how these advancing technologies might eventually be combined and practically applied to the field of upper-limb prosthetics to form a much closer replacement for a lost limb.

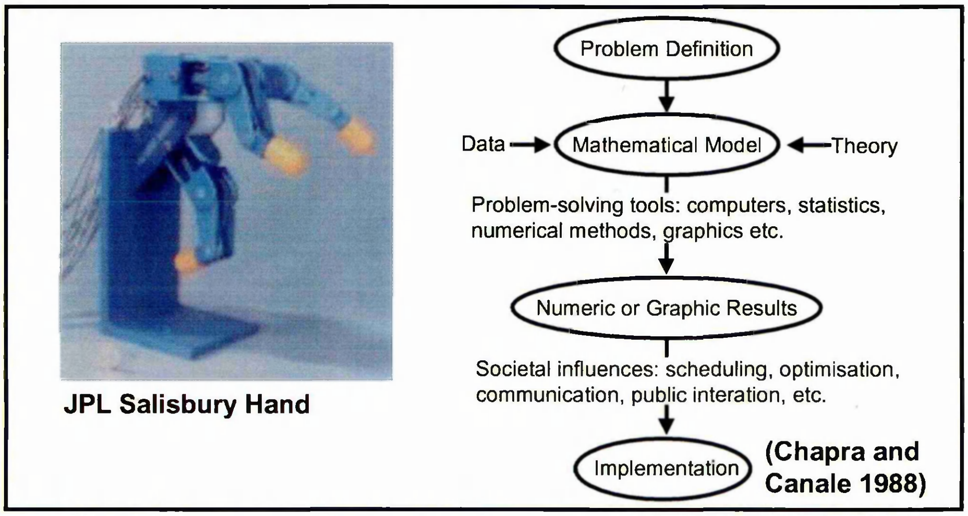


Fig 2.1 The JPL/Salisbury Hand and an Example of an Engineering Design Method from the Same Period

In seeking an appropriate form for such a mechanical platform, conventional engineering design methods, used in previous prosthetic research, may be inappropriate. These methods are used as many of the tasks given to engineering designers are subdivisions of a larger whole (Pitt 1973). Therefore, using 3D structural analysis and other analytical techniques a component can be designed to meet a given specification (Papalambros and Wilde 1991).

However, such methods have not revealed new archetypal prosthesis designs (Banerjee 1982). Similarly, in the field of advanced robotic hands, the application of optimisation methods has not revealed archetypes that combine cosmesis and function (Mason and Salisbury 1985). To illustrate this, figure 2.1 shows the JPL / Salisbury Hand and an engineering design method of a similar period. This hand was developed using mathematical techniques to design a dextrous manipulator with an optimal kinematic configuration of joints for grasping objects (Mason and Salisbury 1985). However, it can be seen that this method has resulted in a device very mechanistic in appearance, which arguably would be cosmetically unacceptable to the amputee.

Thus, methods focussing on optimisation have failed to combine cosmesis and function and a methodology is required that can elicit appropriate new design principles.

Creative Reasoning

Amputees need to carry out normal activities of daily living and so must live and work in the common environment, using everyday products and controls (levers, handles etc.) which have been designed around the anthropometric measurements of the typical human hand (Croney 1980). Therefore, a new approach drawing reference from the human hand appears appropriate. In fact recent studies have indicated that it is essential to observe the human hand closely before embarking on the design of a prosthetic or robotic hand, and have stated it *presumptuous* not to do so (Pons et al 1999, Pieffer 1996).

However, drawing clear design principles appropriate for a robotic or prosthetic device from the complex biological upper-limb is complicated by the subtleties and individual variations of the highly complex biological forms of the human hand (Landsmeer 1976). A method is needed that enables appropriate analogies to be extracted from the study of the human upper-limb, whilst not becoming overwhelmed by its subtlety and complexity.

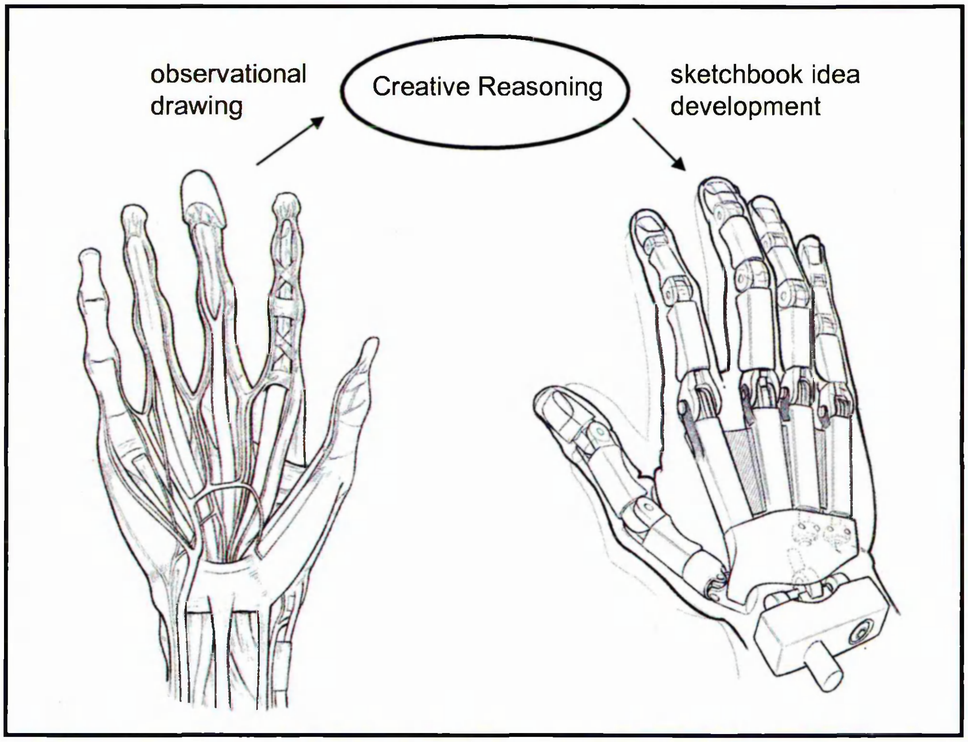


Fig 2.2 Drawings of a Human and a Mechanical Hand

The research method chosen is a form of practice led design research as described by Archer (1995). This places emphasis on creative activity during analysis stages in order to *'shed light on the problem'* (Archer 1995). Within this research project the term 'creative reasoning' has been adopted to describe the stage within the research process when new analogous ideas are generated. The techniques used focus on the close scrutiny of the anatomical hand through 'observational drawing' and 'sketchbook idea development'.

Creative Reasoning

It has been indicated that, through the production of detailed life drawing, the 'producers' three-dimensional knowledge of the subject is enhanced (Simpson 1973). Detailed life drawings made to identify and understand subtleties of human form have a long history and clear examples can be seen in the Renaissance. During this period artists such as Andrea Verrocchio used life drawing studies of the human to enhance his knowledge of human musculature (Conrad *et al* 1995). The technique of detailed drawing made from human anatomy is also profoundly important in the history of medicine (McGrew 1985). Leonardo DaVinci, who studied under the supervision of Verrocchio, applied the method of detailed drawing to, not only surface musculature, but also the study of dissected human cadavers (Conrad et al 1995).

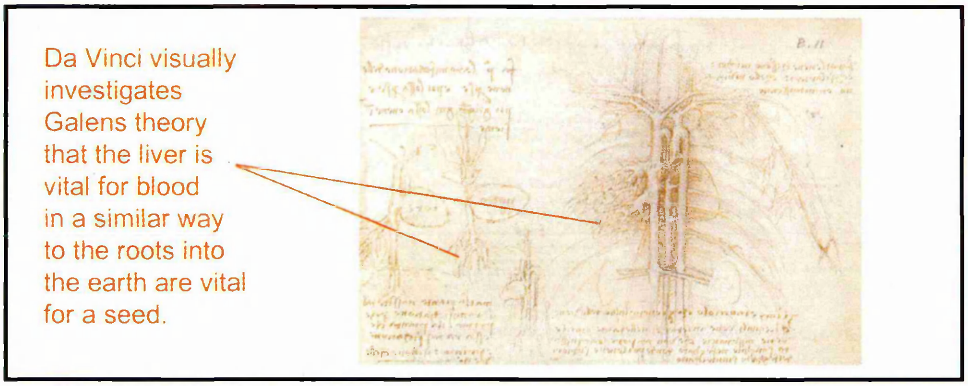


Fig 2.3 A Leonardo Da Vinci Anatomical Study

This process has been referred to as 'observational drawing' within this research project. A stage of observational drawing from three-dimensional skeletal anatomical models has been included as a primary research activity to inform subsequent detailed design work. The drawing techniques used in the main body of the work record shape through delineation, form by hatching techniques and dimensional annotations are added to record scale information. However, observational drawing is not exclusively used in the creative reasoning process. It is combined with reviews of anatomical literature to inform the process of functions of the limb which are not apparent from the study of static three-dimensional limbs.

The subsequent stage in the creative reasoning process is the generation of sketch book ideas. This uses the enhanced knowledge of the limb gained through observational drawing to inform sketches that identify parallels between the complex observed anatomical forms and those of more simple geometrical forms . This has been referred to within this research project as 'sketchbook idea development'. Previously this technique has been used by the anatomist Kapandji for educational purposes. He uses drawings of geometrical forms alongside drawings of the anatomy in his anatomy text books to highlight functions and forms of the anatomy (Kapandji 1982).

Figure 2.3 shows sketch book comparisons made by DaVinci in the time of the Renaissance showing the main arteries of the thorax against compared to a sprouting seed. Through this visual comparison DaVinci questioned Galen's assertion that the liver was the vital organ for the blood (Gombich et al 1989).

Observational drawing and sketchbook idea development are combined with literature review to form the inputs to the process of creative reasoning used to develop skeletal joints analogous to those of the human limb.

Analogy

This research is concerned with investigating mechanical analogies to the biological joints of the limb. Because it appears unlikely that whole biological limb grafts will be feasible in the medium term (Lee *et al* 1999), it is argued that such analogies offer the most promising route to a replacement limb which can match the appearance and function of the original. Such an artefact will never be the same as the human limb, however, it might express a likeness.

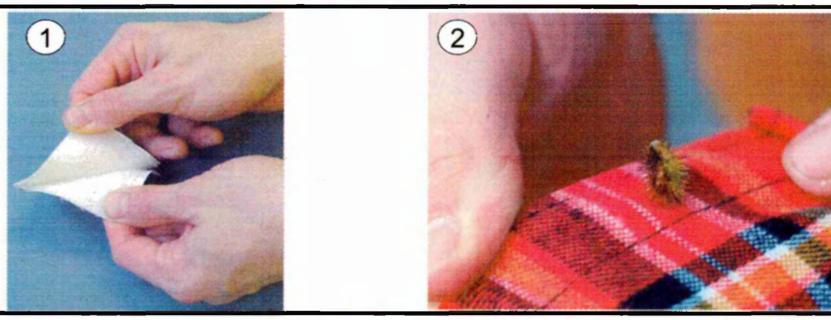


Fig 2.4 Velcro [R] (1) Inspired by the Cocklebur Seed (2)

In language, analogies are used to express likenesses or parallels to clarify or simplify thoughts or concepts. In design and engineering analogy is used as a primary tool to find solutions to problems that may have been previously addressed in other fields or in the natural world (Papanak 1972). Analogy as a means of stimulating new ideas has been described as the most powerful concept (Pugh 1990), and the 'staple diet for the would be inventor' (Thring and Laithwaite 1977).

There are many examples of analogy in design and engineering being used to solve practical problems. '*Sir Marc Isambard Brunel when designing the first river tunnel across the Thames in 1843 conceived the idea of caisson from observing ships worm tunnelling in wood*' (Pugh 1990). The underslung chassis is evident in the insect world, spiders and beetles utilising the lowered centre of gravity to prevent themselves from falling on their backs, as they would not be able to 'right' themselves (Thring and Laithewaite 1977). Figure 2.4 shows how the invention of Velcro was inspired by the observation of the properties of the cocklebur seed (Papanak 1980).

Whilst the use of analogy is very powerful, care needs to be taken to identify the original context of the subject for the analogy. For example, it is important to be aware of the effects of scale. Although mass varies with the cube of the dimensions, strength varies with the square of the cross section (Gordon 1978), therefore, some structures may not be appropriate for direct replication at differing scales (Steadman 1978). Other phenomena have been found to be similarly 'context sensitive'. This has been evident in the field of 'artificial muscle' research. Rapid, powerful dimensional changes of polyacrylonitrile fibres stimulated by diffusion of acids and bases show promising performance at small scales (Salenpoor et al 1996). However, such fibres cannot be similarly arranged to make useful large scale artificial muscles as diffusion of the actuating chemicals into the larger structures is much too slow (Brock and Lee 1994).

However, design principles based on a skeletal analogy of the human limb appear extremely appropriate, as the resulting design ideas will be embodied at a similar scale to those observed. This is important as the inherent mechanical properties of the observed forms will be appropriate to those of an upper-limb prosthesis using the appropriate choice of materials.

Need for Physical Models and their role in Evaluation

Creative reasoning may produce drawings pointing to apparently appropriate analogies of the articulations of the human limb. However, it is important to recognise that they still represent abstractions. Therefore, a stage of model making is an integral part of research which uses practical design methods.

Skilled drawing can mislead both the observer and creator into believing that a mechanism will function when, in fact, it may be fundamentally flawed. Examples of this problem may be seen in the multitude of sketches of perpetual motion machines (Laithwaite 1980). A second pitfall is the appreciation of scale. This is evident in Leonardo DaVinci's ornithopters. Whilst these sketches contain similar forms to those observed from birds they contained no appreciation for the escalation of mass of the structure for it to withhold a human (Gibbs-Smith 1978).

Therefore, the production of physical models permits the design concepts to be tested against reality. In the case of a model developed to be a close skeletal analogy of the human arm; this can be demonstrated in the use of conventional goniometric techniques used to assess the range of movement of the proposed joint designs (Norkin and Joyce-White 1995).

Researchers investigating the nature of the human peripheral nervous system have used a similar method of physical model development to test theories of the reflex nature of human limb movement. For although numerous reductionist experiments have elucidated many aspects of human motor control it is impossible to form a whole picture of human motor control without embodiment into a physical test rig (Hannaford 1995). Similarly, previous work on the development of robotic hands has indicated that the activity of producing of a physical model enables many of the underlying theoretical problems to be more clearly understood. (Jacobsen et al 1984).

The complexity of the human limb suggested that an iterative method based on the production of physical models and prototypes and their subsequent evaluation would lead to an increasingly refined analogy. Fig 2.5 gives an overview of the methods adopted in this research

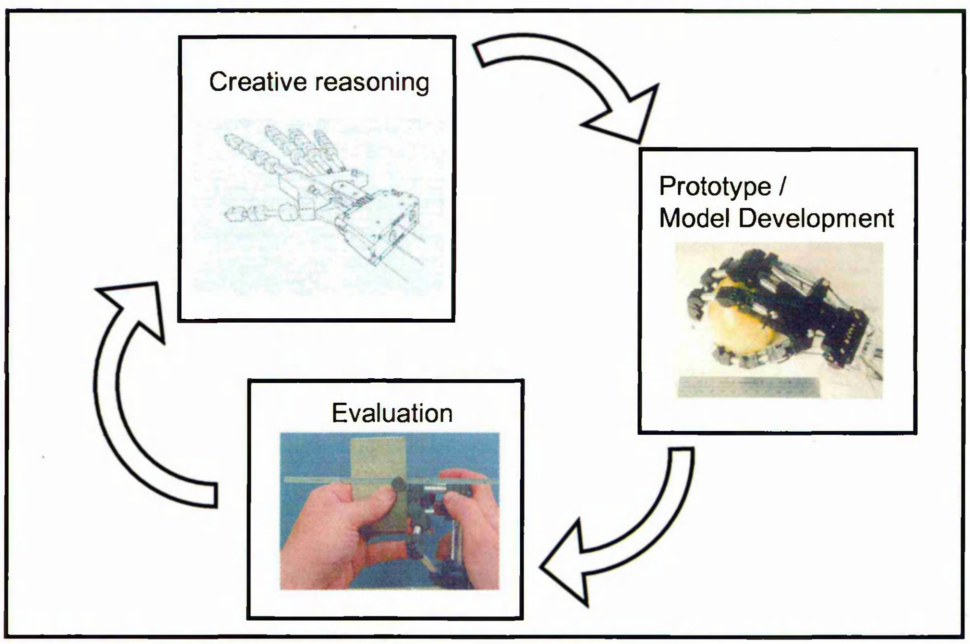


Fig 2.5 A Form of Practice Led Design Research

Need for Physical Models and their role in Evaluation

Another key aspect of the production of physical models in this research is their use as a tool to stimulate criticism from the end-users. The production of physical models permits criticism of the design by a wide range of interested parties at many levels, both qualitatively and quantitatively.

The end-users in this research project are primarily people with absent limbs, however, prosthetists, occupational therapists and prosthetics manufacturers are also 'users' as they too are effected by the design of prostheses. Therefore, an amputee support group has been attended on a regular basis to review the research as it has developed and to gain an understanding of the experiences and concerns of a group of users.

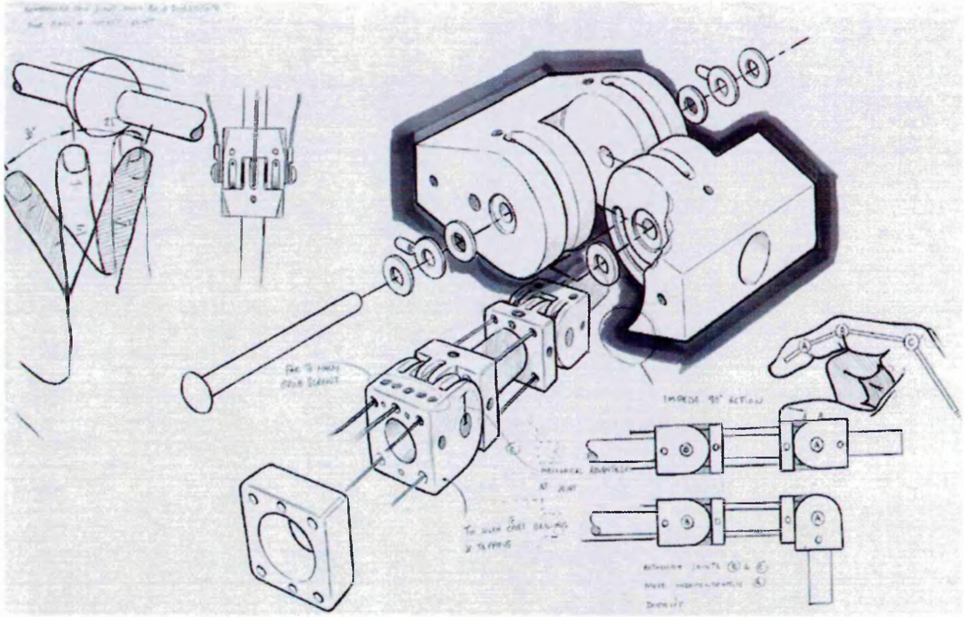
Fig 2.6 End-User - Focus Group (taken from the current research)

The analogous models produced within this project are skeletal analogies, without a soft tissue covering. This indicates that direct comparisons between measurements of the intact human arm may be difficult. To overcome this problem, qualitative evaluation of models by professionals with good anatomical knowledge have formed an important part of the review process.

Designers of the influential myoelectric prosthesis, the 'Utah Arm', recognised that, due to number of criteria necessary to evaluate a new artificial arm design, trial and review by experts was essential (Jacobsen et al 1982). However, a research process conducted through the development of physical models can take this a step further, inviting evaluation *during* the design process and allowing the results to feed into subsequent development. Previous research aimed at challenging the state of the art of prosthetic or robotic hands has resulted in laboratories creating complete systems (Jacobsen et al 1984). However, evaluations of such complete robotic systems have indicated that it is perhaps more appropriate to invite the criticisms at an earlier stage rather than attempt complete systems (Perlin et al 1989).

Physical model and prototype construction therefore plays a central role in the work described in this thesis. These models and prototypes provide a practical means of gaining both valuable evaluative data and as a means to link with other researchers specialising in areas such as actuation and control. Additionally, it was thought that dissemination of knowledge, not only through publications, but through physical models provides a practical demonstration of the challenges still faced in applying new technologies to the field of prosthetics.

3. Development of Anatomically Analogous Interphalangeal Joints



A Sketch Sheet Used in the Development of the Model IP Joints

The development of the skeletal model hand started with the study of the interphalangeal joints, the last two joints of the finger, as these were considered the simplest joints of the human hand, in terms of articulation.

The process identified as creative reasoning, described in the previous chapter, was used to study these joints. Observational drawings were produced from anatomical skeletal models of the human upper-limb to inform sketch book idea development. Additionally, these drawings were complemented by reference to the anatomical literature. The combination of literature review and observational drawing provided both a theoretical understanding of some of the concepts of articulation and a detailed practical understanding of the morphology of the human skeleton.

In the subsequent stage of sketch book idea development ideas were pictorially presented that identified mechanical parallels with the observed skeletal forms. As sketchbook ideas became more refined, a stage of model making was undertaken to test these ideas. The most promising ideas were then prototyped using appropriate techniques to produce joint forms for review. Initial reviewers included amputees and a prosthetics manufacturer.

Literature review indicated goniometric methods for assessing the ranges of movement of the human hand that appeared appropriate to assess the model joints.

The diagram above illustrates one sketch sheet from the sketch book portfolio used in the development of the model joints. Details from sheets such as this, produced as part of the process of creative reasoning are used in the following pages to illustrate the decisions made and the principles elucidated as part in developing the anatomically analogous model IP joint,

This section starts with diagrams explaining some of the anatomical terminology that will be used in the text, and finishes with the challenges that the evaluating the IP joint separately presented.

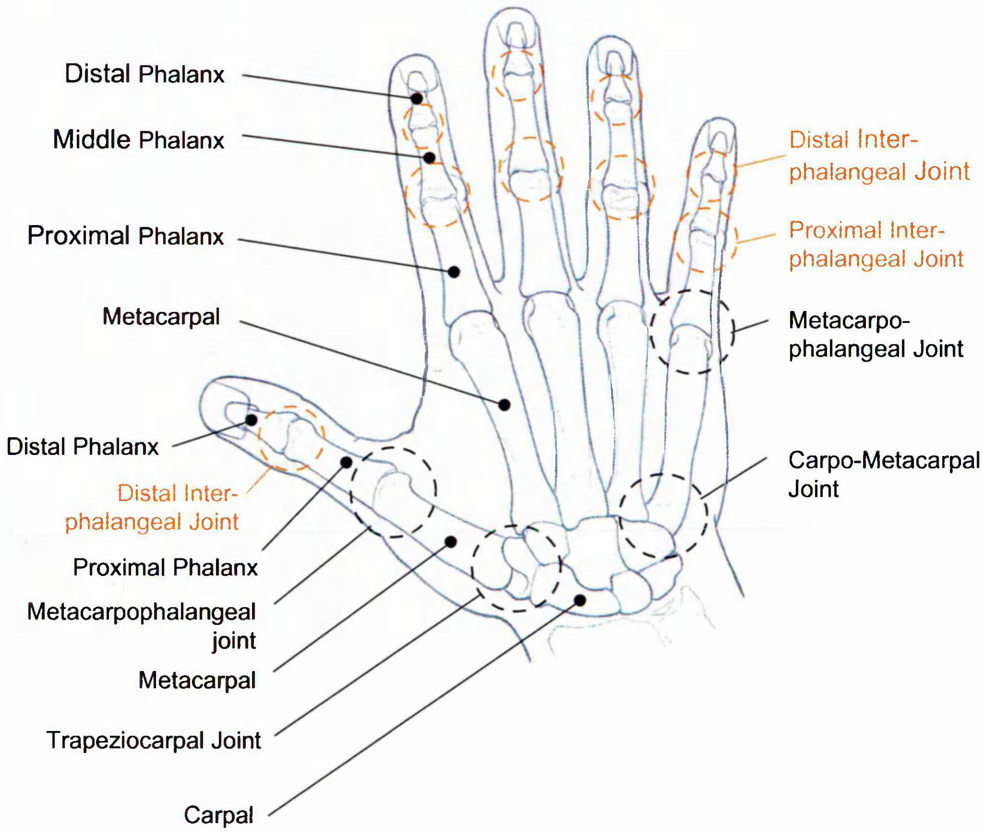


Fig 3.1 The Human Hand - Skeletal Components and Joints

As this section of the thesis describes a skeletal analogy for components of the human hand it is useful for the reader to understand the joints of the human hand.

This figure above shows the outline of a right hand in the palm down or 'prone' position. It shows that the skeletal human hand is composed of multiple similarly named joints. The joints pertinent to this chapter, the interphalangeal joints, have been highlighted in red.

A pictogram of this hand will be placed in the top right hand corner of each page within this section to graphically show what joints the discussion within the text is focussing on.

There is more information on this diagram than is discussed in this chapter but the diagram is placed here, at the start of the main body of work, to serve as a reference for discussions throughout this thesis.

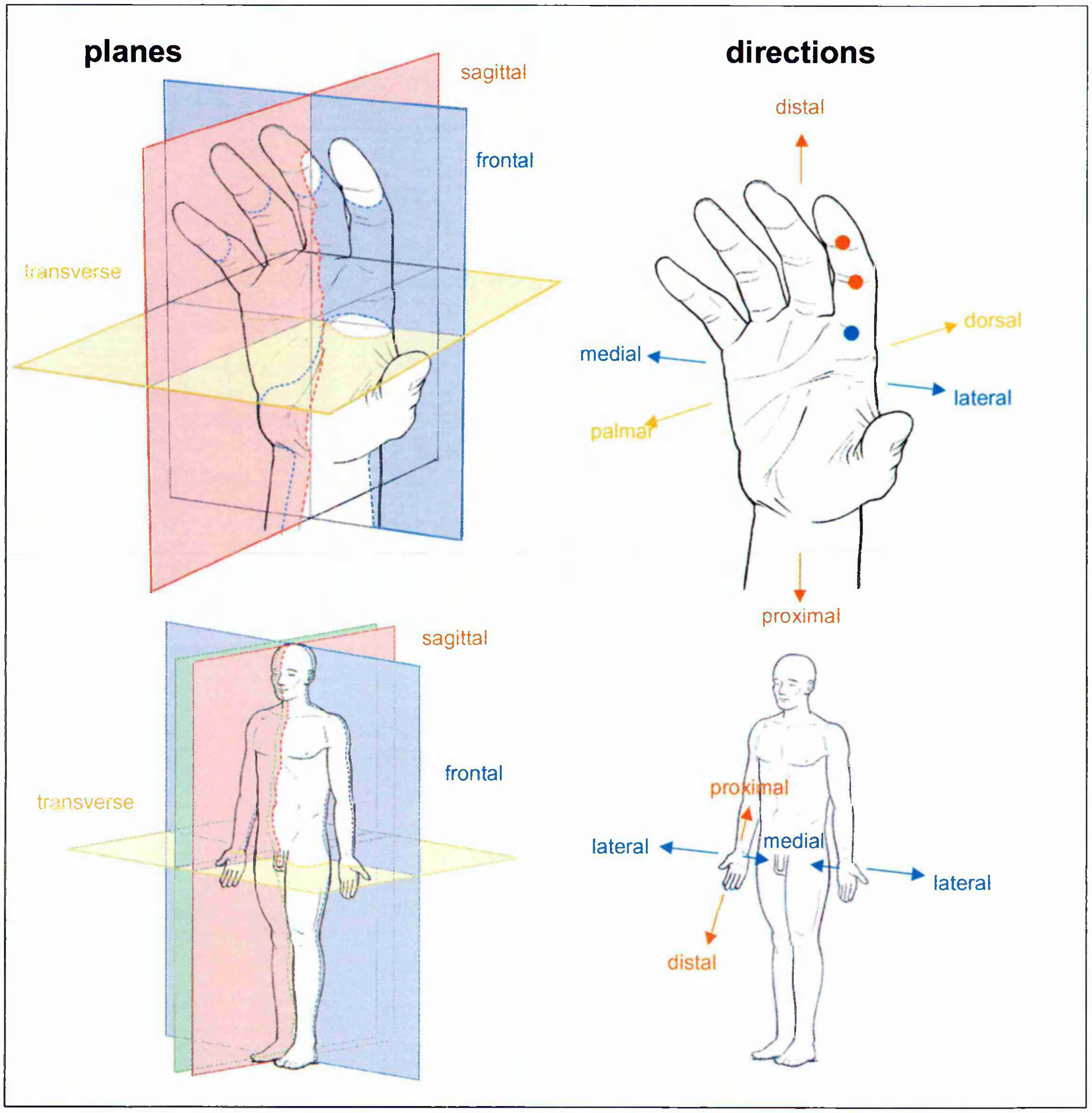


Fig 3.2 The Human Hand Planes and Directions

In addition to being familiar with the skeletal components of the human hand, it is it necessary to be aware of standard terminology used in anatomical descriptions (Kapit and Elson 1993). Planes and directions are given to the human figure in the 'anatomical position' (Kapit and Elson 1993). The diagrams above show how these conventions relate to the hand.

For example, the finger can be described as approximately circular in the transverse plane (Landsmeer 1976) and the metacarpophalangeal joint (blue dot) is proximal to the interphalangeal joints (red dots).

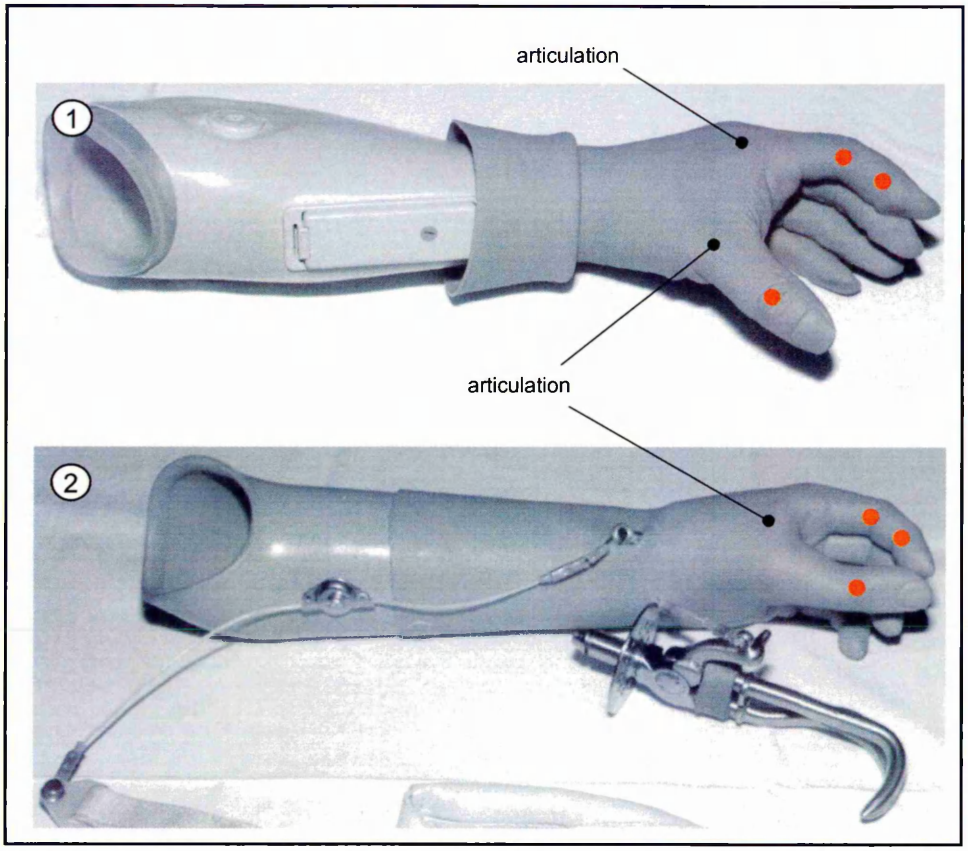
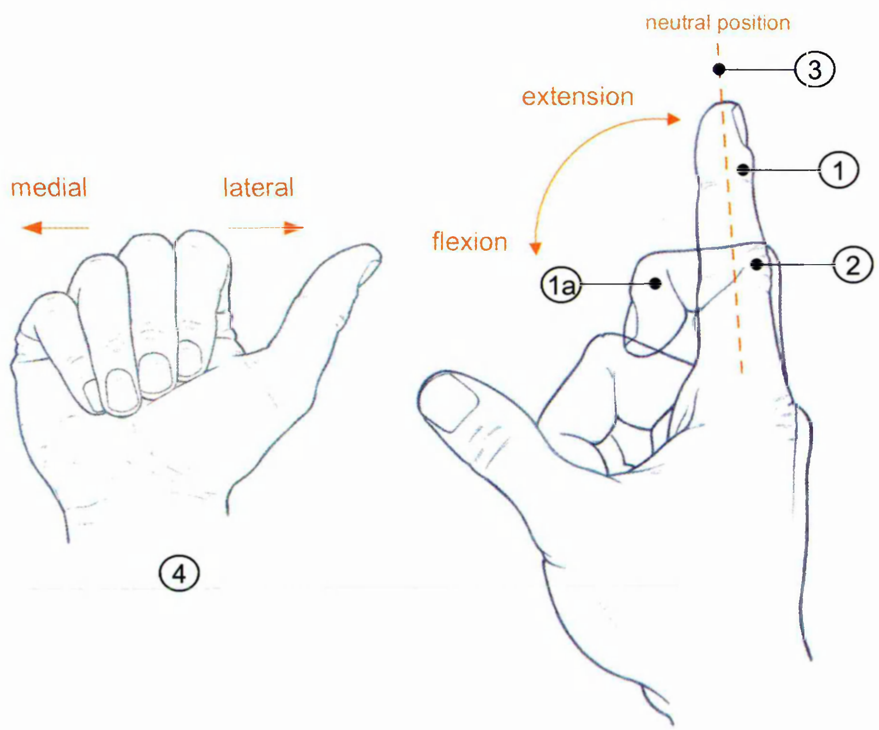


Fig 3.3 Existing Prosthesis Terminal Devices

Although the analogous joints described in the following pages have not been developed incrementally from existing prosthetic archetypes, it is appropriate, as an introduction, to be aware of the form and function of existing prostheses.

The figure above shows a myoelectric (1) and a body-powered prosthesis (2). These devices can currently be prescribed to amputees in the UK. The terminal devices (hand sections) of these prostheses have no articulations at the position of the last two joints of the normal finger, the interphalangeal (IP) joints indicated as red dots (Kapandji 1982). Many reasons have been given for the absence of these joints including limitations of current control strategies to control these extra articulations and the prohibitive cost of the production of extra articulations (Gow 2000). Prohibitive cost has been indicated as a major reason for new ideas and technologies not been manufactured and brought into clinical use, therefore, cost minimisation in any new design is seen as a key criterion (Aghili and Meghdari 1995, Gow et al 1993).

However, from robotics research it can be seen that extra articulations have been added at what may be considered the position of the IP joints to improve the grip functions of robotic terminal devices (Rosheim 1994). Additionally, it has been reported by amputees that there are limitations in the objects that can be grasped when effectively the last two 'joints' of the prosthesis are fixed (Rust et al 1997). Personal communication with amputees has indicated that the absence of articulations at these points in the prosthetic terminal device also have an adverse cosmetic effect.



1 Distal Interphalangeal Joint (DIP)
2 Proximal Interphalangeal Joint (PIP)
4 Radial Pulse
1a DIP in flexed position
3 Neutral Position

Fig 3.4 Movements of the Interphalangeal Joints

The process of finding an appropriate mechanical analogy commenced with the investigation of the movements of human IP joints through a literature review.

These findings by other researchers may be summarised as follows:

1. The distal interphalangeal joint (DIP) joint has a single degree of rotational freedom permitting flexion and extension of the joint. However, the DIP joint can be passively palpated slightly medially and laterally (Kapandji 1982).

2. The index finger can be flexed in a strictly sagittal plane, however, the IP joint axes of the more medial fingers are slightly oblique so that on flexion they converge at the radial pulse (4). This enables the more medial fingers to oppose the thumb like the index finger (Kapandji 1982).

3. The proximal interphalangeal joints (PIP) have a greater range of movement in flexion than the DIP joints (Daniels and Worthingham 1985), and normally no movement in extension past the neutral position.

4. Like the DIP joints the PIP joints can be palpated slightly medially and laterally. The more medial PIP joints have increasingly oblique axes of rotation, but again can be considered as uniaxial in their articulation (Kapandji 1982).

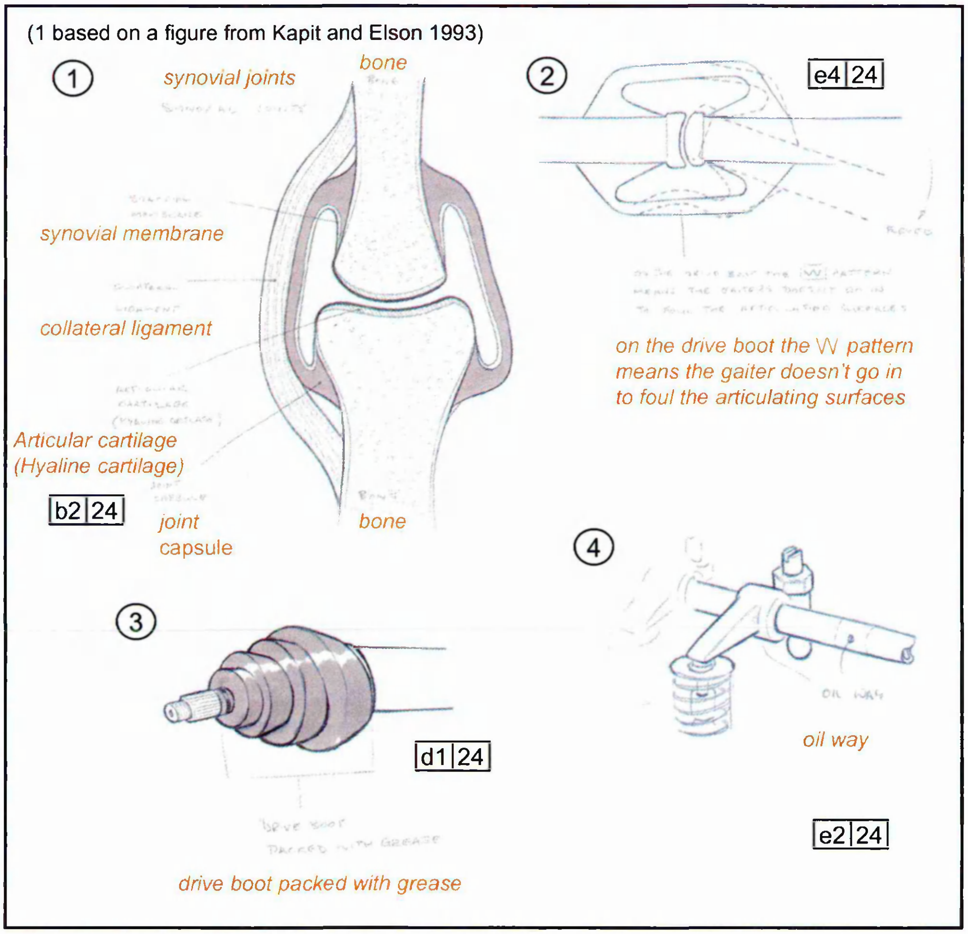


Fig 3.5 Sketchbook Idea Drawings

The literature review additionally indicated that the IP joints (as are the remainder of the joints of the hand) are synovial joints (Kapit and Elson 1993). Synovial joints contain synovial fluid which lubricates the joint, which along with articular cartilage contribute to an almost friction free movement (Kapit, Elson 1993).

Sketch (1) shows the anatomical arrangement of a synovial joint (Kapit and Elson 1993), this sketch was then visually simplified to produce sketch (2). From this simplified sketch possible analogies were considered (3, 4).

Sketch (3), the drive boot of a car, was considered analogous to the joint capsule retaining the synovial fluid. Whereas, sketch (4) likened the articulating segments of the finger running on a film of synovial fluid to a hydrostatic bearing as might be found in an internal combustion engine.

It was evident from this exercise that although analogous aspects could be found in existing engineering components, these were unsuitable for the scale of a model hand so a specially designed solution had to be developed.

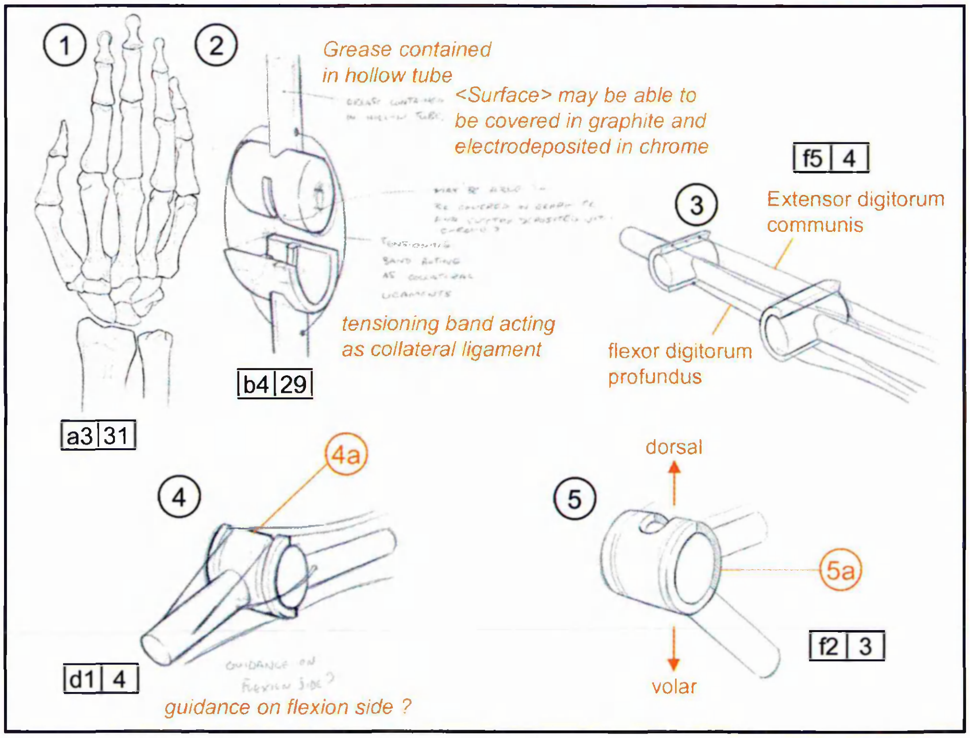


Fig 3.6 Sketchbook Idea Development- Cup and Cylinder Joints

The literature review and initial sketch book ideas investigating potential mechanical analogies were followed by observational drawing studies made from three-dimensional anatomical models (1). This was done to inform the development process of details of the form of the skeletal IP joints.

These observational drawing such as (1) were followed by the production of ideas for an analogous IP joint (2). Sketch (2) shows features similar to the those of the human synovial joint, such as, liquid lubrication and collateral ligaments evident from the literature review combined with a cup and cylinder structure based on observation of the form of the skeletal joints.

The literature review indicated that the fingers of the human hand are activated by tendons. Two of these tendons, the extensor digitorum communis and flexor digitorum profundus run the length of the fingers on their dorsal and volar surfaces respectively (3) (Kapit and Elson 1993).

Sketch (4) was produced to visually test how the joint design would effect an analogous tendon. This exercise highlighted possible problems of wear on a tendon caused by its relative movement over the sharp edges of the dorsal side of the cup (3a).

Sketch (5) explores a potential solution. It shows a hatched section extending around the cylinder to present a constant pulley surface for an analogous extensor tendon to run on (5a). This idea presented the possibility of being able to reproduce the articulation of the finger without the need for collateral ligaments to keep the joint together. This was viewed as a possible means of simplifying the design for manufacture.

Annotations on other sketches performed at this stage included suggestions for possible bearing materials that the joint might manufactured from (e.g. polyamide "Nylon ™").

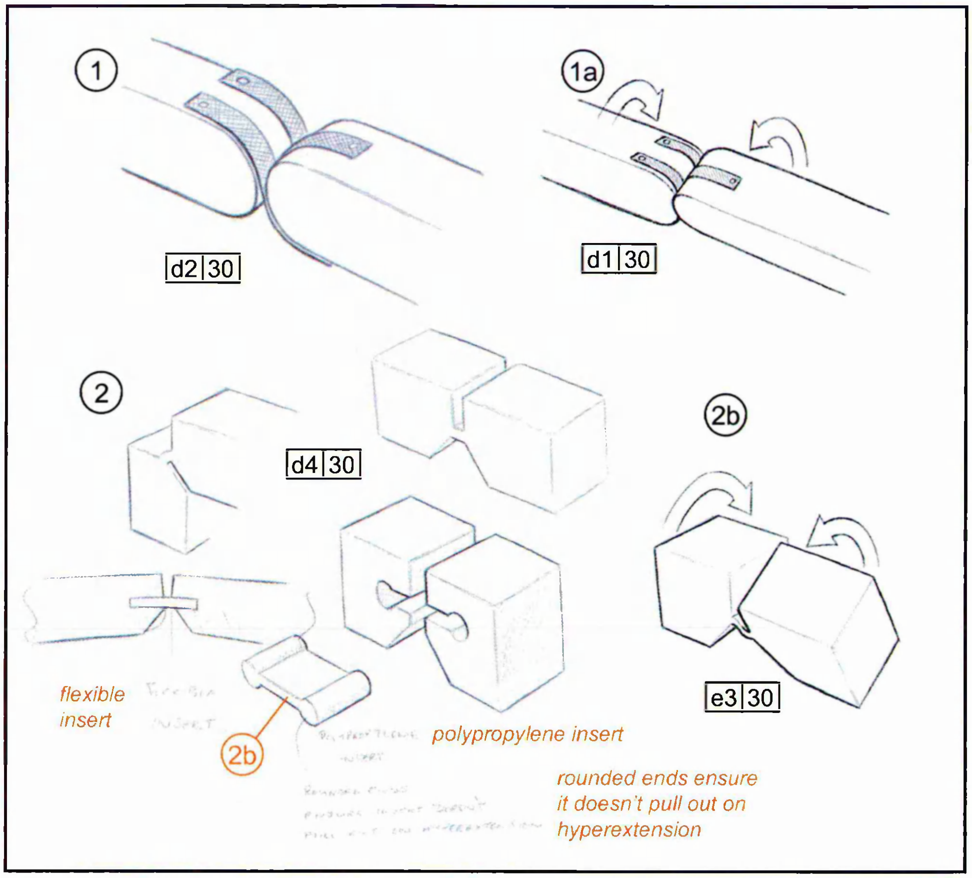


Fig 3.7 Sketchbook IP Joint Ideas - Ligamentous Joints

To test the decision that collateral ligaments would not be needed, it was considered important to explore ideas that used a 'ligamentous' principle (connective soft tissue joining bone to bone) (Kapit and Elson 1993) in their design.

Sketch (1) shows two radiused segments rotating around one another, constrained by crossed 'ligaments' similar to the cruciate ligaments of the human knee (McMinn et al 1993). The idea was rejected as it appeared liable to torsional instability (1a). Also, it has been suggested that, in effect, the IP joint rotates about a single centre (e.g. Kapandji 1982), whereas the rotation produced by this assembly is not about a single centre. This might lead to a cosmetically unacceptable movement in an eventual prosthesis.

Sketch (2) explores a polypropylene hinge shaped to allow flexion and prevent hyperextension. Torsional instability was again foreseen (2b). A solution was considered by increasing the cross section of the polypropylene insert (2a). However, it was thought that this might increase the tendency for the joint to spring back to the neutral position, a property not present in the human synovial joints (Kapit and Elson 93).

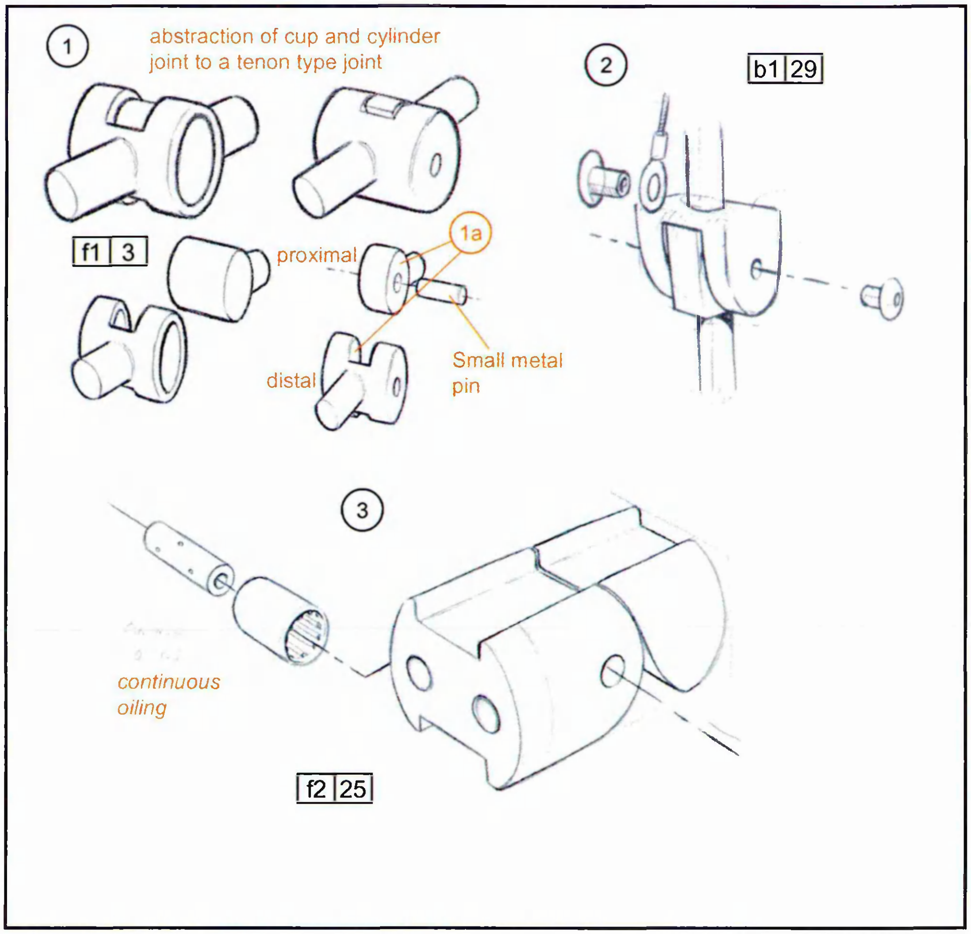


Fig 3.8 Tenon Joint Sketch book Ideas

From the previous exercise it appeared that the cup and cylinder ideas were potentially more successful. Further sketch book idea development resulted in the cup and cylinder arrangement being developed into a tenon type joint (1).

The form of the joint was refined from consideration of the frictional properties of the bearing plastic that the joint might be made from. The articulating surfaces of the cup and cylinder were considered comparatively too large for a freely running plain bearing made from bearing plastic. Consequently, a small metal pin was included in the design to provide both a robust connection between the distal and proximal sides of the joint and, crucially, a smaller area of contact to minimise frictional losses (1, 2).

The interphalangeal joint has no adduction or abduction movements (Kapandji 82), therefore, the lateral and medial sides of the mortise and tenon were considered as thrust bearing faces that would prevent this articulation whilst still allowing flexion and extension (1a).

Alongside the plain bearing ideas, ideas were also developed based on miniature roller bearings (sketch 3) . However, these were rejected on the grounds of excessive weight and problems of durability. It was also considered that such miniature components were too vulnerable to ingress of dirt if used in a future prosthetic hand.

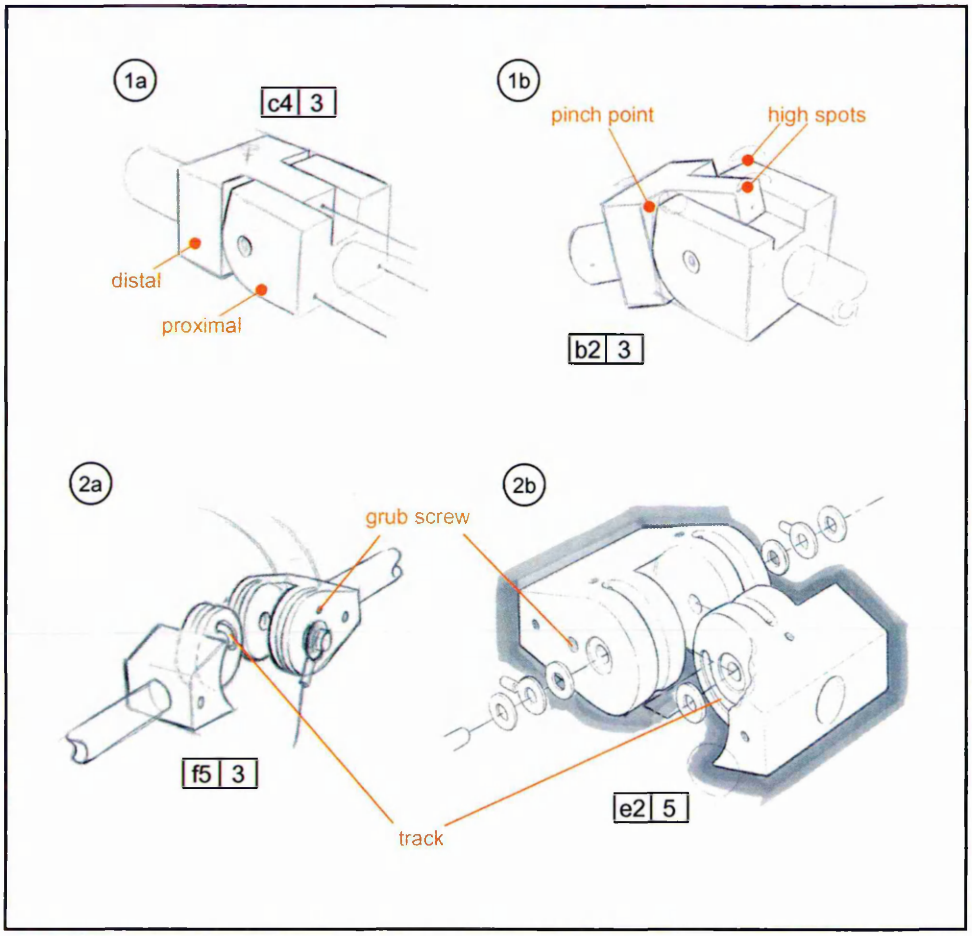


Fig 3.9 Detail Sketches of Tenon Joint Ideas

Refinements to the form of the joint were made through consideration of the range of movement of the joint.

Sketches (1a, 1b) demonstrate how the form of the proposed tenon joint was tested by visually articulating the joint. Sketch (1b) indicated that high spots might protrude from the dorsal side of the joint in the flexed position.

It was speculated that if the joint was to be covered by a thin silicone cosmetic glove, such as those covering the mechanism of the myoelectric devices, these high spots might either tear through the glove on flexion, or could present a 'pinch point' to trap the glove on extension.

Sketches (2a, 2b) show a possible solution using a grub screw running in a track in the interior of the joint, eliminating the necessity for stops on the perimeter of the joint. This was discounted due to the scale of the proposed joint. It was foreseen that without a significant surface area in contact either the grub screw would shear, or, more likely, the softer bearing plastic would deform and then foul the articulation of the joint.

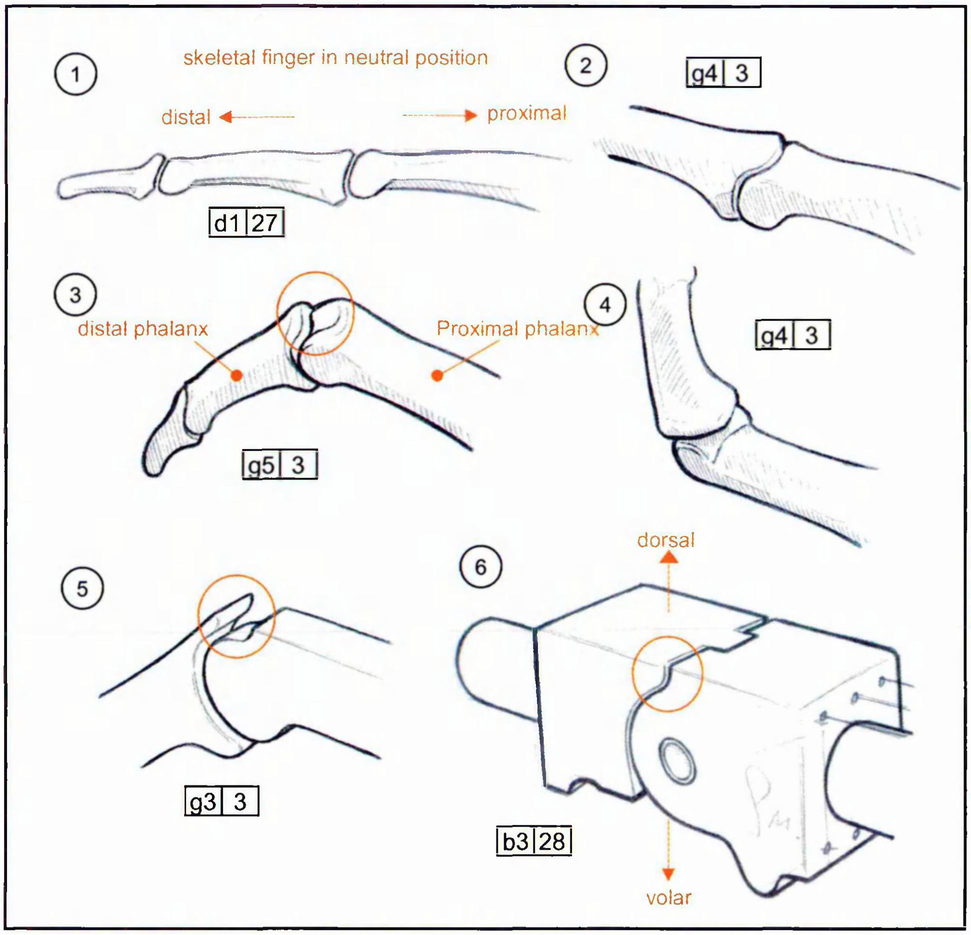


Fig 3.10 IP Sketchbook IP Joint Ideas - Stops and clearances

Further observational drawings (1 - 4) were completed to ascertain how the skeletal form of the IP joint contributed to the constraint of the joint.

Initially, studies were made of the joint in the neutral position (1, 2), however, it was found that greater form detail was elucidated when studies were made of the human skeletal joint in partial flexion (3, 4).

The partially flexed studies indicated a dorsal lip on the distal phalanx corresponds to a slight concavity on the proximal phalanx that appears to help the joint resist hyperextension. This stop is formed in such a manner that there are few sharp edges or tight radiuses on the proximal phalanx which effectively remains stationary to the distal phalanx in flexion and extension movements.

Sketch (5), a simplified of the joint form, was made after the observational drawings to visually summarise the findings from the observational drawings.

Sketch (6) shows how this simplified sketch helped in the development of the dorsal stop of the revised joint design.

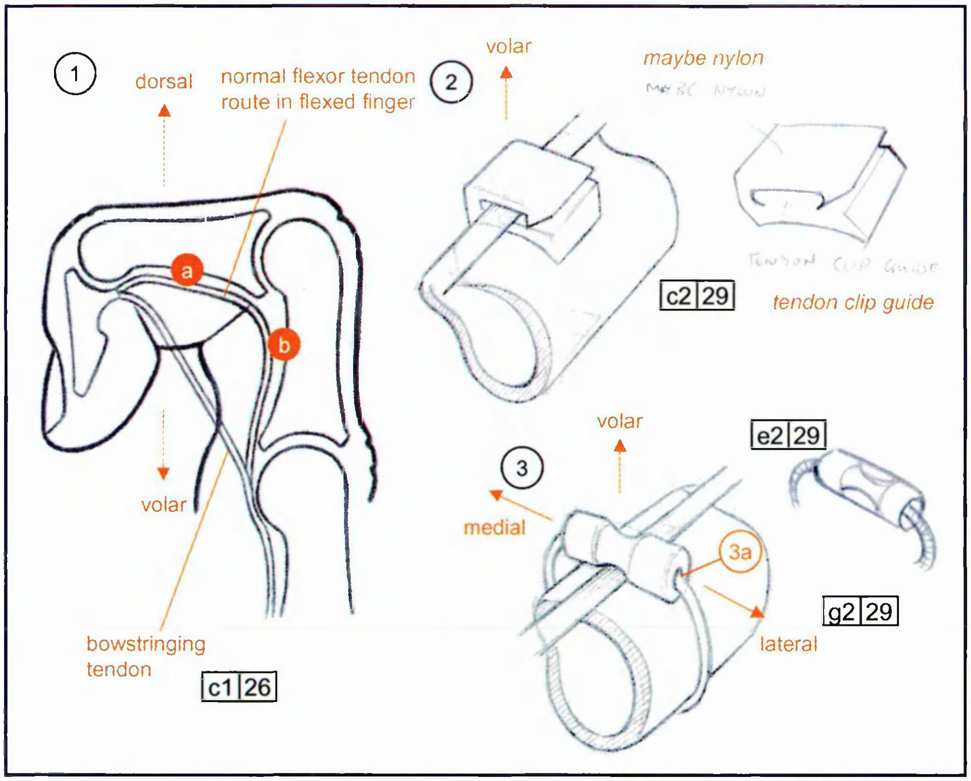


Fig 3.11 Sketchbook IP Joint Ideas - Guides

The previous sketches were undertaken to visually explore the effects of flexion and extension on the dorsal side of the joint. Conversely the above sketches were completed to understand effects of flexion of the joint on the volar side, and in particular, the effects on an analogous flexor tendon.

Sketch (1) shows how, without a tendon guidance system, the tendon follows the shortest possible route, an unacceptable effect known as 'bowstringing' (Kaplan 1984).

Like the IP joints the tendons are lubricated through the pulleys by synovial fluid, thus limiting frictional losses (Kaplan 1984). Therefore, the sketch ideas focused on a practical analogy to keep the tendon close to the flexed joint whilst limiting friction.

Initially a moulded Nylon™ (polyamide) clip was considered (2) that could be positioned between the joints at positions (1a) and (1b). This idea was discounted as it was thought that the stresses would be concentrated on the edges of the clip, wearing any tendon material running within it.

Sketch (3) proposed a cylindrical rolling guide, to overcome the problem of sharp edges in contact with the tendon material. This was rejected as it was considered that the problem of friction would be moved to the medial and lateral sides of the cylinder where it would rub against the static band holding it to the finger segment (3a). Additionally, it was speculated that guides positioned at a & b would still allow an unacceptable bowstringing effect.

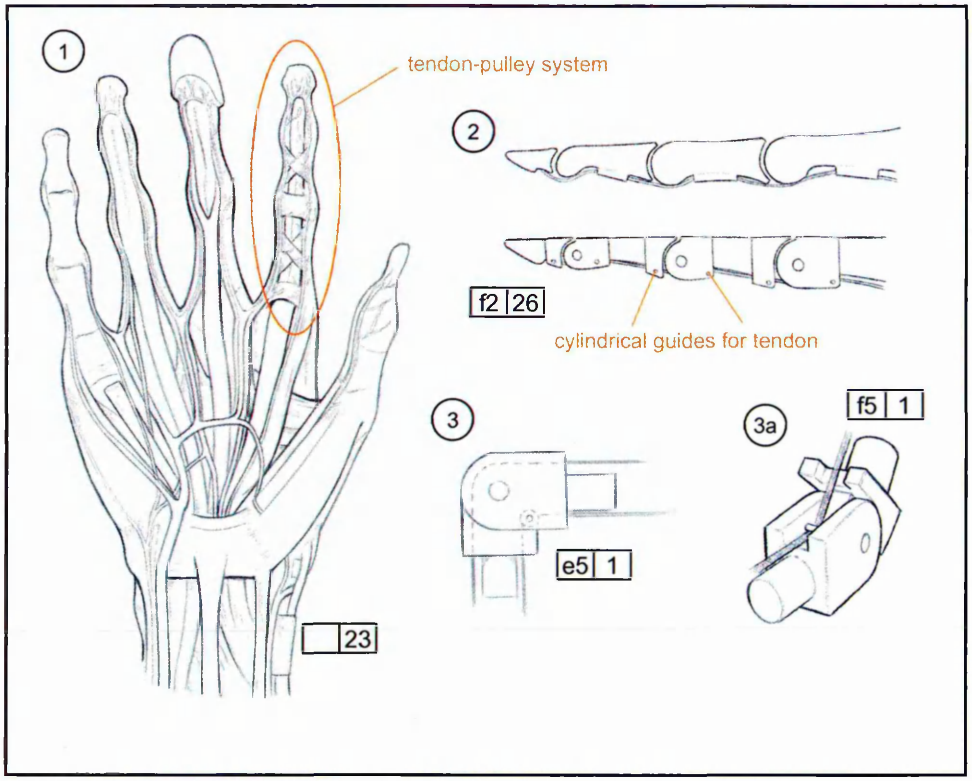


Fig 3.12 Sketchbook IP Joint Ideas - Guides

The inadequacy of the previous sketch ideas indicated that the tendon-pulley system of the human hand might not be fully understood. Consequently, further observational drawing was undertaken from three-dimensional anatomical models to investigate the nature of the soft tissue of the hand and in particular the pulley system of tendons within the finger (1).

This exercise helped to reinforce the location of both the transverse and cruciate pulley bands of the human finger. Importantly, it was observed that the position of the transverse pulley bands are much closer to the centre of the joints than the centre (distal - proximal) of the phalanx. This finding was subsequently checked against against the anatomical literature (Kaplan 1984).

Subsequent joint ideas (2 - 3a) were developed combining the guidance of the tendon with the design of the tenon joint.

Initially, ideas were considered with cylindrical pulleys on both the distal and proximal sides of the joint (2). Through exploring flexion of the joint (3, 3a) it was found that only a single cylindrical pulley was required on the proximal side of the joint. This has the advantage of reducing friction on the tendon which led to the idea of integrating the guidance of the tendon within the joint design.

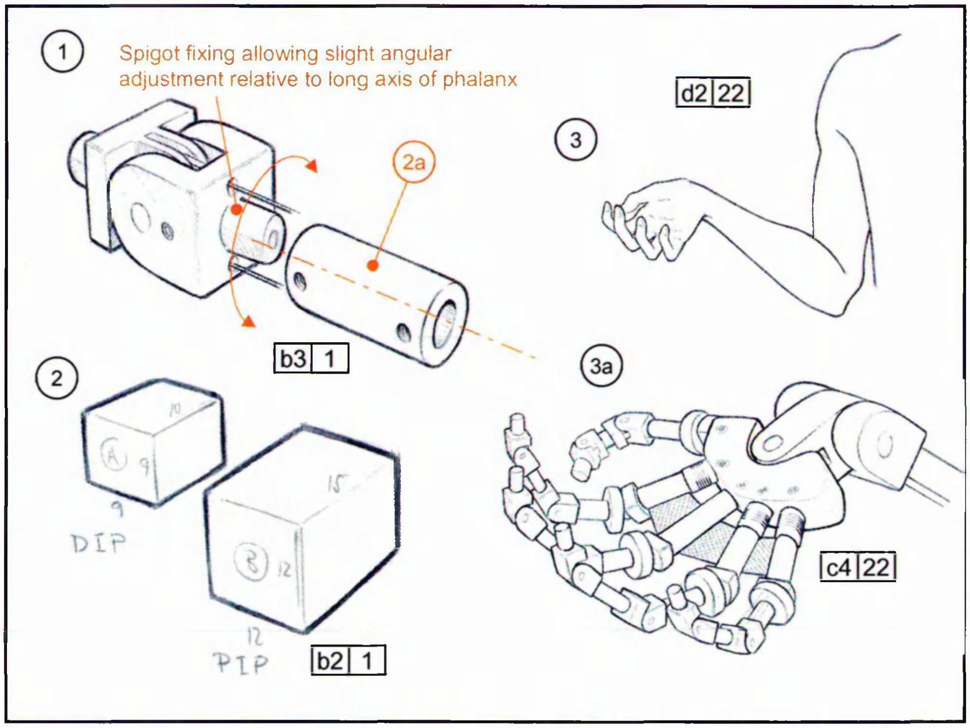


Fig 3.13 Sketchbook IP Joint Ideas - Modularity and Sizing

For cosmetic reasons it is considered advantageous if a prosthetic hand matches the size of the contralateral hand of a unilateral amputee (Gow 1993). However, literature review indicates large variations in hand dimensions (Buchholz et al 1992).

Previous sketch book ideas indicated that it was appropriate to combine the guidance of an analogous tendon within the joint design, concentrating the complexity at the joint, leaving the interconnecting sections between joints as simple struts. It was speculated that uniquely scaled hand configurations could be created by changing the length of the simple interconnecting struts, using techniques appropriate for small scale manufacture.

A cylindrical strut was sketched as the interconnecting element between joints. This was proposed to provide the possibility of slight angular adjustment of the IP joints during assembly to allow a finger configuration to flex towards the radial pulse.

It was necessary to relate the prototype to the dimensions of an appropriate human hand. 71.5% of upper limb amputees in the UK are male (NASDAB 1999) and earlier data indicates that this is also true in other parts of the world (Sheridan and Mann 1978). As the research group included a member with 50th percentile male hand dimensions, the dimensions of his IP joints were measured using vernier calipers and the mean dimensions recorded (1). Using joints from fig 3.10, a pictorial hand configuration was sketched (3a).

From this exercise it was concluded that only one IP joint module would be needed. The average dimensions of the PIP and DIP joints were thus taken to develop detailed drawings of an analogous IP joint prior to prototype manufacture.

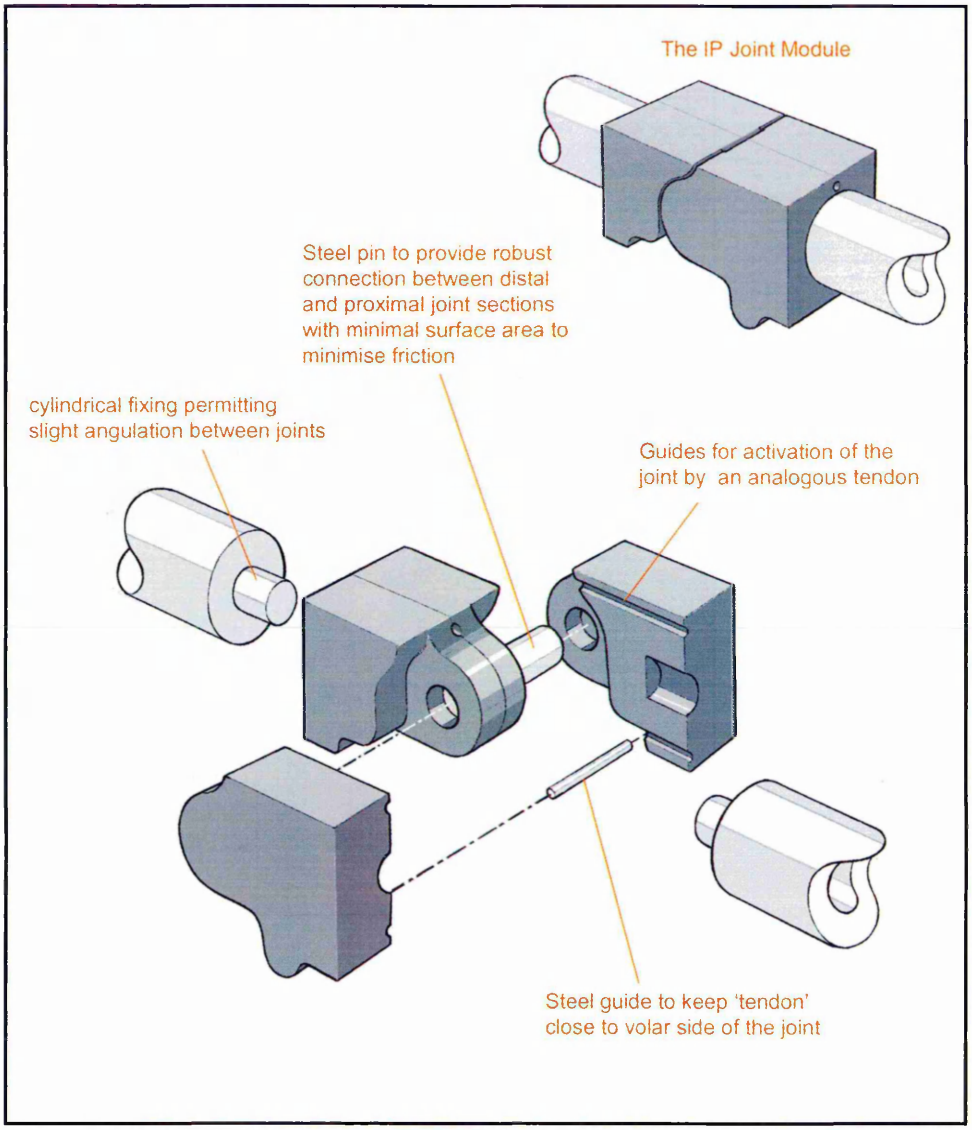


Fig 3.14 Exploded View of the IP Joint

The figure above shows an exploded view of the IP joint design. Design principles embodied in the joint have been labelled.

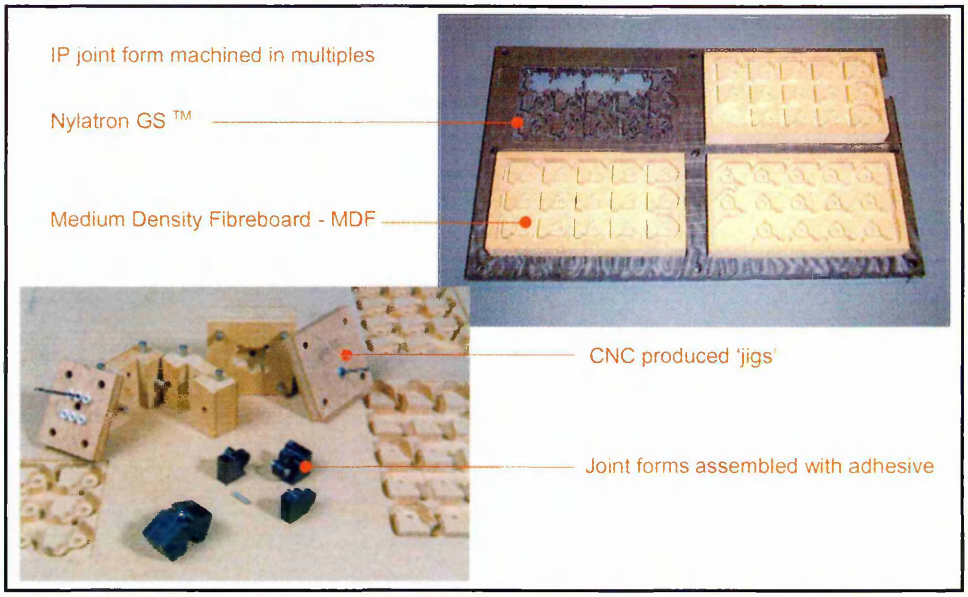


Fig 3.15 IP Joint - Prototype Manufacture

From consideration of the scale and number of joints which must be manufactured to the same design to configure a hand it was considered appropriate to use computer numerical machining techniques (CNC) to create the joint forms.

This process also facilitated revisions of the design to be simply made. In the light of possible revisions the joint forms were initially rapidly machined in medium density fibreboard (MDF) to check that the joint would articulate as proposed in the detailed drawings. Once the forms were confirmed to be correct, multiples of the joint design were machined in a single machining operation out of a lightweight bearing plastic (Nylatron GS ™).

The CNC machined components required further machining on conventional machine tools. This was necessary as the holes required for analogous tendon guidance were outside the plane of CNC machining. To ensure accuracy of the drilling of these holes specially made jigs which were used, again created usng the same CNC processes.

Once machined, the joint forms were assembled using a suitable polyamide adhesive using more jigs to ensure accuracy of alignment.

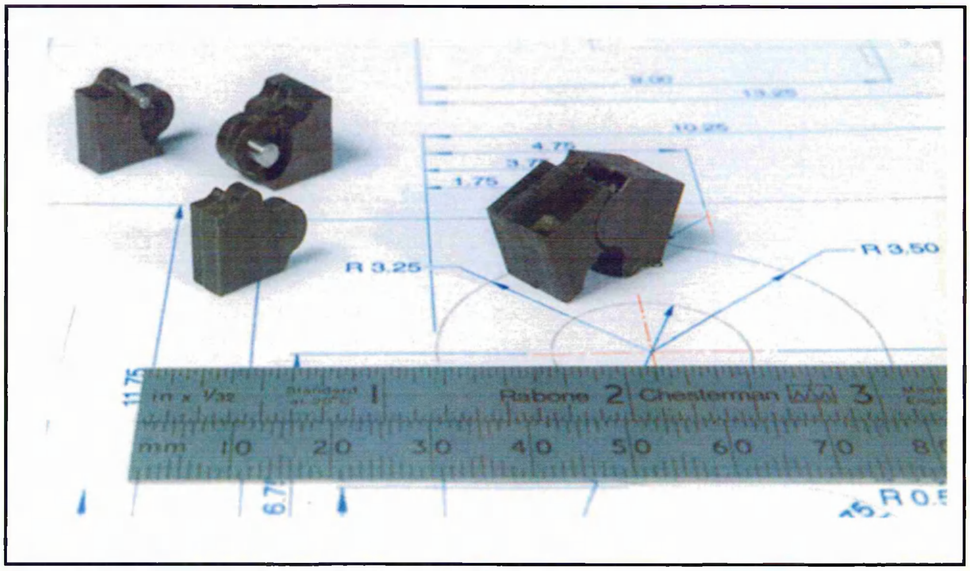


Fig 3.16 The Prototype Analogous IP Joint

The resulting joint appeared to possess a free movement, allowing articulation in a single plane as designed. Additionally, the prototyping methods used appeared appropriate to the production for multiples of these joints necessary for a model hand form.

Due to the anatomically analogous nature of the joints it was thought appropriate for the measurement method used be similar to those used to goniometrically assess the joints of the human hand (Norkin and White 1995). However, using a mechanical goniometer requires that the 'bars' of the goniometer be aligned with the dorsal surface of the finger (Norkin and White 1995). It was considered that these surfaces on the individual model joints were too small using this equipment. Therefore, it was considered appropriate to construct further joints to construct a hand form before assessing the joints goniometrically.

Qualitative Evaluation by Amputees

From the start of the research it was considered necessary to attend an amputee support group to understand more of the issues pertinent to the future design of prostheses from their users. The monthly meeting of the 'Helping Hands' Amputee Support Group (based at the Northern General Hospital, Sheffield) was regularly attended. Several meetings had been attended prior to the production of the prototype finger joint and it appeared that the review of the joint by the group might provide significant information effecting its design.

Prior to the presentation of the prototype joint to the group a short introduction was given indicating the aims of the research and the methods being used. The model joints were then presented to the group for their review.

Notes taken at the time indicate that the group was enthusiastic that new research was being undertaken in the prosthetics field. Comments were made that the methods used enabled the members of the group to see tangible evidence research activity, which was thought positive. However, the group indicated that research based on addressing their immediate needs might be more useful. These needs were indicated as modifications to details of their existing devices including various fittings (catches and buckles) were considered ineffective.

There were few comments specifically about the joints other than enquiries regarding the method of their manufacture and the material form which they were made.

The lack of focussed comments towards the design of the finger joint indicated that a more complete model was needed before meaningful qualitative evaluation could be made by 'end-users'.

Summary

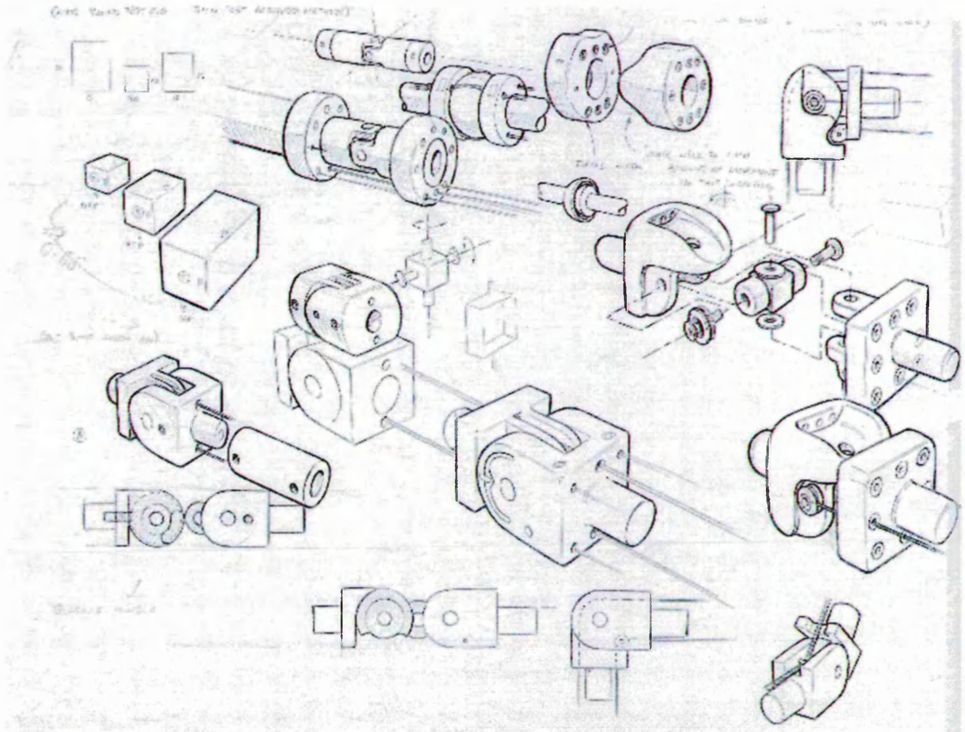
The process of creative reasoning combining observation drawing, sketch book idea development and literature review appears appropriate to eliciting design principles for multiple joints with simple articulations.

The process of observational drawing and sketch book idea develop was found to be iterative. As sketch book ideas developed towards mechanical analogies it was found that detailed aspects of the analogy required the anatomy to be re-observed with closer scrutiny using observational drawing. The development of the dorsal stop on the joint is an example of this iteration (figure 3.10).

The prototyping methods appeared appropriate to the production of multiple precision joints, and presented a means of creating jigs that ensured accuracy in assembly.

In the light of the apparent success of the methods used in the development of the IP joints, similar methods were used to create a mechanical analogies of the other joints of the within the hand (Kapandji 1982). This was done so that a complete hand could be assembled and all the joints evaluated both quantitatively and qualitatively.

4. Development of Anatomically Analogous Metacarpophalangeal Joints and the Assembly of a Skeletal Model Hand



A Sketch Sheet Used in the Development of the Model MCP Joints

The development of a skeletal model hand continued with the study of the metacarpophalangeal (MCP) joints. These were developed to complete the joints necessary to assemble a model 'finger' for subsequent assembly into a model 'hand' as it was evident from the review of the model IP joints that a complete hand configuration was necessary to support the evaluation of the joints.

Sketch book idea development and observational drawing were used as integral part of the creative reasoning phase of the research activity. Additionally, in order to complete the assembly of a model hand joint principles elucidated from the creative reasoning process, focussing on the finger joints, were applied to the joints of the wrist.

This chapter starts with descriptions of articulations of the human MCP joint, for both a prosthesis and a robotic 'hand'. The articulations of the normal human MCP joint are then discussed. This is followed by details of the creative reasoning process applied to the development of analogous MCP joints. The principles deduced are then graphically represented along with their relevant sketch sheets. The application of previously elucidated principles to the development of a model wrist is then discussed.

With a model hand complete quantitative and qualitative evaluation of the joints was possible. This chapter finishes with the evaluation of the model hand and recommendations that were taken forward to the next cycle of development.

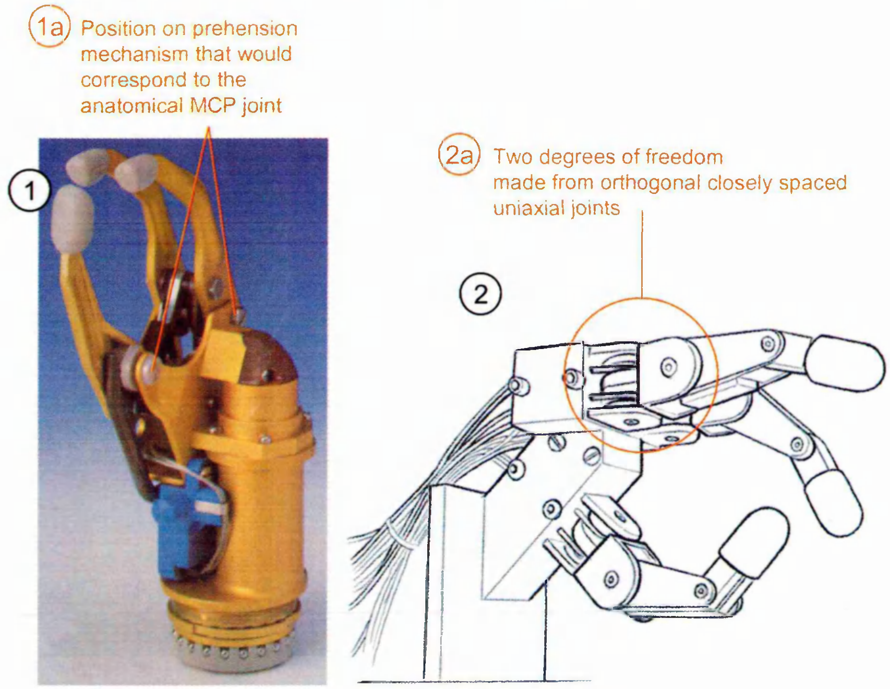


Fig 4.1 Prosthetic and Robotic Terminal Devices - Equivalent MCP Joints

Figure 4.1 (1) shows an Otto Bock prehension mechanism from a myoelectric terminal device. Its structure is so far removed from the structure of anatomical hand that it is difficult to assess an equivalent MCP joint. However, when this mechanism is covered by a cosmetic glove the articulations closest to the position of the MCP joints are indicated in the figure as (1a).

These articulations permit uniaxial rotations around the positions marked (1a). Positioning powered articulations at this point has been stated as allowing an optimal functional grip for a device that only possesses a single degree of freedom powered movement (Gow 2000).

The robotic hand shown in figure 4.1(2) is the JPL /Salisbury Hand (Rosheim 1994). It has joints at the base of each finger that combine to give articulations with two degrees of rotational freedom (Mason and Salisbury 1985)(2a). This robotics research showed that for optimal grasping and dextrous functions a hand configuration was needed that permitted two degrees of freedom at an equivalent position to the human MCP joint (Mason and Salisbury 1985).

The JPL/ Salisbury hand is mechanistic in appearance, therefore, to derive principles for an analogous MCP joint potentially combining form and function it was considered necessary to observe apply the creative reasoning process to the human MCP joint.

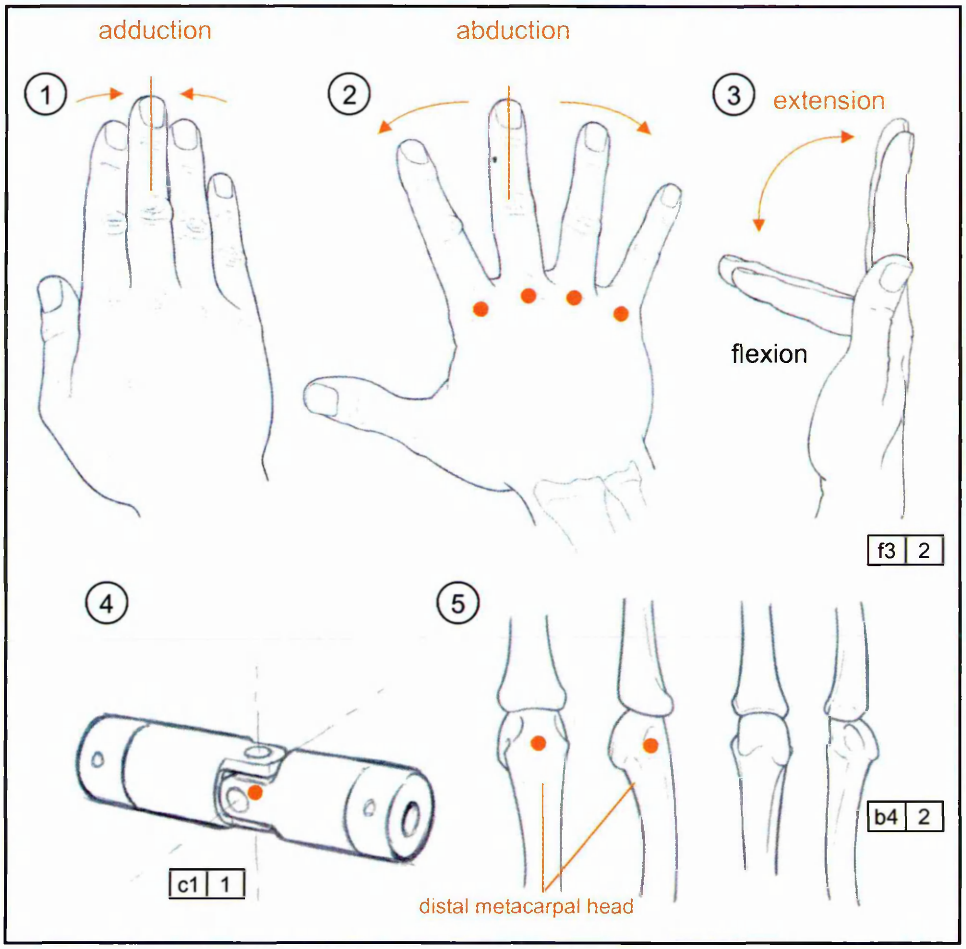


Fig 4.2 Metacarpophalangeal (MCP) Joint Movements

Anatomical literature states that unlike the the interphalangeal joints the metacarpophalangeal (MCP) joints can be actively adducted (1) and abducted (2) as well flexed and extended (3) (Kapandji1982, Williams 1998). A series of drawings of one of the researchers hands (1-3) were completed to examine these movements. This exercise highlighted that the movements of adduction / abduction and flexion / extension appeared to be around a single point at each joint (red marks). This type of articulation can be seen in a universal joint where two orthogonal axles cross on a single centre point indicated by a red dot (4). Previous researchers have likened the movements of the MCP joint to those of a universal joint (Youm et al 1978). However the appearance of the universal joint (4) differs from that of the MCP joints. Therefore, observational studies of the skeletal form of the MCP joint were undertaken to gain knowledge about what might be an appropriate form for an analogous joint. Sketch (5) shows this series of observational drawings, made from orthogonal view points, from skeletal three-dimensional anatomical models. These sketches showed that part of the form of the head of the MCP joint is approximately spherical. Therefore, it was considered consistent that articulations around a roughly spherical head would appear to be around a single centre point. Reasoning based on the spherical form of the distal metacarpal has also been used by (Hagert 1981) in deducing that the MCP joint has a single centre of rotation in planes of both flexion / extension and adduction / abduction.

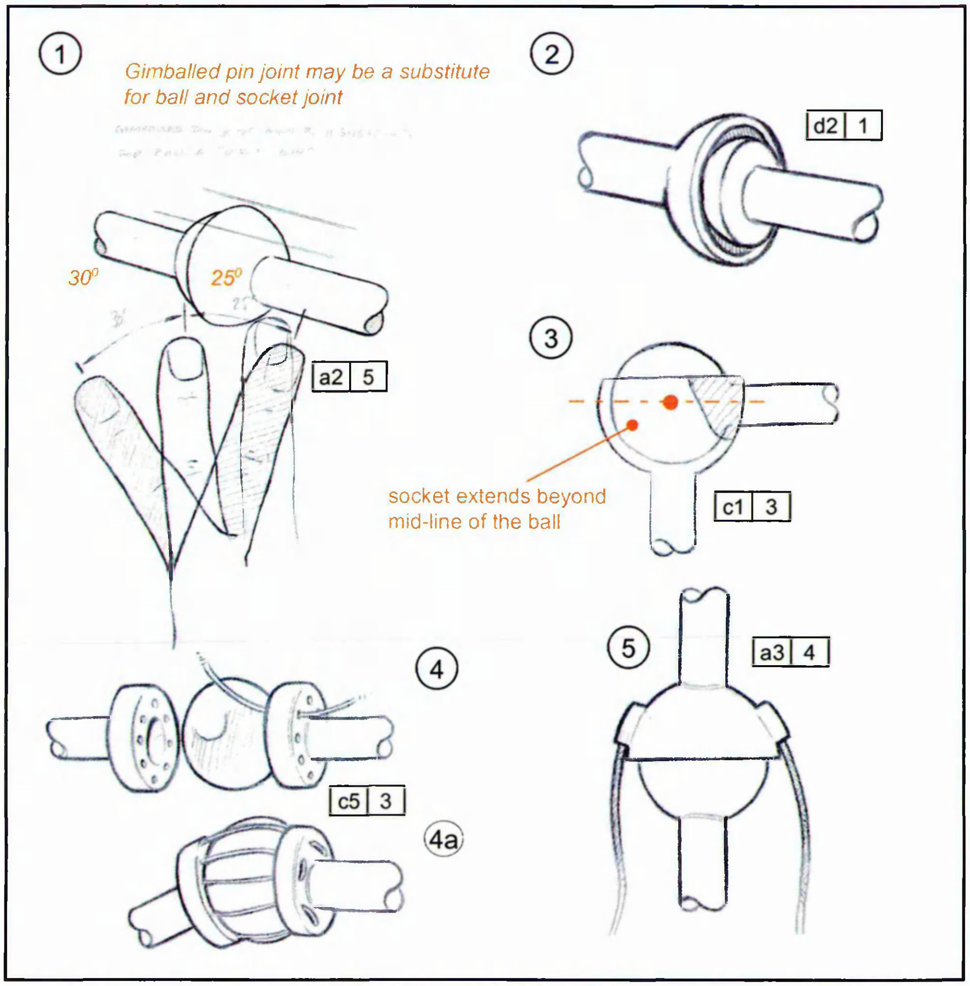


Fig 4.3 Ideas Generated from the form of the Head of the MCP joint

The observational studies of the spherical head of the distal metacarpal bone led to initial analogous joint ideas using a sphere as the articulating surface (1, 2). Initially, commercially available miniature ball and sockets joints were considered such as those often used in gear linkage systems. However, these components are connected together by the socket extending beyond the midline of the ball (3) which limits the range of movement. Whilst they allow a range of movement of approximately 30 degrees from centre, adequate for adduction / abduction (Daniels and Worthingham1986) (1), they would not permit the greater range a movement needed for flexion / extension (Daniels and Worthingham1986). To allow full flexion it would be necessary to remove some of the socket section (3). Sketching this removal of material indicated that the joint might be more likely to dislocate, therefore, sketches were completed to investigate how the joint might otherwise be constructed. Sketches (4) and (4a) explored the use of elasticated thread to join the components. However, these ideas were discounted as it was considered that the joint would then spring back to the neutral position, which does not occur in the human joint. A second idea of placing inextendible ties on the medial and lateral sides of the joint was sketched (5). However, this was also discounted as it would prevent adduction and abduction movements. The annotations on sketch (1) demonstrate that as with the interphalangeal joints pinned joints were being considered as a more practical analogy.

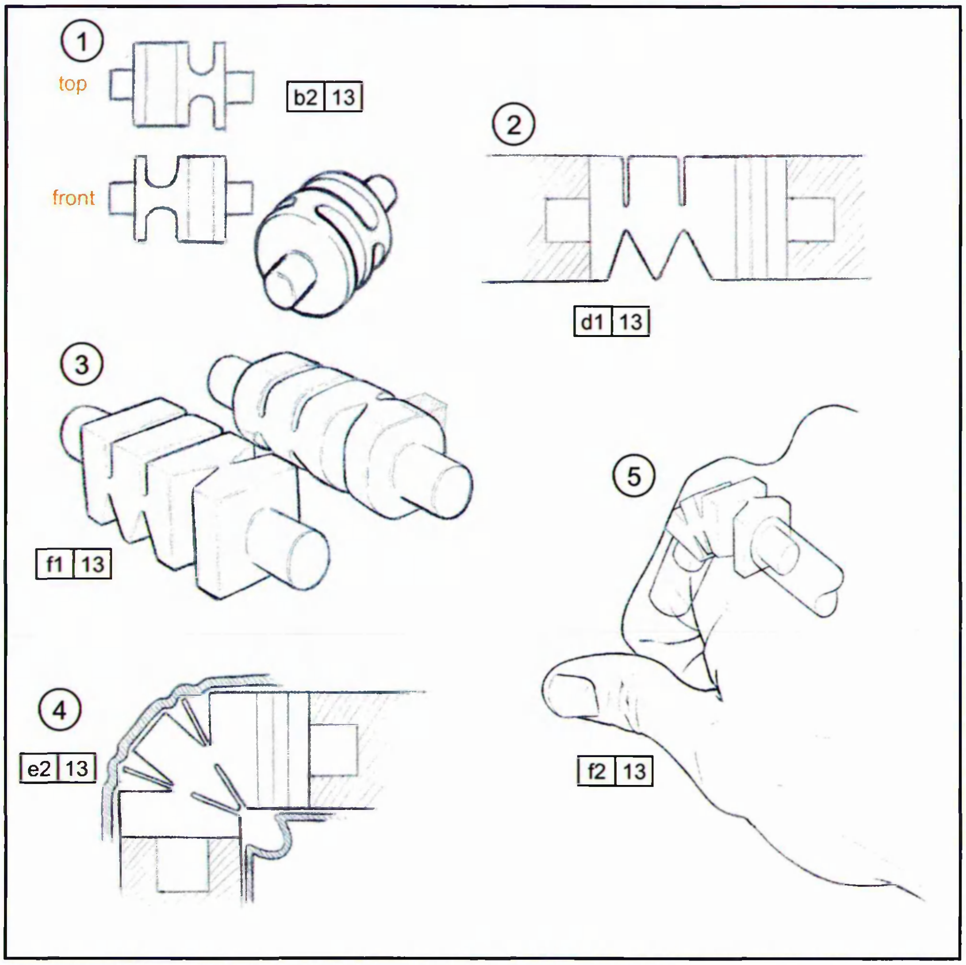


Fig 4.4 Single Piece Hinge Ideas

The relatively complex sketches of the previous page highlighted the need for simpler designs more appropriate for economic manufacture, as cost has been indicated as a major factor in the acceptance of a new prosthetic device (Aghili and Meghdari 1995, Gow 1993) . Consequently, several ideas were drawn that aimed to produce a joint design from a single moulded polypropylene component. Sketch (1) shows how the orthogonal movements of flexion / extension and adduction / abduction might be achieved by producing orthogonal reductions in the thickness of a cylindrical component. This sketch indicated that although a single reduction in the thickness might allow the complete range of motion for adduction and abduction movements it might not permit complete flexion and extension movements. Sketch (2) shows how a series of changes might remedy this. Sketch (3) details how such a simple design might easily be manufactured with a roughly circular cross-section, similar to the human finger (Landsmeer 1976) adding to its cosmetic appearance. By visually exploring the flexed joint it was though necessary to include thin fins to prevent a cosmetic glove being caught in the joint as it opens on flexion (4). Sketch (5) was completed to determine the approximate scale of the joint. From this exercise it was concluded that the articulations of flexion / extension, adduction / abduction might be too far apart to produce a cosmetic movement. Additionally, it was considered that the concerns of torsional stability found in the development of the interphalangeal joints would be amplified by a series of reductions in thickness required for ranges of movement of the MCP joint.

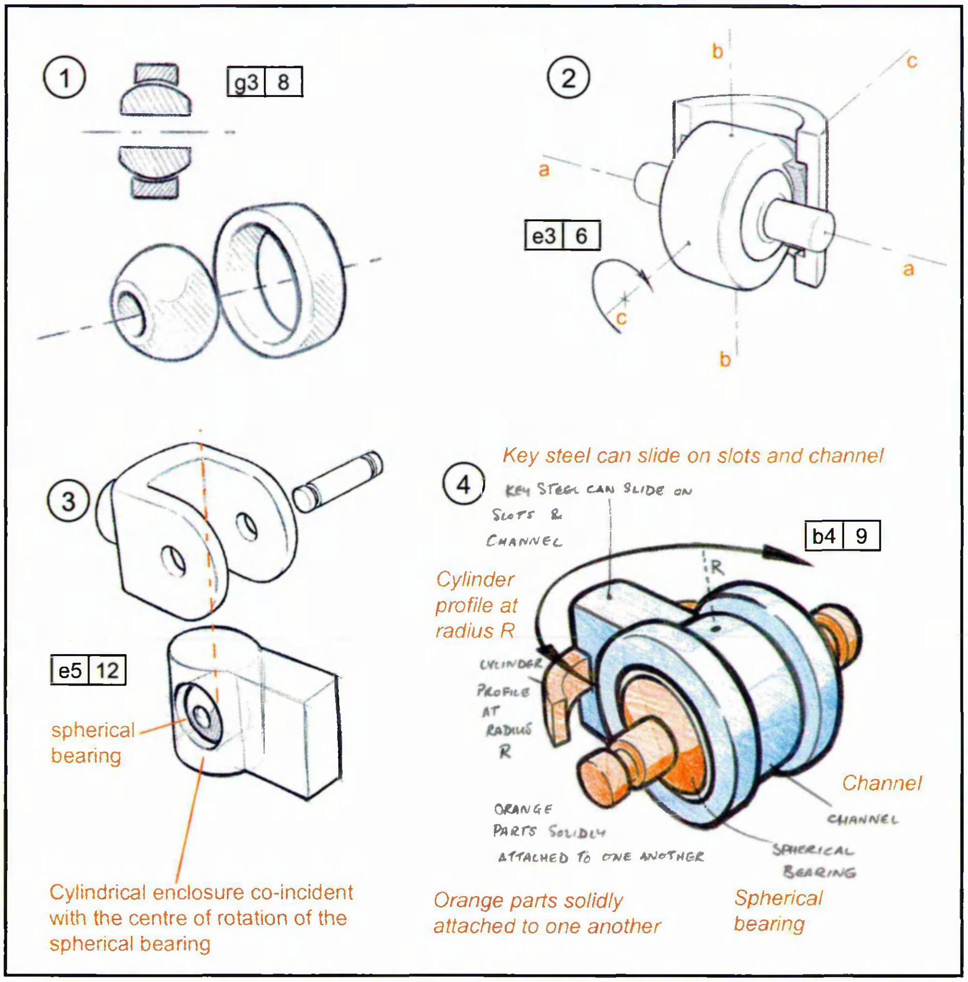


Fig 4.5 Spherical Bearing - Constraint of Rotational Freedoms

In addition to commercially available ball and socket components, spherical plain bearings were considered as components for an analogous MCP joint. This was both due to their ready availability at miniature sizes and also their ability to support relatively large static loads, both rotationally and axially without dislocating. Sketch (1) shows both an exploded view and a cross section of a plain spherical bearing. Spherical bearings are usually made from low friction alloy steel and are commonly found at the ends of pneumatic/hydraulic actuators. They are able to rotate in three orthogonal planes (2). However, from the observational drawing and literature review (Kapandji 1982) it was considered appropriate to limit the rotational freedoms to two, in the planes of flexion / extension (2 a-a) and adduction/abduction (2 b-b).

Using the spherical bearing in the orientation shown in sketch (2) allows for a large range of movement around the axis of flexion/extension (a-a) and limited rotational movement in axis of adduction/abduction (b-b), similar to that of the human MCP joint (Daniels and Worthingham 1986). Two ideas were considered to constrain the third axis of rotational freedom (2 c-c). These included producing a cylindrical enclosure coincident with the rotation centre of the spherical bearing (3); with its long axis running in the axis of adduction/abduction. The second idea focussed on the use of two orthogonally placed pieces of key steel (4).

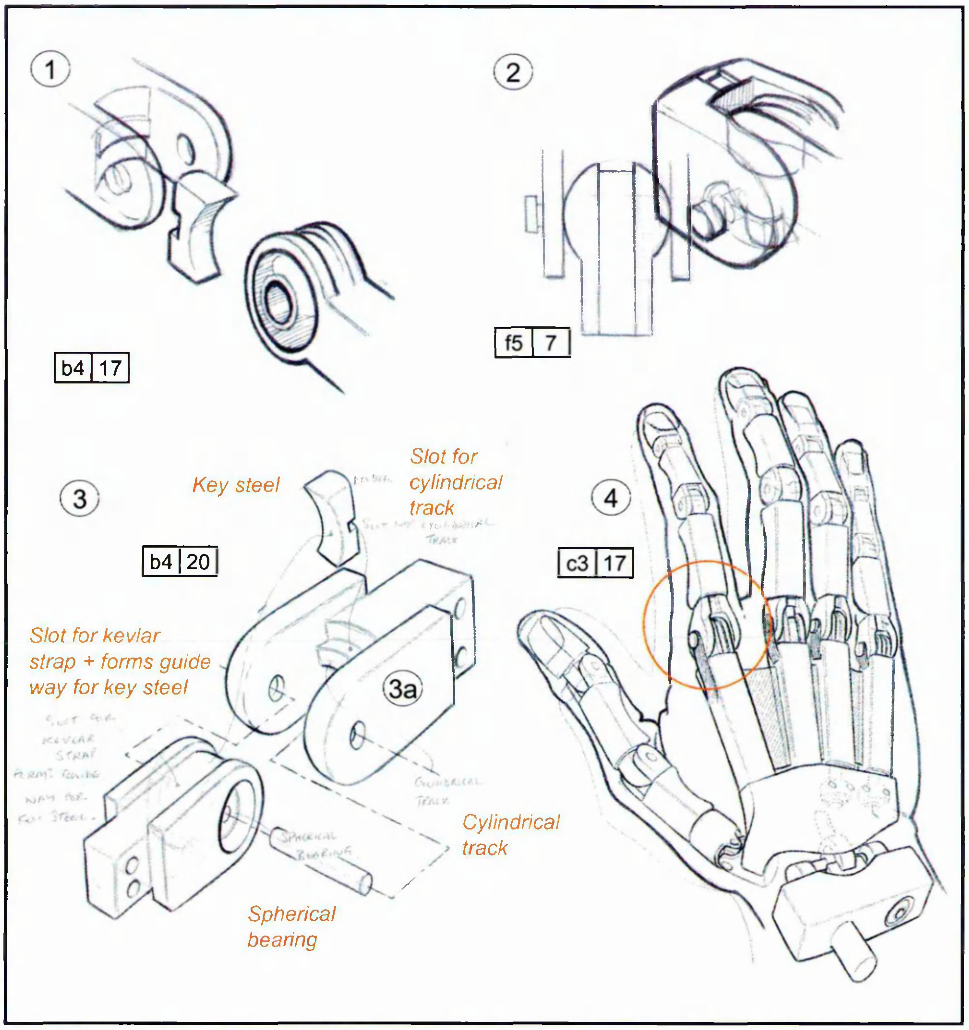


Fig 4.6 Spherical Bearing 2 - Constraint of Rotational Freedoms Cont.

The two means of constraining the rotational degrees of freedom of the spherical bearing were incorporated into analogous joint designs (1, 2). Sketch (3) shows how the guide channel for the key steel, required to constrain the joint, could also be used to guide an analogous tendon, and how a cylindrical track, again required for constraint, could be combined into the distal component (3a). In addition to detailing the enclosures around the spherical bearing, sketch (4) shows how drawings were completed to ascertain the relative scale of the joint when placed in the configuration of a human hand. From this exercise it was determined that the cylindrical idea (2) may be more productive than using the sliding key steel. It was envisaged that the material for the majority of the joint would be a bearing plastic, and it was foreseen that rotational forces transmitted to the key steel from the remainder of the finger would deform the bearing plastic track. The cylindrical constraint form of sketch (2) was chosen in preference as it was considered that torsional forces would be spread over a larger area.

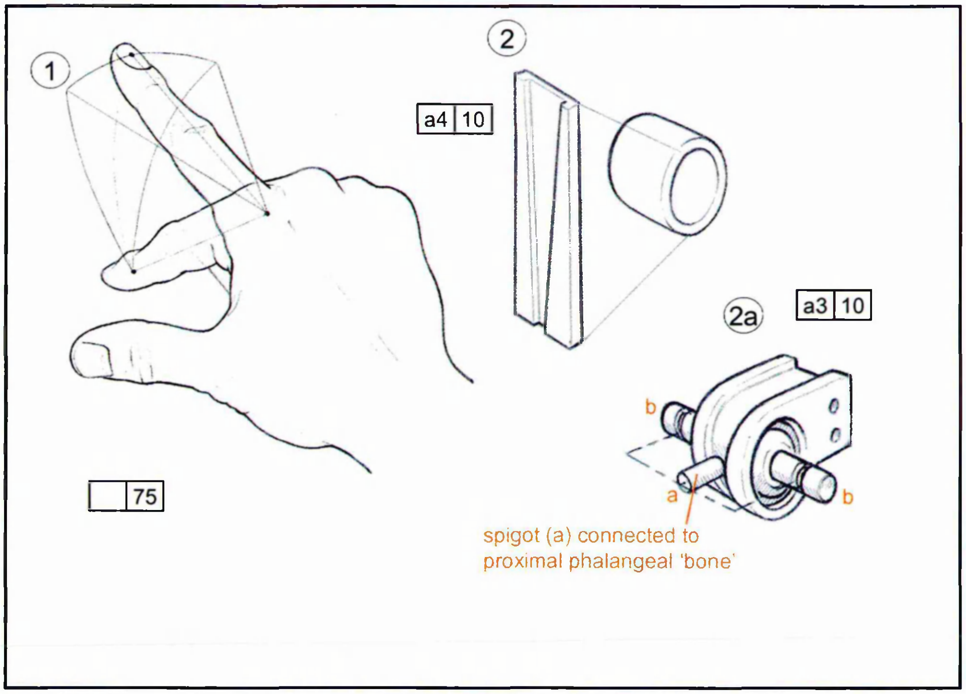


Fig 4.7 Spherical Bearing - Progressive Constraint

From observational drawing of one of the researcher's hands and reference to research studying the function of the hand (Williams 1998) it became apparent that the range of movement of the MCP joint in the plane of adduction / abduction diminishes as the joint is flexed (1).

In the neutral position the range of adduction / abduction movement is maximal, whereas with the interphlalangeal joints extended and the MCP joint fully flexed there are no discernible adduction/abduction movements (Williams 1998). Two ideas were considered to approximate this progressive constraint.

The first idea focussed on a tapering groove projected onto the cylindrical surface of the distal metacarpal component (sketches 2 & 2a). With a spigot (a) connected to the proximal phalangeal component through the axle (b-b), to progressively constrain lateral movement as the joint is flexed.

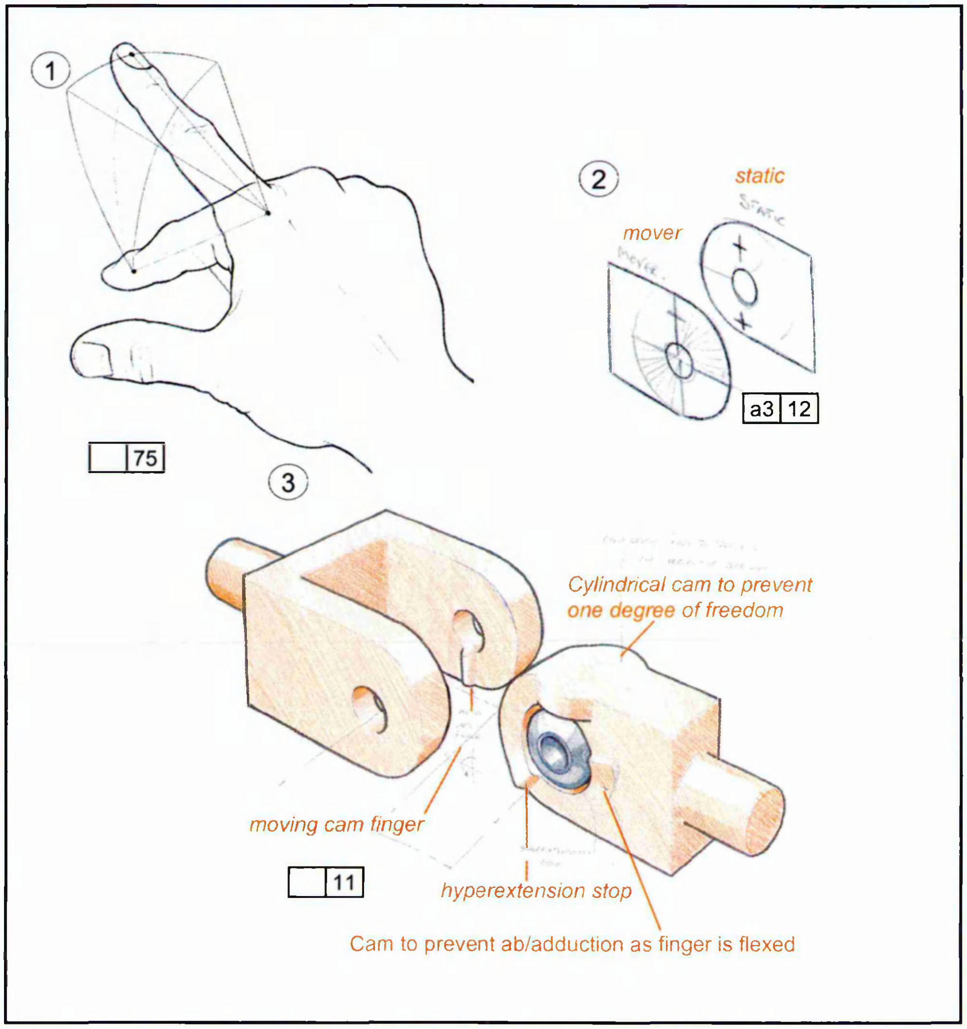


Fig 4.8 Spherical Bearing - Progressive Constraint (cont.)

A second idea resulted from consideration of the lateral and medial sides of the joint design. It was considered that for a 90 degree flexion movement there will be a unique quadrant that can be used as a cam surface (2).

This idea was explored in sketch (3). When the joint is in the neutral position a cam 'finger' connected to one side of the joint is aligned with the cylindrical cam allowing maximal adduction/abduction, whereas at full flexion the cam finger contacts with a cam on the opposite component to prevent lateral movement.

This concept was preferred to the spigot concept of the previous page as maximal lateral constraint coincides with a maximum 'moment arm' between the cam finger and distal metacarpal component.

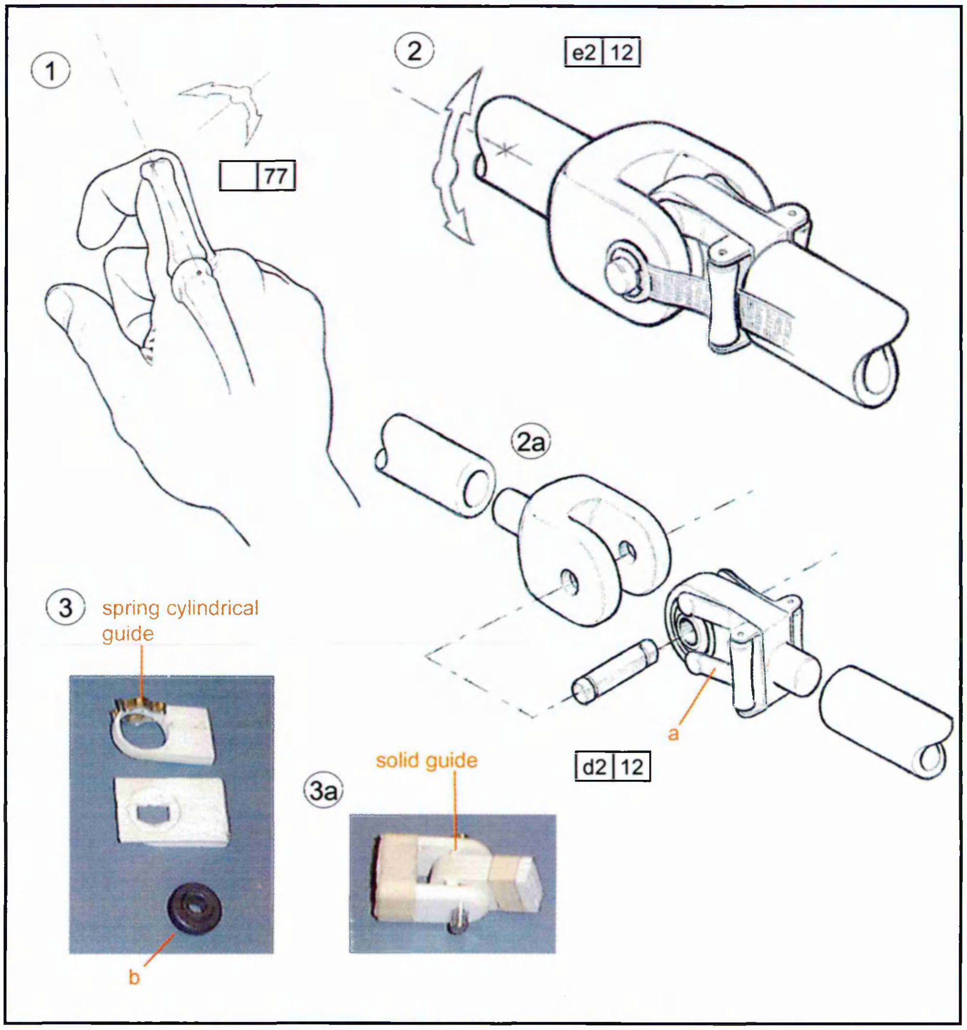


Fig 4.9 Spherical Bearing - Sprung Constraint

Further observational drawing (1) combined with palpation of one of the researcher's fingers, revealed passive axial rotation was possible at the MCP joint.

Palpation demonstrates a sprung quality to this movement, returning the finger to the neutral position. In attempting to mimic this action the solid cylindrical cam was replaced by a spring steel guide (a) shown in sketch (2a).

Both the solid cylindrical cam (photograph 3a) and the sprung steel idea (photograph 3) were prototyped from a lightweight polystyrene material. This exercise showed that although both ideas appeared promising for further prototyping, the weight of the metallic spherical plain bearing might make the joint ideas too heavy for application in a future prosthetic hand.

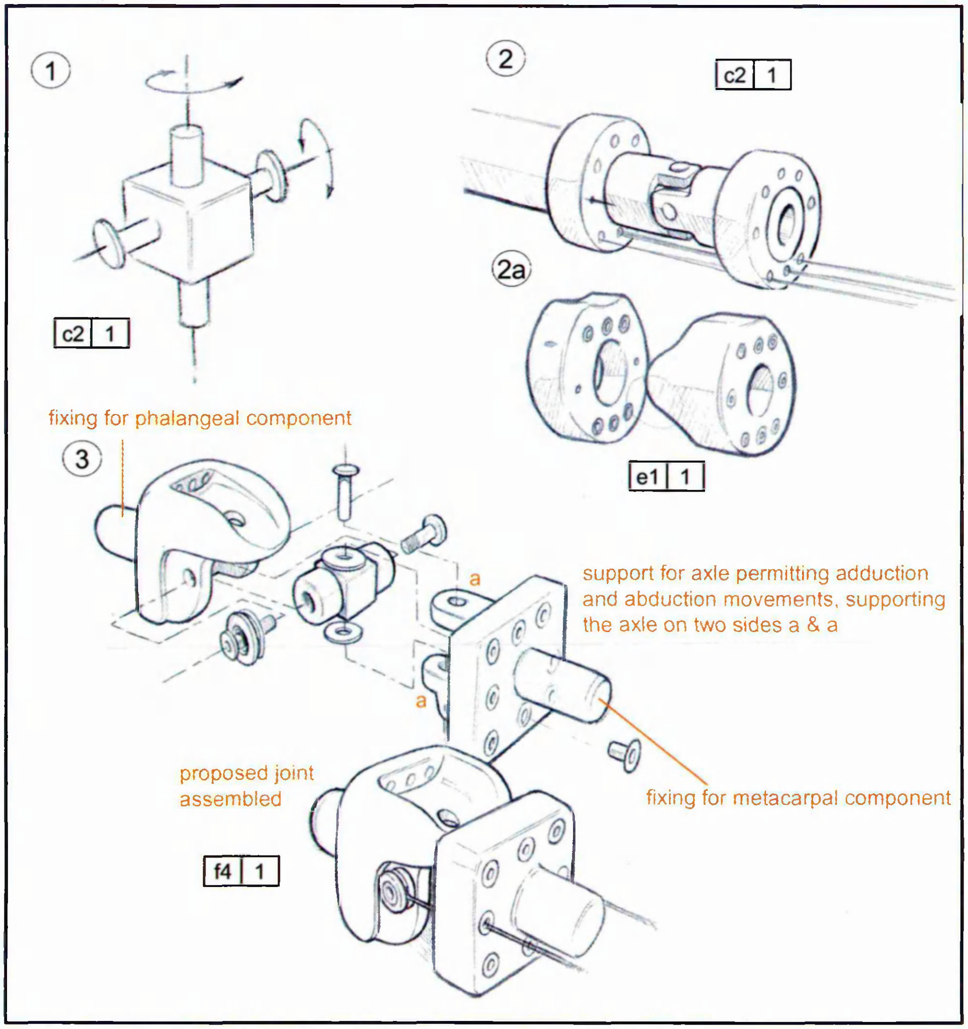


Fig 4.10 MCP Articulation Based on Universal Joint Principles

It was concluded from the spherical bearing prototypes that weight considerations dictated that steel components should be minimal. Therefore, further sketch ideas were based on the universal joint, as the function of this type of joint relies on orthogonal axles rather than bulky steel forms (1).

Initially, joint ideas were based around commercially available miniature components. From further sketchbook development it was evident that collars might need to be fitted to the joints for guidance of analogous actuating tendons, and to provide constraint for the ranges of movement (2, 2a).

The extent of the proposed modifications indicated that a specifically designed joint was justified. Sketch (3) shows how mechanical fixings were suggested both as a means of connecting either side of the joint and also to act as the axles around which the joint would articulate.

Initially, as in (3), the orthogonal axles were to be supported on either side of the joint form (a-a) (3). However, it was found from measurement of readily available miniature fixings that this would make the joint too bulky. Therefore, further joint ideas were developed using a cantilever support for the articulation of adduction/abduction.

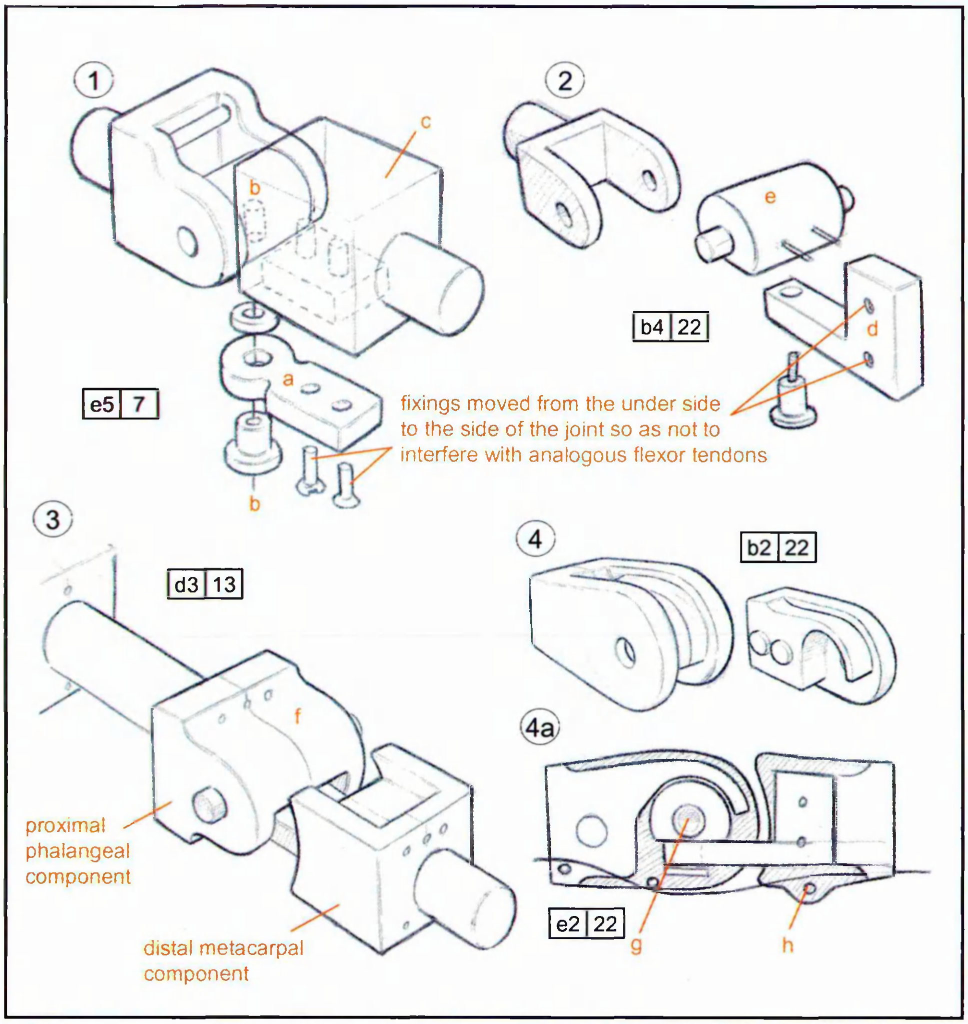


Fig 4.11 Universal Joint Ideas

Sketch (1) shows that initially a simple plate design (a) was considered as the cantilever support for the adduction / abduction axis (b-b). However, it was thought that using mechanical fixings to join this to the distal metacarpal part of the joint (c) might interfere with the guidance of analogous flexor tendons. Consequently, component (d) in sketch (2) shows the cantilever support as an 'L' shape where the fixings are on the sides of the joint.

Iniitally, the axle for flexion/extension was drawn as large component, to present a smooth surface over which analogous flexor tendons could pass (e) (2). However, with reference to weight it was considered inappropriate, instead it was considered better for the tendons to pass over a bearing plastic enclosure (f) (3).

It was proposed that this enclosure be made in two halves to fit onto the sides of the the flexion / extension axle (g) (4a), and that in a future manufactured item the sides of the bearing plastic component be ultrasonically welded together.

Sketch (4a) proposed that guidance pins for an analogous flexor tendon (h) could be trapped in a sandwiched design in a similar manner to those guiding the analogous flexor tendon in the interphalangeal joints.

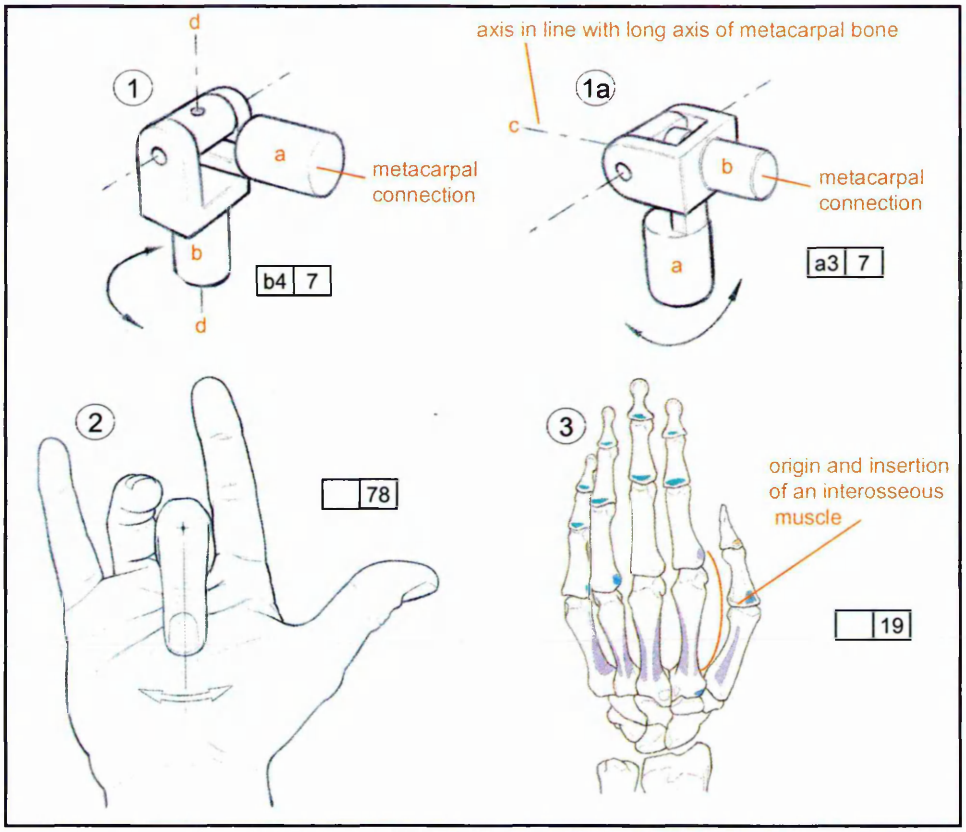


Fig 4.12 Universal Joint Ideas - Orientation

Once the basic form of the axles was decided, the articulations were visually tested in sketches (1, 1a). From this exercise it was found that exchanging component (a) and component (b) on the distal end of the metacarpal section would result in very different articulations at full flexion.

In the neutral position both configurations would have similar articulations, however, when fully flexed the configuration in sketch 1a would possess a lateral articulation in line with the long axis of the metacarpal bone (c); unlike sketch (1) that still rotates along axis (d-d).

To identify which configuration represented the closest analogy, one of the researchers hands was palpated. On flexing the middle finger it was clear that an active adduction/abduction motion was possible, similar to that of permitted by axis (d-d) (1).

Further observational drawing was completed to understand more about the interossei, the intrinsic musculature of the hand that actuates the adduction / abduction movements of the fingers (Kapit and Elson 1993). These were done from three-dimensional anatomical models marked with the ‘origins’ and ‘insertions’ of the interossei, and these were sketched in purple (3). From this exercise it was determined that the axle configuration in sketch (1) would be the closest analogy as the position of the interossei appeared to give no mechanical advantage to produce the movements of sketch (1a).

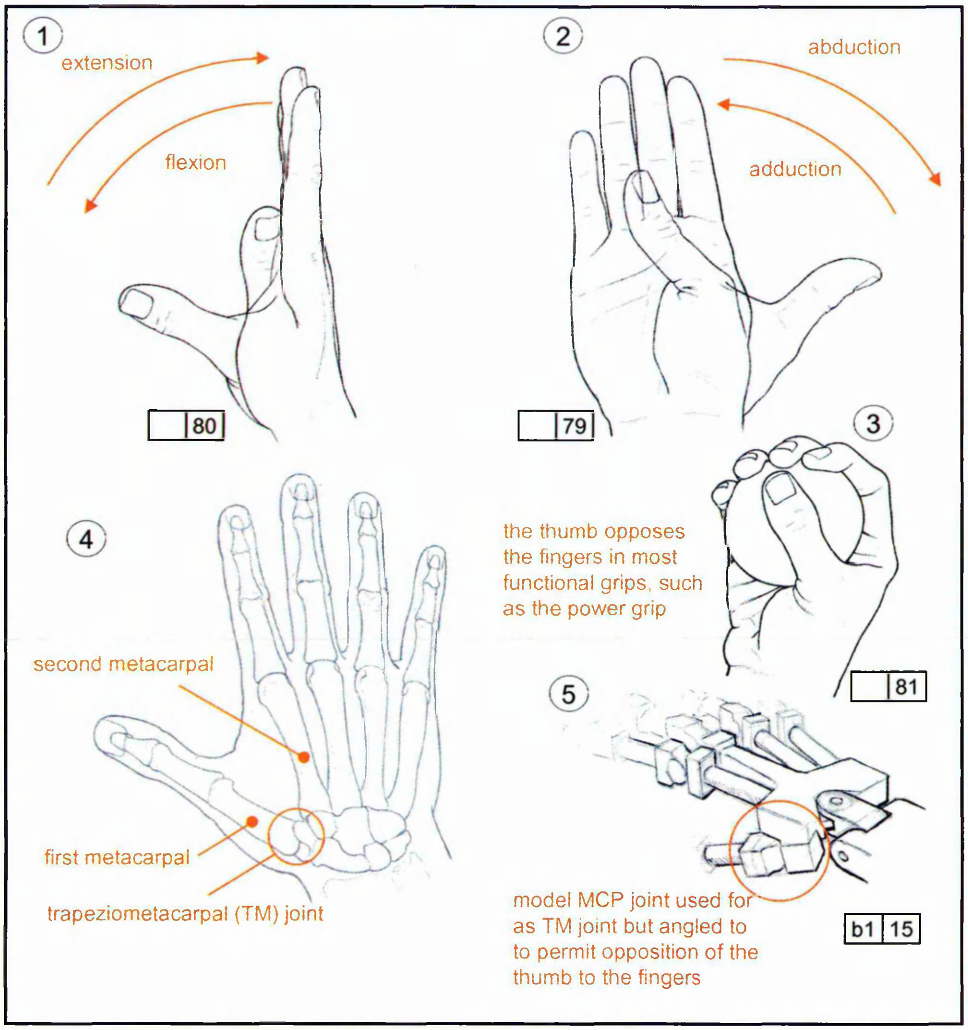


Fig 4.13 Orientation of the Universal Joint for a Trapeziometacarpal Joint

A literature review indicated that the trapeziometacarpal (TM) joint of the thumb possessed articulations that could be considered as similar to the joint form proposed for the analogous MCP joint (Cooney et al 1981). This allows movements of flexion and extension (1) and adduction/abduction (2) (Kapit and Elson 1993).

To achieve, opposition (3) and other functional movements (Kapandji 1982) it was necessary to angle the axes of the joint relative to the plane of the palm (Conney et al 1981). Therefore, it was considered that the proposed MCP joint was appropriate to use as a TM joint to achieve the range of movement of the thumb, only the joint should be angled to the palm. Measurements were taken from the intact hand of one of the researchers to determine the angles of orientation of the model joint necessary to enable the MCP joint to function as a TM joint. This was done using goniometric techniques to measure the angle between the first and second metacarpal shafts (4) both in the frontal and sagittal planes when the hand was relaxed. It was found that the first metacarpal was approximately abducted 40 degrees from the second metacarpal in the frontal plane, and flexed 30 degrees in the sagittal plane (5).

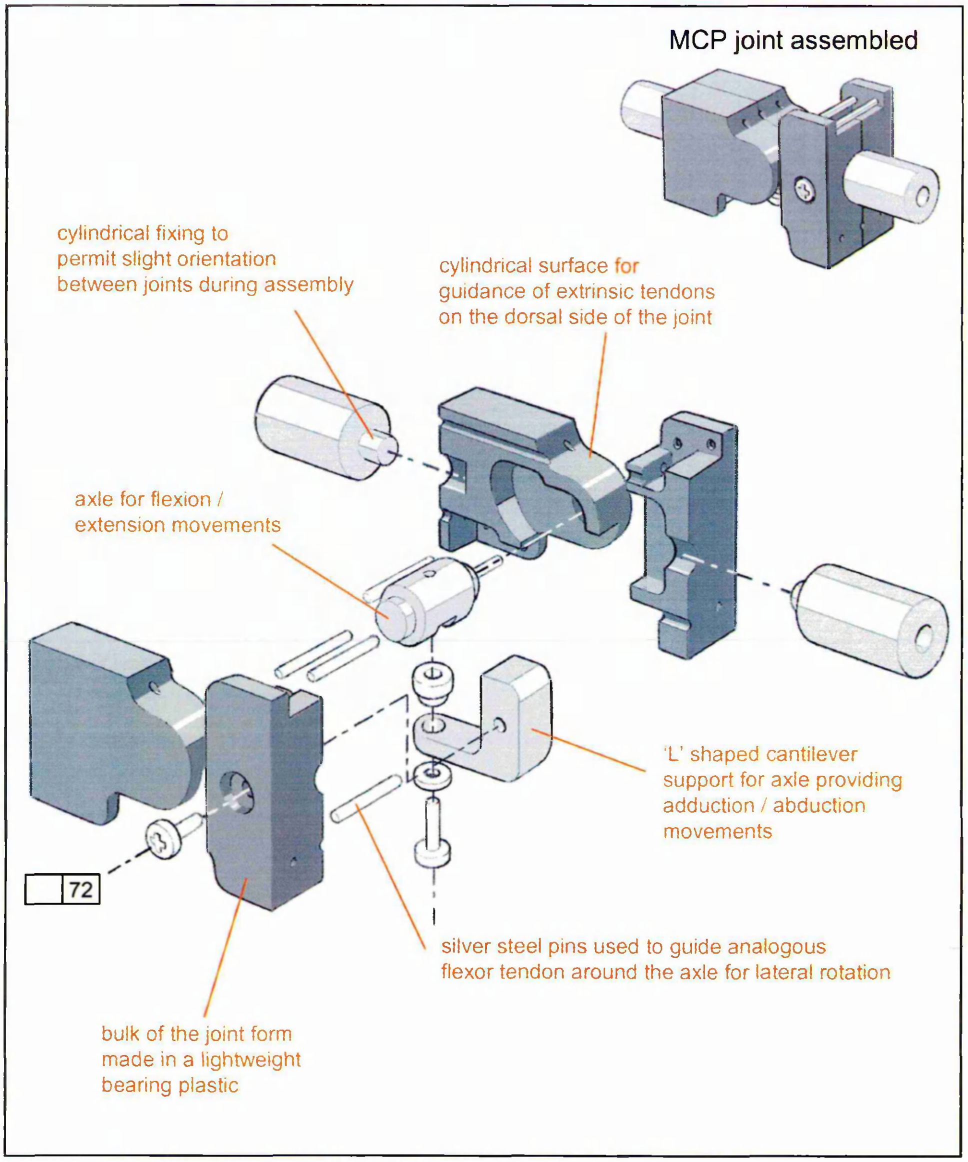


Fig 4.14 The Analogous Model MCP Joint

The figure above shows an exploded view of the model MCP joint, labelled with the design principles embodied within this design.

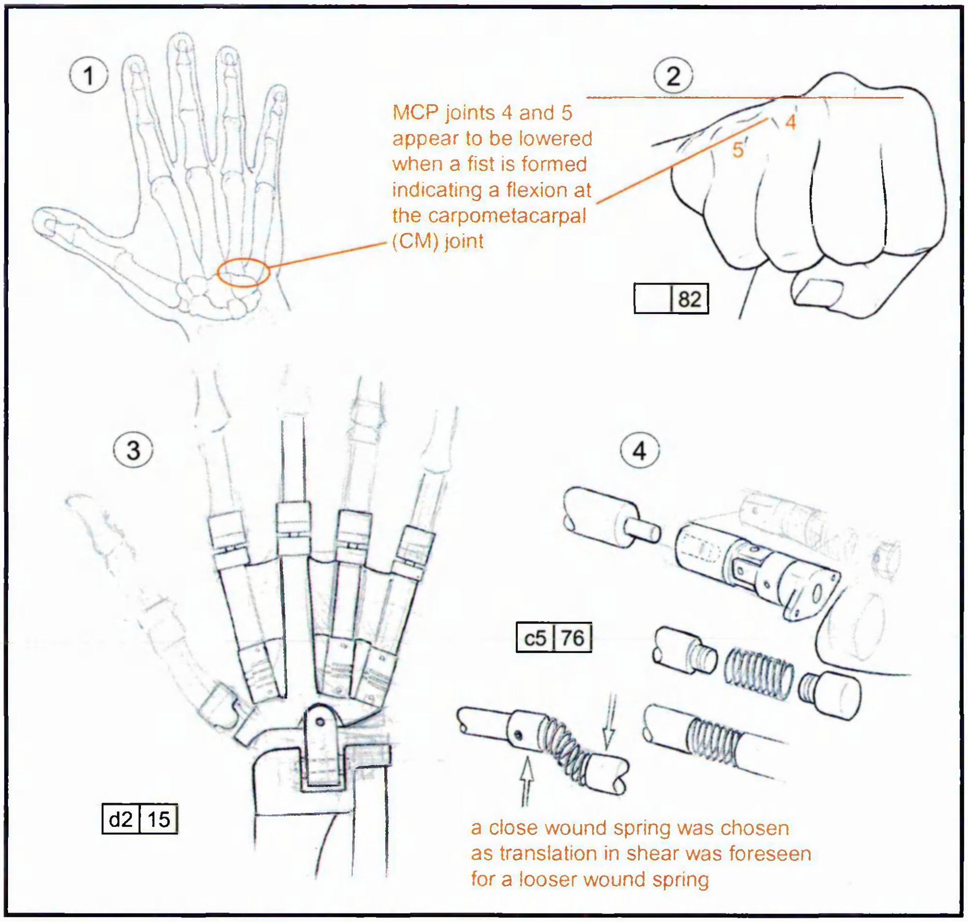


Fig. 4.15 Carpometacarpal Joints Development

From observation and palpation of intact hands it was concluded that the range of movement of the last two digits (four and five), are effected by the position of the more proximal joints, the carpometacarpal (CM) joints (1). This finding was verified against anatomical literature (Kapandji 1982, Landsmeer 1976). It appeared from palpation that these joints possessed two degrees of freedom in flexion / extension, and adduction / abduction. The action of the joints on the hand appeared most marked when making a fist. The MCP joints of digits 4 and 5 appeared to flex, lowering them from their previous position, approximately in line with MCP joints two and three (2). Again this was verified against anatomical literature and found to be a normal action of the hand (Landsmeer 1976).

The CM joints of digits 4 and 5 appeared to possess ‘sprung’ action, unlike the MCP joints, returning them to a neutral position. Consequently, use of the designed MCP joint design at this point appeared unsuitable. Instead, simple ideas using a spring as an initial approximation of this joint were considered. It was thought that placement of a close wound extension spring in line with the long axis of the finger would permit the small angular changes that were observed, whilst positively returning the joint back to a neutral position (4).

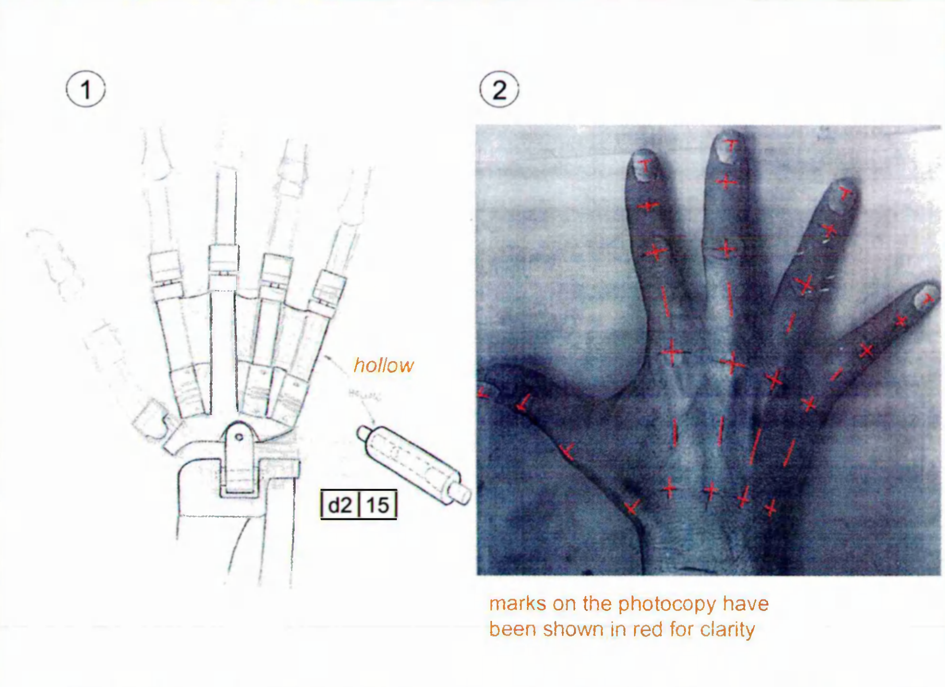


Fig 4.16 Strut Development

In the development of the IP joint it had been considered appropriate to provide a cylindrical bore in either end of the joint to provide a fixing method that would permit the joints to be slightly angled relative to one another. For similar reasons a cylindrical fixing method was chosen for the MCP joints.

The struts between joints must not only maintain both the relative angle and distance between the joints, but also be lightweight so not to detract from the lightness of weight of the joints in evaluation. Therefore aluminium tube was considered appropriate, possessing rigidity over the short spans required and being light in weight. The cylindrical section also permitted the joints to be slightly rotated relatively to one another along the long axis of the tube (1).

The necessary lengths of the aluminium struts were determined for the model from a photocopy of one of the researchers hands, which had been palpated and marked with the apparent joint centres (2). The lengths of the proposed joints was subtracted from the lengths between centres to determine the strut lengths needed.

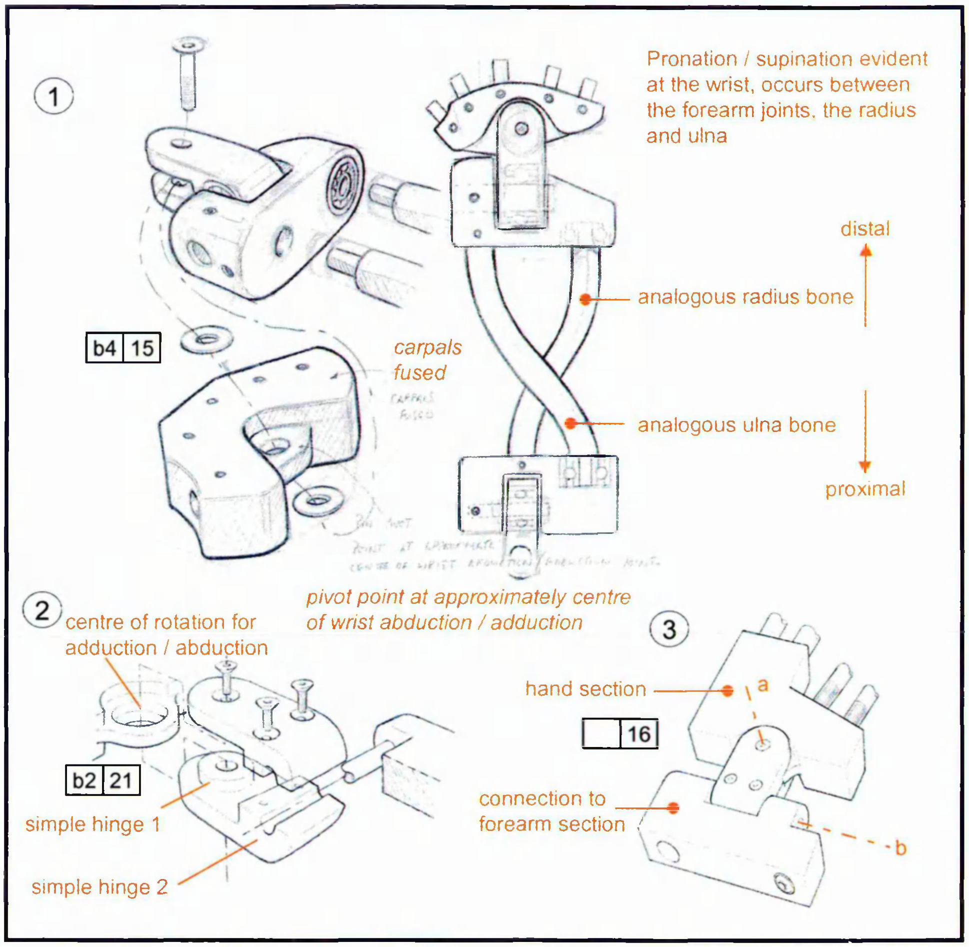


Fig 4.17 Mk1 Wrist

With designs for the IP, MCP amd CM joints it appeared that the only joint remaining before the assembly of a skeletal model hand for review was the wrist. One of the researchers hands was palpated and it appeared that this joint permitted two degrees of freedom, in the plane of flexion / extension and adduction / abduction. This was found to be consistent with anatomical literature. (Kapandji 1982). However, it was noted that positioning of the hand relies on a third rotational degree of freedom in line with the long axis of the forearm termed pronation and supination movements (Kapandji 1982). Review of the skeletal anatomy at an anatomy teaching laboratory indicated that pronation / supination was not achieved through articulations at the wrist, rather between articulations at the distal and proximal ends of the forearm (1). Again this was reviewed for validity against anatomical literature and found to be consistent (Kapandji 1982). Therefore, a decision was made to only provide articulations for adduction / abduction and flexion / extension within the model wrist. The apparent centres of the articulations were determined from palpation of one the researchers hands and marked on the skin. The centres of rotation appeared separated. The centre of rotation in the plane abduction / adduction being more distal than that of flexion extension (2). Therefore, it was considered that simple hinge joint principles such as those used for the IP joint could be used for the articulation of the wrist. Two joints were required with their axes of movement separated orthogonally (3 a,b). The ranges of movement of the wrist were taken from anatomical literature and use in the design of the two joints (Daniels and Worthingham 1986).

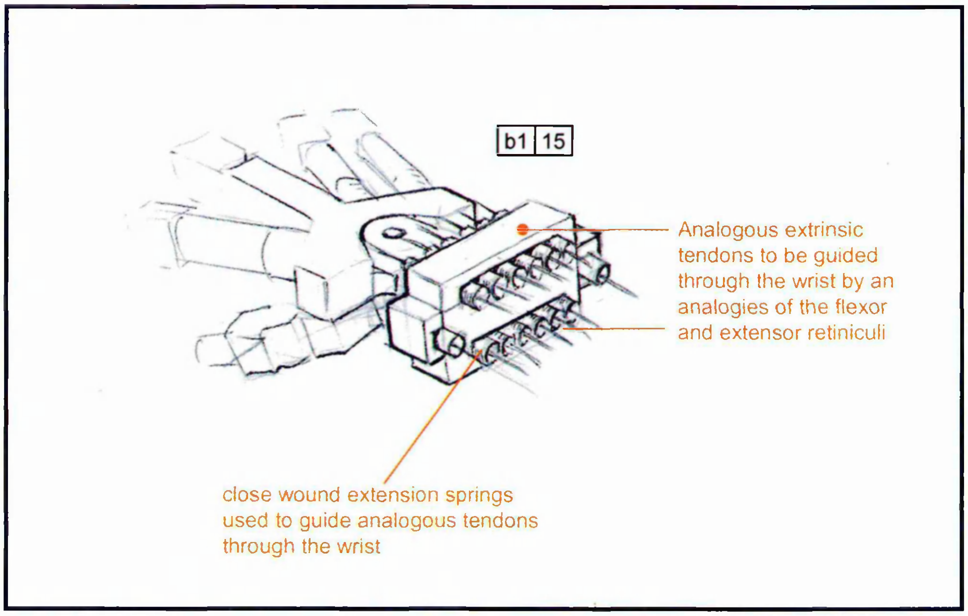


Fig. 4.18 Mk1 Wrist

The extrinsic extensor tendons to the fingers are guided through the anatomical wrist by the extensor retiniculum (Kapandji 1982). It was noted from anatomical texts that this appeared to be at approximately wrist level (Kapit and Elson 1993). Therefore, it was considered appropriate to provide guidance for the wire tendons motivating the fingers of the mechanical analogy at a similar level. It was thought advantageous to provide a method to increase the radius of curvature of the passage of the tendons through the wrist to limit friction effects, and a possible tendency the tendons might have to 'dig in' to the structure of the wrist guide. Extension springs were included in the guidance structure of the wrist to provide this increased curvature.

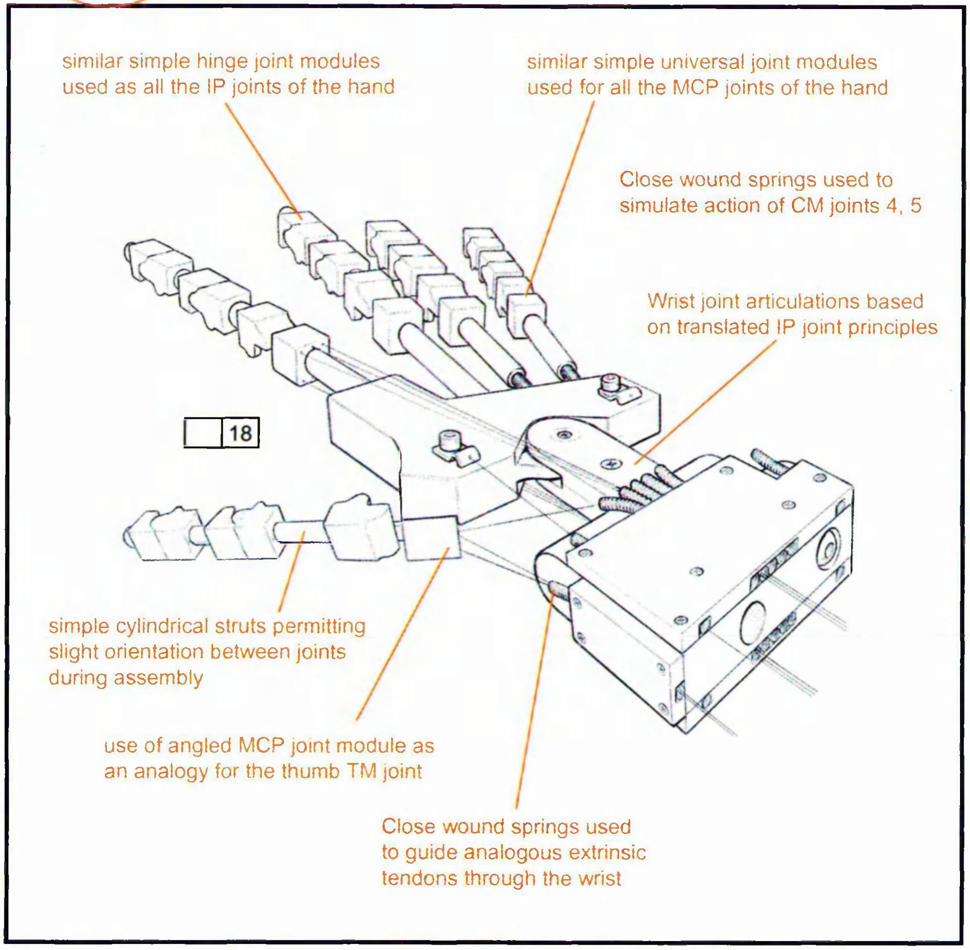


Fig. 4.19 Drawing Showing Joints Assembled into a Skeletal Hand Form

This drawing was made prior to the assembly of the finger joints and wrist section into a 'hand'. It shows the angled placement of the MCP joint used as a TM joint for the thumb, and the use of extension springs to guide the wire tendons from the fingers through the wrist.

This pictorial plan was done to to ascertain whether the designs could practically be combined with the IP joints at an appropriate scale to produce a convincing skeletal hand form. It was considered from this exercise that the individual components could be assembled convincingly. Therefore, detailed engineering drawings were made of the proposed MCP and wrist joints proir to prototype production. These were made both using traditional drafting techniques and CAD software.

(12)

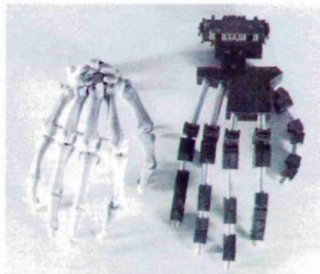
Fig 4.20 Jigs for Machining of CNC Joint Forms

The detailed drawings were subsequently used to programme a CNC machine tool. In a similar manner to the manufacture of the IP joints, multiples of the MCP joint forms were machined in a single sequence.

Like the production of the IP joint, the MCP joints required jigs to be made using CNC to ensure accuracy for subsequent conventional machining. Due to the extra degree of freedom of the MCP joint its form is more complex, this resulted in consequent added complexity in the arrangement of jigs and holding fixtures.

Prototype production of the wrist was also completed using these techniques.

(12)

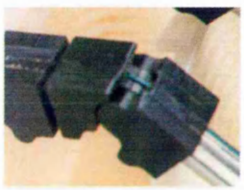


The skeletal model hand has been designed to be the same scale as the average human hand.

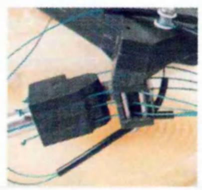
Because it is anthropometrically similar to the human hand it can be configured around many domestic products based on anthropometric constraints.

The hand is of modular construction and can be changed in size by altering simple interconnecting struts

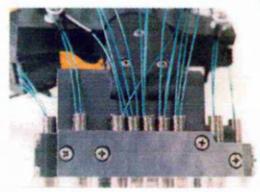
all the IP joints are of the same modular design

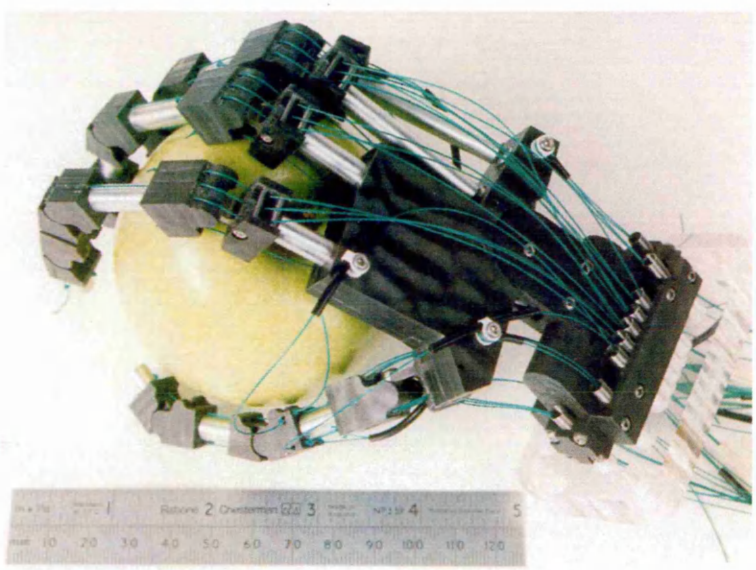


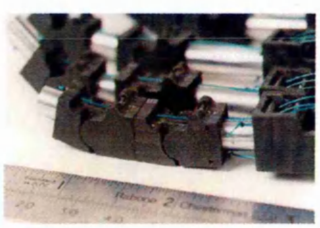
all the MCP joints are of the same design - the thumb TM joint is also an MCP module



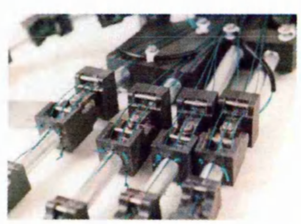
The model has an two degree of freedom articulated wrist which the analogous extrinsic tendons pass through







analogous extrinsic flexor and extensor tendons used to flex and extend the finger joints - additionally tendons activate movements of the wrist



silver steel pins guide the analogous tendons around the joints to prevent bowstringing

Fig 4.21 Design Principles Embodied Within the Skeletal Model Hand

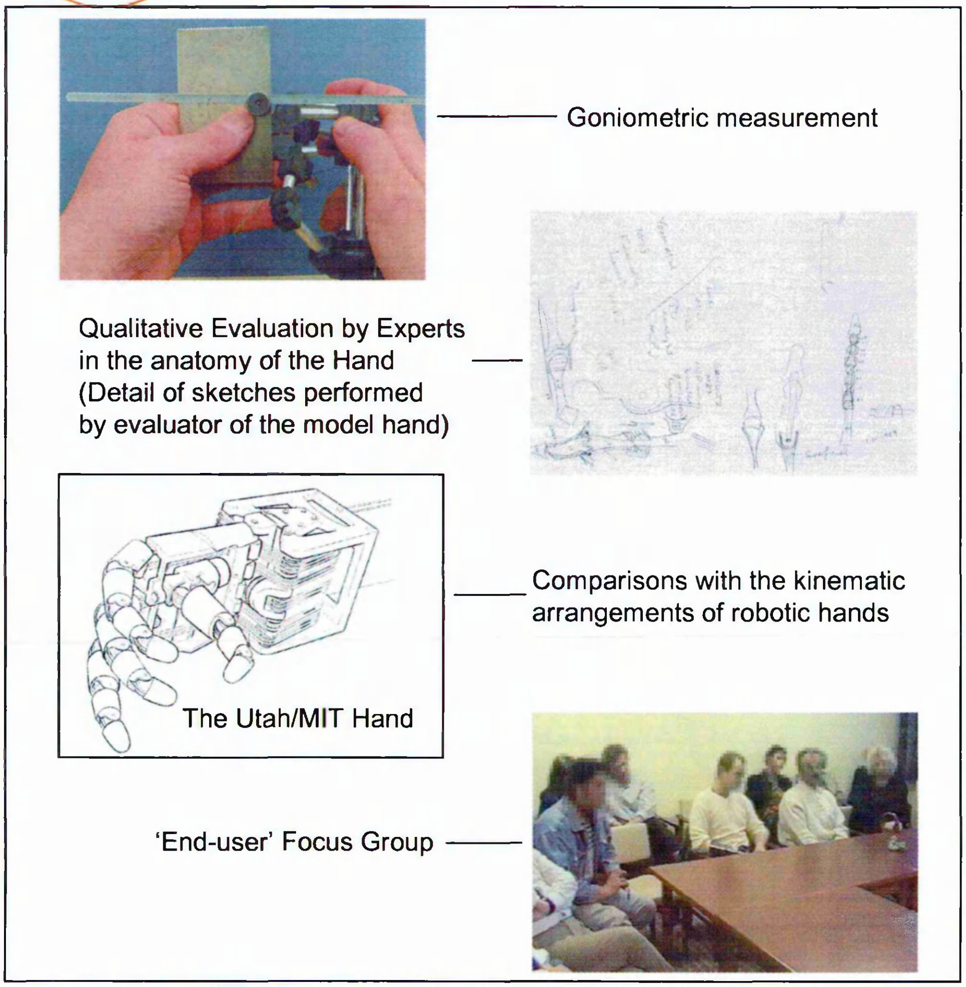


Fig 4.22 Evaluations for the Skeletal Model Hand

The assembly of the skeletal model hand provided the possibility for a wide review of the design joints and the design principles embodied within the model.

To assess the joints it was considered appropriate to use goniometric techniques similar to those used to assess joint range of movement in the intact hand (Norkin and White 1995). A 'pretensioning jig' was also constructed to evaluate the extrinsic actuation of the model.

It was proposed that the 'closeness' of the analogy of the joints to the human joints could additionally be assessed by qualitative methods. It was envisaged that this could be performed by experts in the anatomy of the human hand through visually assessment and palpation the model hand.

Additionally, it was thought that the model hand had reached a level of completion where it could be compared with the kinematic design of previous robotic hands. Although, it was recognised at this stage that the model lacked actuation of the joints.

The completed hand also provided the opportunity to extract valuable criticism on the model from prosthesis 'end-users'. It was hoped this evaluation might indicate how the design principles within the model might benefit a future prosthesis. The groups chosen as end-user's were primarily amputees but also include prosthetics, occupational therapists and a prosthetics manufacturer.

WRIST

Wrist flexion (degrees)
Model
90
Human
85

Wrist extension (degrees)
Model
45
Human
85

Wrist abduction (degrees)
Model
30
Human
15

Wrist adduction (degrees)
Model
43
Human
40-45

Values for human joints taken from Kapandji (1982)

MCP

	Model MCP Joints (degrees)			
	passive		active	
finger	R.U.D.	F.E.M.	R.U.D.	F.E.M.
Index	71.0	128.5	similar to passive	
Long	72.0	125.0		
Ring	72.0	131.5		
Small	71.0	125.5		

	Human MCP Joints (degrees)			
	passive		active	
finger	R.U.D.	F.E.M.	R.U.D.	F.E.M.
Index	62	155	50	148
Long	53	151	40	145
Ring	55	159	38	149
Small	68	172	57	152

Values for human joints taken from YOUM, Y. et al (1978)
R.U.D.-radius -ulna deviation (adduction / abduction movement)
F.E.M. -flexion - extension movement

Flexor and Extensor Excursion to Flex MCP Joint (mm)	
Model Flexion (FDP)	Model Extension (EDC)
18.0	9.5
Human Flexion(FDP)	Human Extension (EDC)
21.4 (mean figure)	16.8 (mean figure)

Values for human tendon excursion taken from YOUM, Y. et al (1978)
FDP -flexor digitorum profundus
EDC -extensor digitorum communis

IP

Interphalangeal Joints (degrees)	
Model DIP Joints	Model PIP Joints
90	90
Human DIP Joints	Human PIP Joints
80-90	110-120

Values for human joints taken from Daniels and Worthingham (1986)

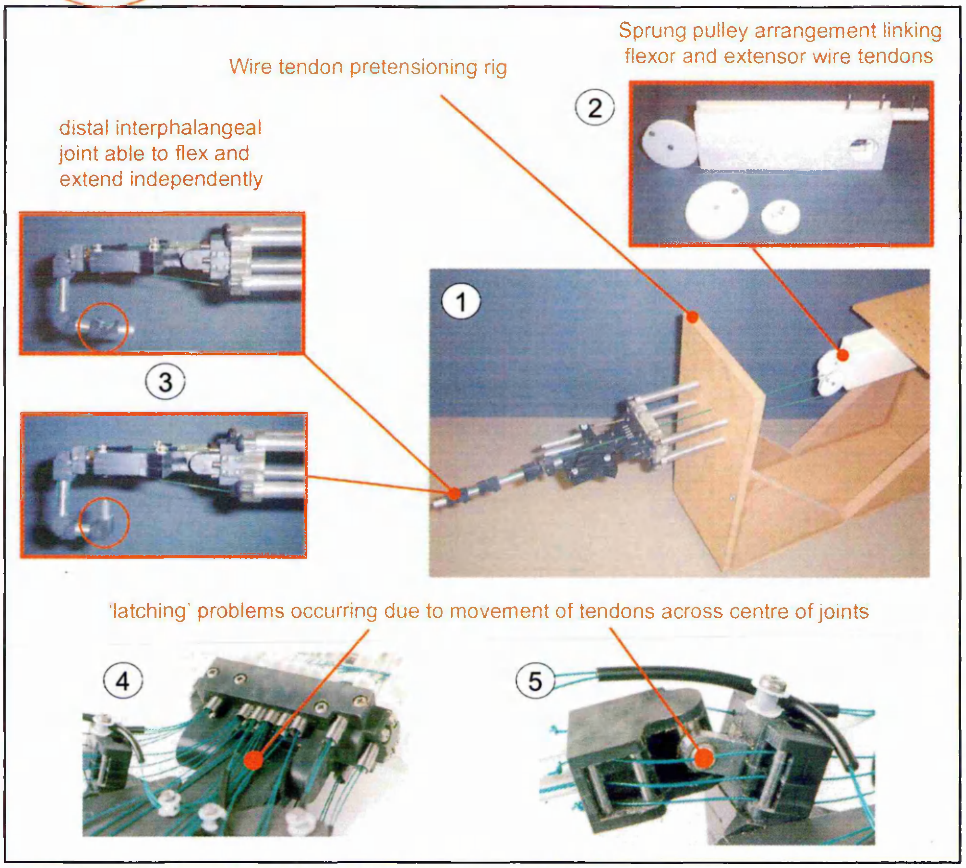


Fig 4.23 Pretensioning Effects on the Skeletal Model Hand

To evaluate the limitations of activating the model joints using wire tendons, it was necessary to build a 'pretensioning rig' to support the model hand and apply tension to the tendons (1).

Wire tendons that were approximations for the flexor digitorum profundus and extensor digitorum communis where linked through tensioning pulley wheels shown in (2). When flexing and extending the finger using this device it was observed that the DIP joint would flex independently to the PIP joint (3). On activation from these tendons in the human hand the DIP and PIP flex and extend together (Kapandji 1982).

Using the pretensioning rig shown it was observed that the use of exclusively extrinsic actuation tendons proves to be problematic when combined with an articulated wrist. It was found that on flexion of the wrist the fingers would extend at at the MCP joint, and the converse would occur on extension of the wrist. Observing the intact hand it is possible to flex and extend the wrist without altering the position of the finger joints. Observation of the tendon excursion for the model fingers when the wrist was moved indicated that a mechanism was required to compensate for the extra tendon excursion required for the wrist if the model fingers were to remain in position.

Additionally, 'Latching' problems were observed when the model tendons were pretensioned. This problem appeared at the MCP and wrist joints. Latching was identified as the joint not remaining in neutral position, instead tending to maximum adduction or abduction. Latching appeared to be caused by the movement of tendons across the centres of these joints in the plane of adduction / abduction (4, 5).

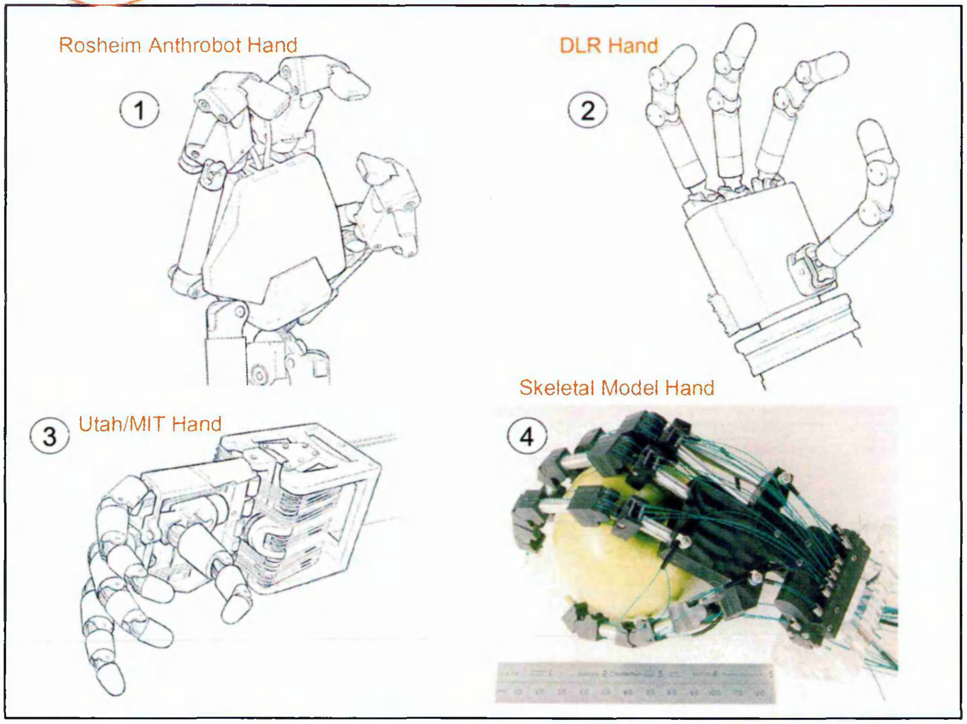


Fig 4.24 Comparisions with Advanced Robotic Hands

The robotic hands (1-3) outlined above are fully actuated devices capable of controlled movement (Rosheim 1994, Herzinger 1995, Perlin et al 1989), whereas the model hand is currently an articulated model with potential for actuation. However, it is appropriate to compare the kinematic design and structure of these advanced robotic hands with that of the skeletal model to inform future cycles of design which must include investigating actuation and control of the model.

Scale

The scale of the skeletal model hand is similar to that of the human hand, as is the Utah/MIT Hand (Jacobsen et al 1984) and the Anthrobot Hand (Rosheim 1994). However, the DLR hand is 1.5 times the scale of a normal hand (Liu et al 1999).

Actuation Stategies

The increase in scale of the DLR hand has been attributed to size constraints of the electric motors which are within the volume of the hand (Liu et al 1999). This is avoided in the Anthrobot hand, as the actuators that move the fingers are on the reverse of the hand (Rosheim 1994). However, this has resulted in a non-anthropomorphic finger design. Actuation comes from 'extrinsic composite tendons' in the Utah/MIT hand. Therefore, the large powerful pneumatic actuators to move the fingers are not required to fit within the volume of the hand (Jacobsen et al 1984). However, this approach has been shown to require a more complex control system (Lin and Huang 1996). The model hand may be considered to follow a similar tendon actuation strategy to the Utah/MIT hand.

Joint Kinematics

From the outline drawings it is clear that the skeletal model hand is the only one to possess the anatomical four fingers and a thumb.

The number of fingers has been reduced in the robot hands in part to reduce control system complexity. Historically computational constraints have limited co-ordinated multifinger control (Okada 1982). It has been found however, that manipulation is an essential part of hand function, and this can only be achieved using a minimum of four fingers (Pons et al 1999). Therefore, the Anthrobot Hand cannot easily perform manipulative and regrasping functions. All the hands have fingers jointed in a series - parallel arrangement. This means that as well as permitting rotation in the plane of flexion and extension, the joints also allow adduction / abduction movements. This arrangement has been found to be optimal for both dextrous operations and securing objects within the grasp (Pons et al 1999, Mason and Salisbury 1985). The skeletal model also follows this arrangement of joints.

Both the Anthrobot and DLR Hand share approximately similar finger joint kinematics. The joint nearest the palm on both devices has two actuated degrees of freedom, in the planes of adduction / abduction and flexion / extension (Rosheim 1994, Herzinger et al 1995). On both robotic hands this joint is orientated so that the maximum range of adduction / abduction movements occur when the robotic finger is aligned with the palm. The skeletal model hand follows a similar joint arrangement permitting two degrees of freedom about a single centre point. However, the two degrees of freedom in the Utah/MIT Hand are achieved by two separate joints. One for flexion / extension, aligned in series with the two distal joints, and a more proximal joint whose axis of movement is aligned with the long axis of the palm. This results in maximum adduction / abduction movements in a plane normal to the palm of the hand (Biggers et al 1986). This is a non-anthropomorphic configuration and has been criticised as not permitting some useful hand configurations (Perlin et al 1989).

Joint Placement

The placement of the most proximal joint of the 'thumb' has been shown to have a significant effect on the functionality of robotic hands (Perlin et al 1989). Both the Utah/MIT hand and the DLR hand have proximal thumb joints that originate normally from the palm. In the Utah/MIT hand the thumb is placed on the midline of the palm. This was initially due to cable routing, but also supported a desire to produce a single mechanical structure that could be used both for left and right hands (Jacobsen et al 1984). This placement of the thumb prevents the hands from being able to perform a grip on the lateral side of the first finger. Additionally, placement towards the centre of the palm has been shown to limit the robotic hands ability to use certain hand tools (Perlin et al 1989). Both the Anthrobot and skeletal model hand have more anthropomorphically positioned proximal thumb joints.

Coupled Joint Movement

Within the skeletal model hand the distal and proximal analogies of the human interphalangeal joints are motivated by common flexor and extensor wire tendons. This results in the most distal interphalangeal joint flexing before the proximal interphalangeal joint. Within the human anatomy the flexion of these joints is by certain tendons can result in a coupling between the DIP and PIP joints (Kapandji 1982). Like the skeletal model there appears to be no coupling of these distal joints in the Utah/MIT hand. However, Both the DLR and Anthrobot hands couple the movement of these joints. This is achieved in the Anthrobot hand through a rigid link (Rosheim 1994) and through a pulley system in the DLR hand (Herzinger 1996)

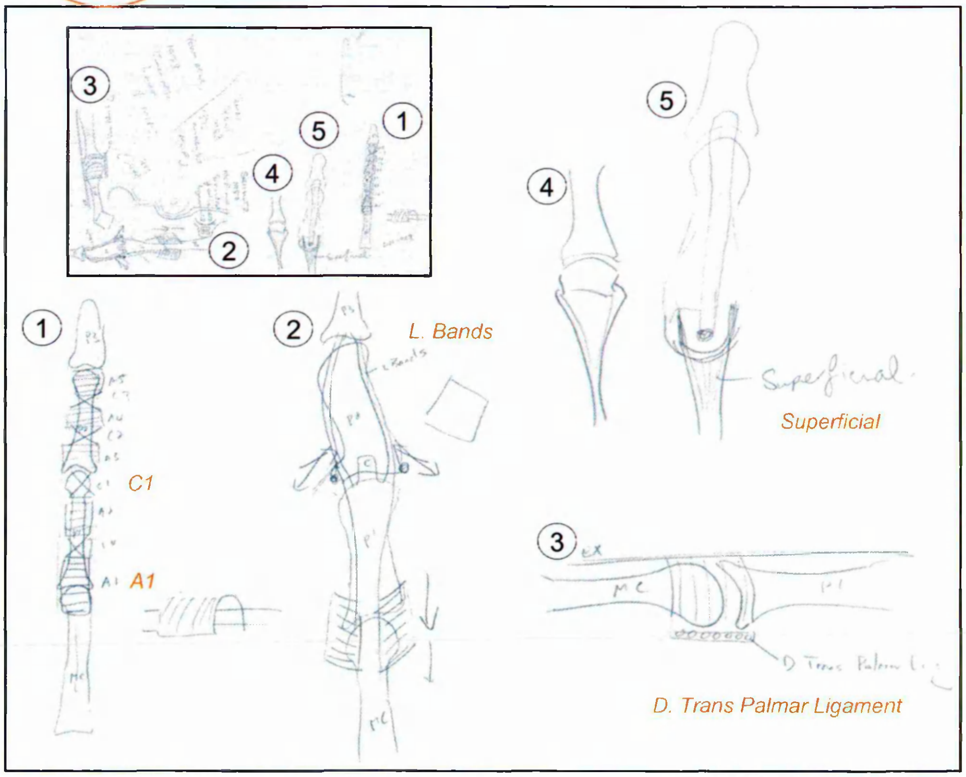


Fig 4.25 Evaluative Sketches Produced by Dr. N. Williams

The model hand was taken to the Royal Hallamshire Hospital for qualitative evaluation by Dr. N. Williams, a consultant hand surgeon with a specialist interest in the development of new prosthetic MCP joint implants. Precedents for this kind of qualitative evaluation for analogy did not appear to exist within this field. However, it appeared appropriate to approach a professional with this specialist knowledge to assess his views on the closeness of the model joints to those of the human hand.

Difficulty had been encountered understanding some of the anatomical literature in the preliminary data collecting stages, due to unfamiliarity with the nomenclature used. It was considered appropriate to take a sketchbook to the interview to allow Dr. Williams to graphically describe his thoughts and observations. Additionally, during the interview Dr. Williams was encouraged to draw tendon routing on the hand of the researcher, again to aid effective communication. These sketches along with notes taken by the researcher at the time represent the record of this evaluation.

The evaluation took place in one of the research laboratories of the Medical Physics department at the Royal Hallamshire Hospital. The interview duration was approximately one hour. It proceeded first by Dr. Williams being presented with the model, then a brief summary of the technical evaluation was given to him. To document this interview notes were taken.

Aims

The stated intentions of the evaluation were for Dr. Williams to assess how closely the analogies of the human joints had been met in the model.

Detail of the Evaluation

(1) Dr. Williams first comment was that for the large number of articulations the model possessed it appeared to be very light, comparable with that of a human hand.

(2) From the palpation of the model IP joints Dr. Williams considered the ranges of movement of the joints to be within the correct range for the normal human IP joint. He added that the IP joints also possessed some lateral movement again similar to that in the human joint IP joint.

(3) He commented that the joints may need to be slightly angled out of line along the long axis of the finger, to enable the fingers to close upon the radial pulse, rather than in the parallel manner that he observed (fig 3.4).

(4) Dr. Williams commented that the silver steel pulleys appeared to work well in combination with the fine steel wire to guide the actuating tendon without it 'bowstringing' (fig 3.11). He commented that these appeared a close analogy to the annulus pulley bands such as the one he labelled A1. However, he indicated that within the human hand there are additional cruciate (crossed) bands over the joint itself on the palmar side, which he labelled C1 (fig 4.25(1))

(5) Dr. Williams indicated that the arrangement of tendons that actuate the model finger were not the same as those of the human finger. However, he considered the tendon arrangement effective on the model, and was able to use the tendons to flex and extend the PIP and MCP joints independently. His chief concern was the addition of extra extensor tendons on the model needed to independently flex and extend the MCP joint. He sketched a diagram to show how there is only a single extensor tendon to each of the majority of the digits and each of these tendons split into two lateral bands proximal to the PIP joint (fig. 4.25 (2)) . It was his view that the observed flexing of the DIP independently to the PIP joint was in part due to the diversion of the tendon arrangement to that of the anatomy.

(6) Dr. Williams proposed that problems associated with the model MCP joint latching was again probably due to the tendon arrangement of the model diverting from that of the human anatomy. He indicated that although the interosseous muscles of hand which control adduction and abduction movements of the fingers are inserted into a common extensor hood over the MCP joint, their principle 'lines of action' are to the lateral and medial sides of the MCP joint. He added that the dorsal transpalmar ligment is connected medially and laterally to the extensor digitorum communis tendon over the MCP (fig 4.25 (3)). This ensures that the tendon remains aligned towards the midline of the joint, therefore, preventing the latching effects seen in the model.

(7) Dr. Williams highlighted the tendon arrangement on the palmar aspect of the model. The model possesses two extrinsic tendons actuating both adduction / abduction and flexion the MCP joint (fig 4.25 (4)). He indicated that although this arrangement appeared satisfactory for the model, the human superficial flexor tendon infact wraps around the profundus tendon (fig 4.25 (5)). He pointed out that this enables both the extrinsic finger flexor tendons to pass through the MCP joint close to its midline without adversely effecting the adduction / abduction movements of the finger.

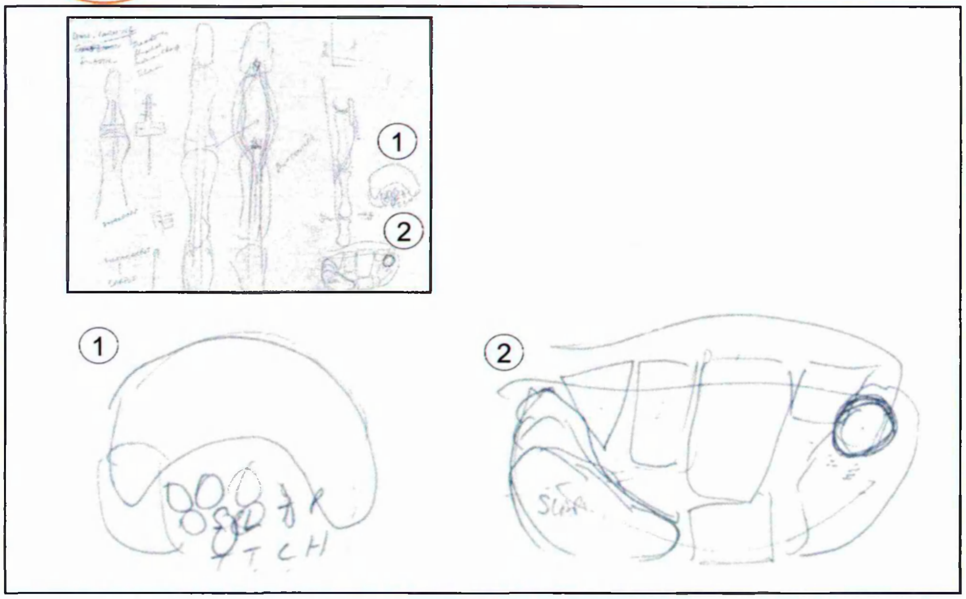


Fig 4.26 Further Sketches Produced by Dr. N. Williams

(8) Palpating the model MCP joint Dr. Williams considered that the joint showed a range of movement that he considered within normal limits in flexion and adduction / abduction. However, he indicated that the joint was able to hyperextend beyond normal limits.

(9) Grasping the model hand Dr. Williams considered that the inclusion of articulations corresponding to the fourth and fifth carpometacarpal (CM) joints was appropriate and anatomically consistent. However, indicated that these joints required constraints as currently the articulations were too 'mobile'.

(10) Palpating the model thumb, Dr. Williams was content that the two degree of freedom joint at the base of thumb gave the thumb a correct range circumduction. However, pointed out that the placement of the thumb joint could not be accurately assessed due to the unfamiliar form of the model carpus (wrist section).

(11) Dr. Williams was informed of the problems of the wrist 'latching' in the plane of adduction / abduction when the extrinsic finger tendons were pretensioned. Dr. Williams indicated that the anatomical carpus is arched in cross-section permitting routing of extrinsic finger flexor tendons close to the centre of the palm (fig 4.26 (1)). He offered that observing the routing of the human flexor tendons might indicate solutions to the latching problem.

(12) From observation of the placement of the sprung guides on the model wrist, Dr. Williams offered that the placement may need adjustment. He offered that the anatomical guides for the extrinsic flexor tendons stretch over the arch of the wrist carpus. He indicated that the anatomical carpal tunnel extends from the trapezium to the hook of hamate (fig 4.26 (2)) . Therefore, the placement of the flexor tendon guides on the model was too proximal. However, the guides on the reverse of the hand were closer to the placement of the anatomical extensor retiniculum.

Evaluation for Principles Appropriate to a Future Prosthesis

Mr. D. Linford, the commercial manager of Vessa Ltd., was asked to review the model hand. Vessa distribute upper-limb prostheses manufactured by their sister company in the USA. Mr. Linford has more than 20 years experience in the industry, communicating with with prosthetists and users as well the as managing commercial and technical problems of production.

The review of the model took place in an office at Psalter Lane School of Cultural Studies, Sheffield. Present, other than D. Linford, were the researcher and the supervisors, Prof. A. Wilson and Mr. C. Rust. Notes were taken during the evaluation by both the researcher and the supervisors for subsequent analysis.

The model was presented to D. Linford complete with all its attached wire tendons, however, it was not supported in the pretensioning rig. This was done for demonstration of the potential of the tendon-like actuation of the joints.

Aims

Before the model was presented to D. Linford the aims of the project were outlined. Stressing that analogy to original anatomy had been a key part of the design of the model. Additionally, it was stressed that the model was not intended as a prosthesis in its current form but that the aims of the evaluation were for D. Linford to indicate what he considered were principles within the model that might be appropriate for a future prosthesis.

Detail of Evaluation

Both the researcher and the supervisors had noted the following key points from D. Linford's evaluation of the model:

(1) On first viewing the model D. Linford had remarked on its complexity. Stating key aims principles of successful prostheses was simplicity, and that high complexity and consequently high cost prostheses could not be supported by the current prosthetics market.

(2) From further investigation of the modularity of the joints D. Linfords view of the model changed. He noted that the model was arranged from two joints. His view was that this considerably altered the economic viability of the multi-articulated design.

(3) On pulling the wire tendons he was pleased with the ranges of flexion and extension, and palpating the thumb indicated that its ability to oppose the fingers was important.

(4) His concluding comments were recorded verbatim by the researcher and the supervisors.

'This appears to be the most significant new development in prosthetics since the concept of the myoelectric prosthesis.'

Fig 6.27 Still from Focus Group Video Record

The driving motivation for the project developed from the human needs of the amputee. Therefore, it was considered important to ascertain amputees views on a wide range of topics including the design of a future prosthesis. In particular it was important to how their exposure the skeletal model hand might alter these views.

It was considered appropriate to do this using a focus group format (Krueger and Patton 1988). This was because it was felt that the sensitive nature of the discussion might best achieved using a peer group format (Renzetti and Lee 1993). Additionally, it was felt that from the members selected a diversity of views would be evident and this would add to the evaluation.

The focus group consisted of 13 amputees from the 'Helping Hands' amputee support. There was a male bias within the group, however, this is reflected in the total number of upper-limb amputees (NASDAB 1999). The average age of the amputees attending was estimated at 40 years, this appears to be reflected in national statistics (NASDAB 1999) .

The focus group was organised in accordance with accepted practices, such as appointment of a moderator and reporter (Krueger and Patton 1988). As one of the aims of the focus group was to ascertain aspirations for a future prosthesis it was though appropriate to illustrate some some of the questions for the focus group with clips from Science Fiction. Video clips from The Terminator (Cameron 1984), RoboCop (Verhoeven 1987) and Blade Runner (Scott 1990) were used to illustrate questions surrounding the integration of human and machine components. Factual documentary clips were also used to illustrate ideas of human movement effecting perception (Hennequin 1990, Johnstone 1994 and Disney 1933).

A video-recording was made of the proceedings of the focus group. This video record was replayed for analysis to a group of professionals including representatives from fashion design, furniture design and researchers specialising in anatomy and physiology. This diversity was considered important to obtain an objective consensus on what were considered the salient issues to the amputee. From the video record this could be assessed from both amputees verbal and non-verbal communication (Silverman 1997). The questions posed to the focus group are listed below. These are followed by the findings of the analysis of the video record of the proceeding of the focus group together with relevant quotes.

Focus Group

Questions for Focus Group

(1) *How do you relate to your appliance - as part of yourself or as a tool?*

(2) *In wearing a prosthesis do you perceive yourself as robot-like, or feel others perceive you this way?*

(3) *If you possessed a more hand-like prosthesis would you wear it in a greater range of circumstances?*

(3a) *Would you expect a more hand-like prosthesis to have similar functions to the human hand?*

(4) *Would you prefer to own your prosthesis?*

Analysis of Proceedings

(1) Amputees viewed their existing prostheses as inadequate. They also believed that there was nothing better available and had low expectations for future devices. These views were strongly expressed and reflected a generally negative view of upper-limb prostheses. For example, the technology used in current artificial arms was deemed *'stone age'*.

'I think it is a necessary evil to wear them..'

'I'm always glad to take it <the prosthesis> off....But I like to do things, so I've got to wear it'.

'You have to force yourself to use them'

'It's so obsolete what we've got, that it's not true really, but it is , isn't it.'

'This question here - how do you relate to your appliance - I think, "that bloody thing" and how clumsy it is....At the moment what we've got is a pretty crude set of 50's and 60's tools..'

(2) Individuals in the group indicated that their feelings of separateness to prosthesis could be attributed to lack of confidence in current control methods, and also to uncomfortable suspension methods.

'...when your working with an artificial limb , it's like doubly concentrating for that arm as well as your own arm..to enable you to do a certain job....if you can't do it, you lose self-confidence in that limb and it just becomes a dead weight.'

'It doesn't matter how much it looks like a hand it's not connected to your brain, so you will always have to look at it and concentrate on it..you always have to be looking at what your doing...the first time I used it <cosmetic prosthesis> I stood up went like that <motions swing across table>. Cleared the table of drinks,..it was very embarrassing...I don't wear it anymore.'

'... if it was comfortable it would feel more like you, more like part of you and you'd want to wear it more'

Focus Group Continued

(3) Many amputees made limited use or no use of their prosthesis because of suspension problems and / or an uncomfortable fit.

'… the worst thing for me is discomfort'.

'It's the discomfort of them; it's the thought of putting them on. They rip you to pieces'

(4) The hard surfaces of existing prostheses caused problems, especially when dealing with children.

'You can't play with a child when you've got it on <indicates prosthetic socket> without being scared to death...when I'm playing with my grandchildren I'd rather take my prosthesis off.'

' She <young child> really has hurt herself against that <elbow position of the prosthesis> and I have really cringed…It's really rock hard there'

(5) In order to function 'normally' amputees indicated they need to carry a number of different attachments for their prosthesis and considered this unsatisfactory.

'…it's like walking around with a bag of tools to do one or two different jobs…you need a different appliance to do every job you want to do, It is very difficult to do that'

(5a) Some amputees had made attachments or adaptations for their prostheses and indicated that the ability to adapt the prosthesis was important.

'…I've made that <indicates aerosol cup on end of a split hook to move the gear lever in a car>. I couldn't get anything else to use a manual gearbox car.'

'…I wish I could take that bit of meccano set off and put another bit of meccano set on, that would make it more adaptable.'

'…I have many attachments and I make my own…'

(6) The amputees recognised that natural movement was an essential part of cosmesis. One amputee recounted perceptions when he had viewed himself on video (before viewing the model hand).

'You see a person sat on the bus with their arm like that <arm across lap>…and you think that's an artificial hand.. You watch the way people walk, or the way people sit …I've become quite good at spotting people who wear artificial limbs... We use a video at work. And I've seen myself on that…I've noticed…just how artificial the movement looks, and the way the limb works…your hand has all this flexibility of movement and I just don't think you can replicate that..'

Another amputee shared his comments on viewing a lady with a cosmetic covered myoelectric prosthesis on the introductory video.

'The thing that stuck in my mind was that she hadn't got a wrist, in the prosthesis. And it's obvious to anybody.'

Focus Group Continued

(7) Initially, before introduction of the model hand, amputees were divided between those prioritising function and those prioritising cosmetic prostheses. The group did not expect both needs to be met by a single device.

'..I don't think you can get both <cosmesis and functionality> in one appliance. I think you need two separate ones.'

'..part of the process of losing a limb..coming to terms with it is to see it as a tool…If you hang on to the idea of a replacement limb it's much more difficult to live with it..'

'I see it as a tool and something I have to use to get on with my life.'

'It's a TOOL that's all it is, it's a TOOL'

'I don't really care what it looks like…I'd love to be able to make it work.'

'..from a female point of view, I don't agree with that….I only use it cosmetically and I like it to look part of myself….I've never had anything that does anything and now I'd like one to go out with that looks nice..and one that can help me do various things around the home'

'Mine does nothing...It's got to look cosmetically good for me to wear it….I won't go anywhere without mine. I have to look like everyone else…without it I feel off balance'

(8) The presentation of the model was followed by a change of perception towards the idea that a single device could embody both cosmesis and functionality.

'Ideally you'd <indicating the rest of the group> like it to be cosmetically good and to work properly as well.'

'If your going down, in a new direction, it needs to look cosmetically good and be functional.'

'…I think that's what we should be aiming for...To make something that looks like a hand and functions like a hand, as near as what can be done with the technology that we've got.'

'…There's the cosmetic side and there's practical side, and yes please, we'd all like both...'

(9) Some amputees indicated that their main need was for a cosmetic device, and this was extremely important for their self-confidence. However, one member of the group stated her views had changed since becoming a parent because of the wide range of tasks required for child-care. Arguing that her cosmetic needs required the limb do more for her to appear normal.

'…. I've got a one year old baby and now I could really do with something that does something a little bit more than this <point to cosmetic hand>…Really my worse bit now is that I've got to take her <young child> places where probably every other mum is fully limbed, and I'm not. And I find that people watch how I do things with her, and I could just do with something that this arm <cosmetic prosthesis> would do..'

Focus Group Continued

(10) The group shared her perception that upper-limb prostheses were much less successful than lower-limb prostheses. One user, who also had a lower-limb prosthesis, stated that her artificial leg was satisfactory and met her needs and expectations, however, her artificial arm was very unsatisfactory.

'The legs are fantastic.'

'…legs seem more advanced than arms. Arms seem to have stood still.'

(11) The group showed consensus to paying significant sums of money privately if the a high technology limb replacement was available.

'Anyone would pay a house, the price of a house to get a hand. There isn't anybody here who wouldn't pay that, in fact they'd probably pay twice that..'

'Yes, if it we're available you'd have it.'

(12) The focus group component of the design methodology was seen as positive.

'I think the fact that your coming and asking the people who have to wear them is important. Because I think that generally things were made, then fitted to people, without actually asking the people what their needs were.'

Discussion

Creative Reasoning

The method of design using creative reasoning to extract analogies from the original anatomy has resulted in ideas that when detailed and dimensions are practical for prototype manufacture.

Physical Model Production

The production of models as an integral part of the design process has enabled ideas to be internally evaluated and revised if necessary. An example of this can be seen during the design process. A design concept based around commercially available spherical bearing was rejected when a simple model was made and the comparatively large weight of the components appreciated.

Prototyping Methods

The prototyping methods used appear appropriate for producing the multiple relatively simple joint forms. However, the machining strategies used have resulted in rectilinear forms unlike the complex forms of the human joints. It would appear more appropriate to investigate further prototyping techniques to achieve more complex forms, as well as articulation closer to the skeletal original.

Use of Physical Models for Evaluation

Using the tendon pretensioning rig entirely unforeseen 'latching and coupling' effects were observed indicating both closer observation of tendon routing and the limits of mechanical analogy. The coupling problem of wrist and fingers indicates that a mechanical analogy may not be appropriate. Further literature review indicates that this mechanism is controlled in the human by low level synapsing within the spinal cord (Fox 1993). Review of robotics literature indicates that current research is investigating how these mechanisms might be implemented into algorithmns for electronic control systems (Hannaford et al 1995). The pretensioning rig also indicated that a system based on exclusively extrinsic actuating tendons might be prohibitively complex. The literature indicates that current research is underway investigating novel materials that might provide an analogy for the intrinsic' muscles of the hand (Della Santa et al 1997). Which may lead to simpler control systems.

Comparison with robotic hands indicates that kinematic design principles elucidated in the research may hand an application in a future in telepresence research. As the articulations of the model prove a close match to those of the human 'master' control glove compared to the other devices.

Models have played a crucial part in the evaluation of the 'final' design. Their use has been valuable in extracting valuable details about where the models are considered to deviate from the anatomy.

From the goniometric data it can be seen that some of the model joints require revision to their ranges of movement to make them a closer analogy to the human joints. This can can be achieved through revisions to the 'stops' in the designs without changing their underlying principles of articulation.

The model has enabled expert qualitative criticism on designs, and this has often indicated practical solutions. An example of this came from the evaluation of Dr. N. Williams, who indicated further reference to the anatomy might indicate solutions to the problems of latching of the model joint.

Use of Physical Models for Evaluation (cont.)

This qualitative review was shown to compliment the quantitative assessment of the model joints. For example, the comparisons of the ranges of movement of the model and human MCP joints in of movement data for adduction / abduction are approximately 10 degrees more for the model joint. This can be remedied by simple revision to the joint stops. However, from Dr. Williams qualitative assessment of these joints it was indicated that the human MCP joint exhibited constraint that resulted in a complex path of circumduction, and this was absent in the model. Therefore, indicating more extensive revision of the model MCP joint

Potential for Design Principles to be Embodied in a Future Prosthesis

It has been shown that the resulting model hand assembled from these joints is able to be configured around 'ergonomically' designed objects such as door knobs, handles etc. Therefore, in terms of articulation, the model shows functional potential. The hand is of a similar scale to that of a skeletal hand and can be fitted within gloves designed around the dimensions of the human hand. Once inside the glove the fingers can still be flexed using the extrinsic tendons. This suggests a potential cosmetic benefit to the model design.

Review by a prosthetics manufacturer strongly indicated that the modularity of the joints was desirable. His views indicated that modularity may be a means of introducing a new complex prosthesis at a price tolerable to the prosthetics market.

Wider Issues Raised by Focus Group

The model has also has served as a means of changing user's views. End users previously showing polarised views, in regarding prostheses categorised as either functional or cosmetic, showed their views to be changed by exposure to the model.

The focus group provided the amputees with a forum for which they indicated issues going beyond those posed by the moderator. From the proceedings of the focus group it appeared the design teams (researcher and supervisors) basic assumption that amputees were not happy with existing prostheses was reinforced. However, a key issue to the amputees was the need for a better, and more comfortable means of suspending the prosthesis from their body.

Additionally, it was indicated that the exoskeletal approach to prosthesis deign was not considered acceptable. This was due to unsuitability of the rigid exoskeletal socket. Performing child care activities was indicated as especially problematic due to these rigid surfaces.

This cycle of the research has shown that the creative reasoning process can extract analogies from the anatomy that are practical for prototype manufacture.

The use of CNC processes is appropriate for the production of multiple simple joints.

Design principles appear to be most successful when they are a close analogy of the human joints.

Development of a Skeletal Model Arm

5. Development of Anatomically Analogous Forearm Joints

6. Development of an Anatomically Analogous Elbow Joint

7. Development of an Anatomically Analogous Wrist Joint and the Evaluation of the Skeletal Model Arm

Overview

The work presented in the following three chapters represents the second cycle in the development of the articulated model skeletal arm.

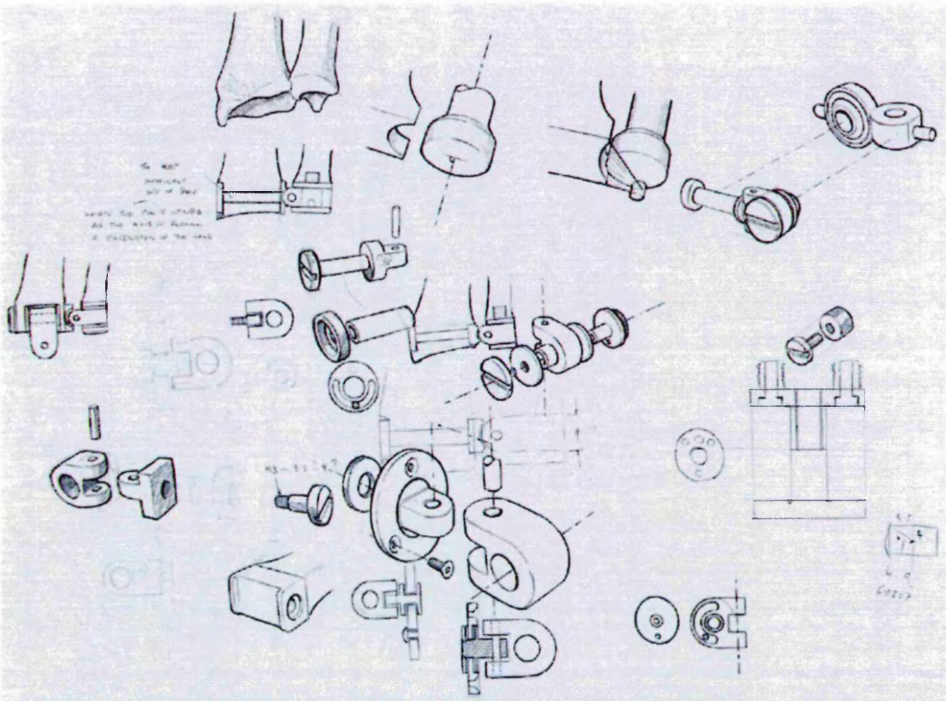
The creative reasoning process appeared successful in the development of the skeletal model hand, therefore, it is used again in this cycle of development.

From the evaluation of the model hand it was evident that the most successful analogies of the joints were those that were the most closely observed in the creative reasoning stages. Therefore the following chapters are characterised by more thorough observation and literature review.

As with the model hand, extensive qualitative evaluation has found not to be meaningful until significant sections of the articulation of the limb are complete. Therefore, the main evaluation features at the end of these chapters once the whole model limb has been assembled.

Similar to the presentation of the chapters on the model hand the following chapters use the drawing produced as part of the development work to explain the path of development of the model limb.

5. Development of Anatomically Analogous Forearm Joints



A Sketch Sheet Used in the Development of Forearm Joints

The forearm was taken as the next anatomical segment for analogy as it is the next proximal section of the upper-limb. Additionally, the design of joints for an analogous forearm are required to complete the articulations evident at the level of the wrist.

The methods used to study the joins of the forearm were similar to those used in the chapters detailing the development of the model hand. However, it was found that additional mathematical analysis was required in the design stages to assess potential linked joint configurations

The diagram above is an example of one of the sketch sheets used in the development of the forearm joints. Details from such sheets are used as figures and referenced in the text to elucidate the development of the joints

This chapter starts with a summary of the prosthetic devices that provide articulations that roughly approximate those of the forearm. A brief description is then given of the anatomical movements of the forearm, pronation and supination. This is followed by the detail of the creative reasoning process applied to the study of the forearm, and the development of analogous concept joints.

This chapter finishes with the movements permitted by the joints designed being quantitatively compared with an intact human arm using specially designed splints.

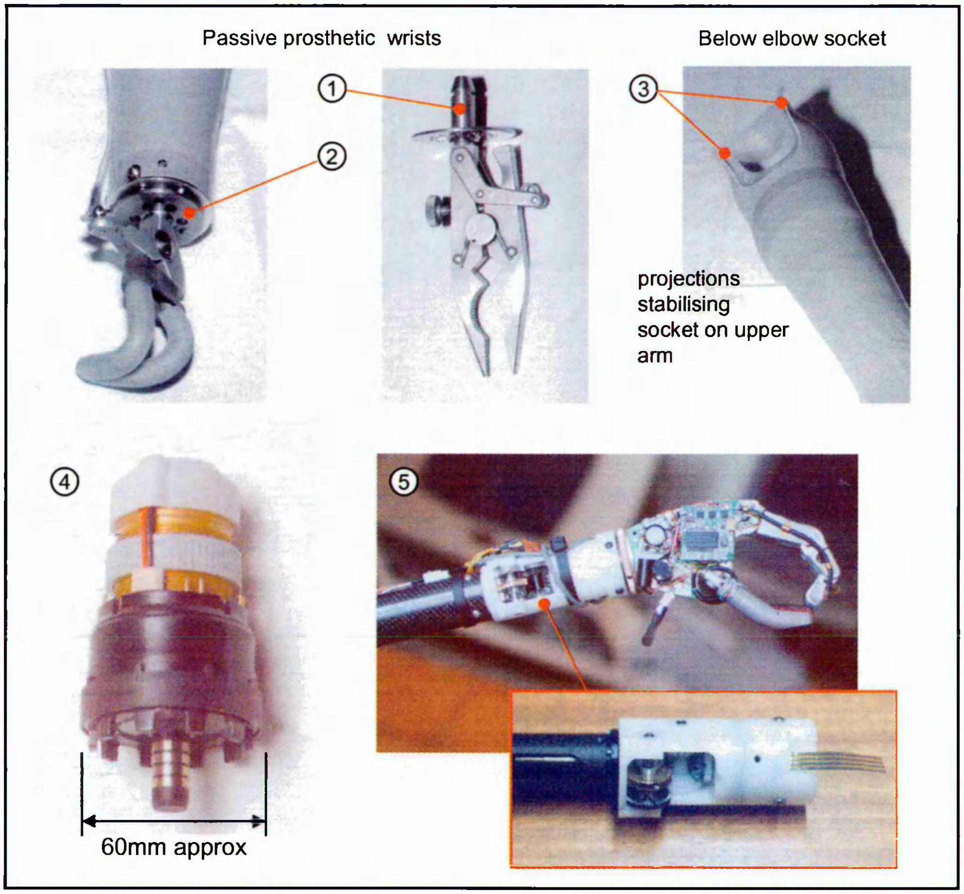


Fig 5.1 Prosthetic Wrists offering Pronation and Supination

Body-powered upper limb prostheses usually incorporate a passive wrist. This often consists of an axial strut (1) around which the terminal device rotates. The strut is connected to a circular steel plate with a concentric ring of holes drilled through it (2). A correctly positioned detent on the socket locks the axial angle of the terminal device by projecting though one of the holes in the ring. These devices are for use by unilateral amputees, as their action relies on the amputee orientating their prosthetic wrist with their intact hand, before attempting a task. The mechanical rotation of the wrist becomes important as it has been regularly observed that below elbow amputees showing some residual pronation and supination have prosthetic sockets stabilised on their arms in such a manner that this rotation is locked (3) (Martin 2000). The mechanical wrist arrangement permits the wrist unit to be rotated through 360 degrees much farther that the normal human range of motion in pronation and supination (Kapandji 1982).

The fitting of powered prosthetic wrists is becoming more common (Martin 2000). However, problems still remain in their control (Datta and Brain 1992) and from the increased weight and bulk to the prosthesis (Martin 2000). It can be seen from the Otto Bock powered wrist shown (4) that, like the elbow, to achieve appropriate power from a 6 volt DC electric motor requires a bulky gear mechanism. Figure 5.1 (5) shows current research into reducing the bulk of this gear mechanism by using a differential type gear arrangement. In this mechanism planetary type gears attached to the motor that drive a “worm” gear which is then connected to a crown wheel that finally drives a bevel gear connected to the terminal device.

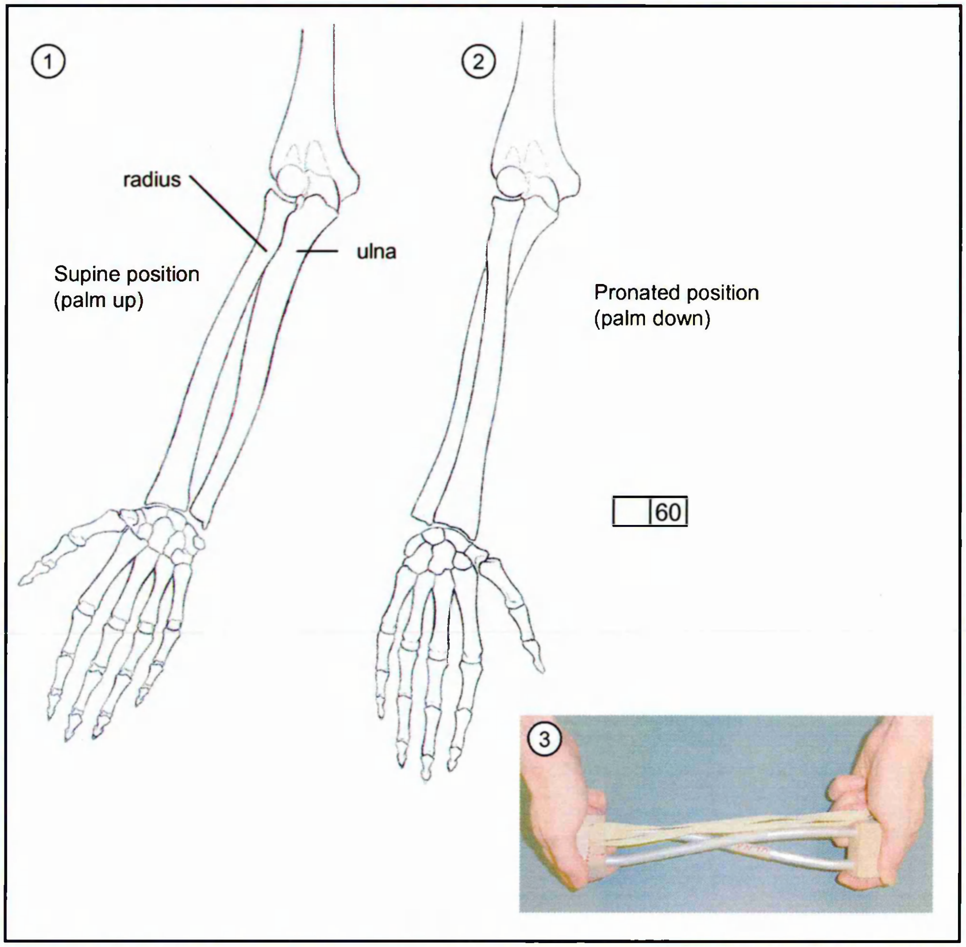


Fig 5.2 Initial Sketch Ideas

Rotation of the human forearm occurs by the rotation of the radius bone about the ulna (Smith et al 1996). With the arms by the sides and the palms facing forward, the forearm is said to be supinated. If the palm is then rotated medially towards the body with the palm facing backwards, then the forearm is pronated. In the supinated position (1) the radius and ulna run parallel to one another, whilst in the pronated position the radius crosses the ulna (2) (Kapandji 1982). For this to occur the bones need to be cranked along their length. To understand the cranked nature of these forms a simple model was made using two aluminium rods (3).

This mechanical arrangement appears much more complex than that of the simple axial strut necessary to achieve a axial rotation. However, the strength of the hand may be attributed to the comparatively large extrinsic muscles of the hand that are situated in the volume of the forearm (Kapit and Elson 1993, Chao et al 1989). The extrinsic finger tendons must pass through the wrist. This passage would not be possible if the wrist simply rotated on a single axial strut (Kapandji 1982). Kevlar bands were used on the simple model to examine how the extrinsic tendon action remains unimpeded by forearm rotation (3). To replicate the movement of the forearm closely for cosmetic purposes, and to allow the potential for anatomically analogous actuation the apparently more complex anatomical solution to long axis wrist movement was chosen for a basis of mechanical analogy.

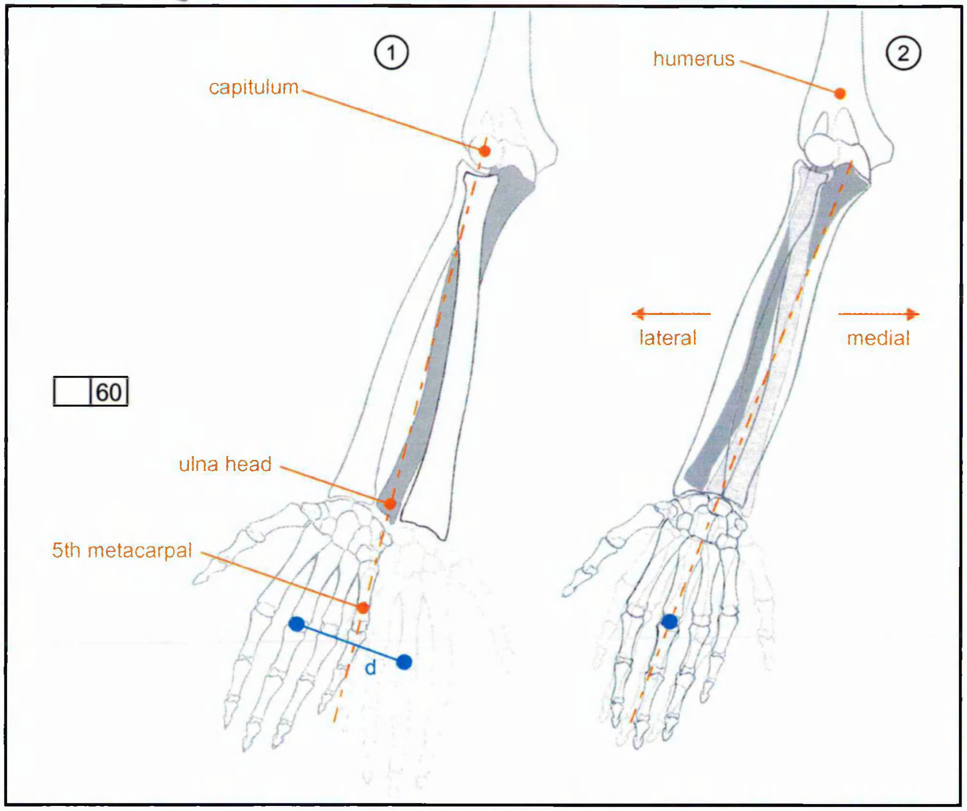
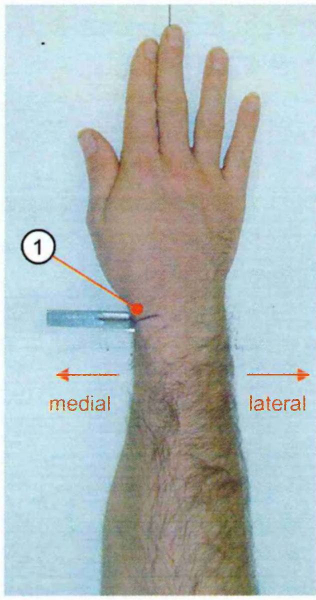


Fig 5.3 The Axis of Forearm Rotation

Biomechanics texts indicate that the rotation of the forearm can be considered to occur along a line extending from the centre of capitulum to the approximate centre of the head of the distal ulna (Smith et al 1996, Norkin and Levangie 1992). It can be seen from figure 5.3 (1) that if this centre line is extrapolated to the hand then it extends through the fifth metacarpal (small finger). Therefore, as the forearm is rotated, a point on the 3rd metacarpal can be seen to move a distance *d*. However, other anatomical texts additionally refer to an 'axis of pronation-supination' (Kapandji 1982). This axis extends through the centre of the third metacarpal, with the effect that the hand may be rotated without consequent translation of the third metacarpal (Amis 1990). During forearm rotation the distal ulna appears to translate medially to laterally as the arm is pronated and reverses in direction as the arm is supinated. Kapandji indicates that when the elbow is flexed at 90 degrees, apparent translation of the distal ulna head may be due to compensatory movements of humeral rotation (Kapandji 1982). In order for the distal ulna head to translate without compensatory rotation of the humerus requires either that there is a rotation between the humerus and proximal ulna (humero-ulnar joint), or that the ulna itself is deforming. There is no radiographic evidence for distortion of the form of the ulna contributing to pronation-supination movements, therefore, debate has focussed on the existence of a humero-ulnar medial to lateral rotation. Using LED's mechanically connected to cadaver limbs, (Youm et al 1979) report photographic results of distal ulna translations during pronation and supination movements. Additionally, Amis states medio-lateral rotation at the humero-ulnar joint of the order of 10 degrees occurring during pronation and supination (Amis 1990). However, other researchers using radiographic techniques have detected no medio-lateral rotation at the humero-ulna joint (Chao and Morrey 1978)



y = recorded values (mm)

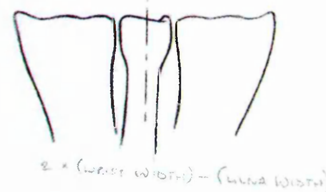
Width w (mm)
58.23
58.23
58.17
58.21

Width u (mm)
22.05
22.10
22.25
22.13

Y (mm)
73.0
72.5
75.0
74.0
73.0
77.0
74.0

(2)

x = 2(wrist width)-(ulna width)*



Expected value x=(2*w)-u (mm)
(2*58.21)-22.13) = 94.29

Difference x-y (mm)
94.3-74.0= 20.3

Fig 5.4 Initial Pronation Supination Measurements

Due to these uncertainties it was considered that measurements were needed to inform the design process. It was considered appropriate to a use a male with 50th percentile hand dimensions as the subject for these measurements. The same subject had been used in previous experiments which ensured continuity with the development of other analogous joints.

Initial measurements of wrist width, and ulna head were taken using digital vernier calipers. The wrist was palpated to find the styloid process of the radius (1), which was marked on the skin. This was chosen as due to minimal tissue coverage over this anatomical feature. The arm was then positioned on a sheet of paper with a line ruled on it. First the olercranon process (elbow bulge) was placed on this line, then the arm was positioned so that the third finger was aligned with the same line. With the arm in pronated position, using an engineers square, a mark was placed on the paper corresponding to medial position of the styloid process. This procedure was repeated with the arm in supinated position. The distance perpendicular to the scribed line on the paper between the marks was then recorded using a steel rule accurate to 0.5mm. The position of the hand in pronation and supination was approximately parallel to the plane of the paper in transverse section, Therefore it was reasoned for the ulna to remain stationary during this movement, a value of (2*(wrist width)-(ulna width)) would be expected to be the recorded distance on the paper (2).

During these initial experiments the wide error in the recorded results show that it was difficult to ensure humeral rotation was not influencing the results. However, a difference of approximately 1/3 of the width of the wrist between the expected result and the recorded result indicated that the mechanism of pronation-supination may be more complex than that of a single axis (figure 5.2 (1)). Consequently, more observational drawing from skeletal models was pursued to find indications of the mechanisms for more complex rotations.

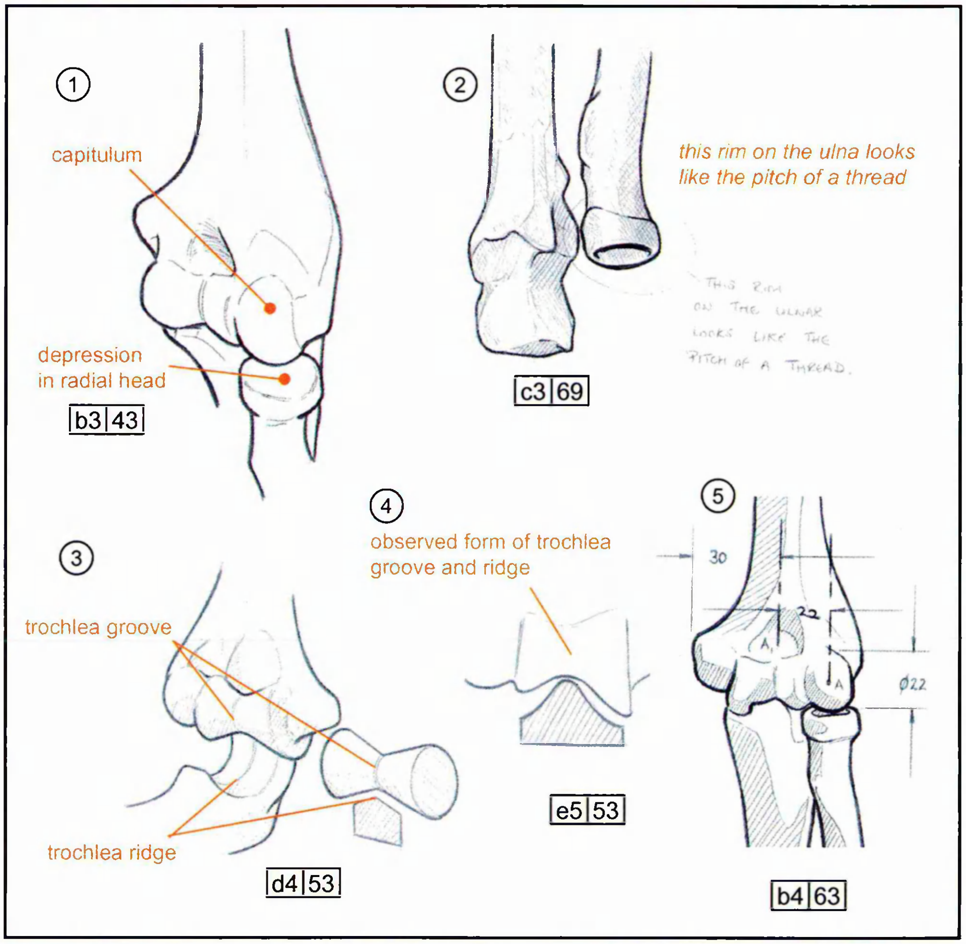


Fig 5.5 Observational Drawing of the Forearm Joints at the Elbow

Observational drawing studies from three-dimensional skeletal models indicated the capitulum to be approximately spherical, and the proximal head of the radius to possess a similar spherical concave depression. These observations were subsequently checked against the anatomical literature (Norkin and Levangie 1992) and was found to be correct. Initial literature review indicated that the humero-ulnar joint possesses a single degree of rotational freedom (Norkin and Levangie 1992). This possession of a single degree of freedom has been attributed to the highly contiguous fit of the trochlea ridge of the ulna within the trochlea groove (Kapandji 1982). However, the trochlea groove and trochlea ridge of the skeletal models was palpated and a large amount of freedom of movement was perceived. From observation of the form of the trochlea, it is evident that the groove is not sharp but akin to the depression around an hourglass (4). An observation confirmed in the literature (Norkin and Levangie 1992). The skeletal trochlea ridge of the ulna appears slightly sharper in its convexity than the trochlea groove is concave. This was initially attributed to the absence of cartilage in the skeletal joint. However, reference to photographic cross-sectional studies indicate the trochlea and trochlea notch not to be totally contiguous on the lateral border; possibly permitting a medio-lateral rotation (Guyot 1990). Due to the observed differences in the trochlea notch and groove it was reasoned that if a medio-lateral articulation exists it is likely to be close to the centre of the trochlea groove. Estimates of the distance between the centre of the spherical capitulum to the centre of the trochlea groove were made and marked on the observation drawings (5).

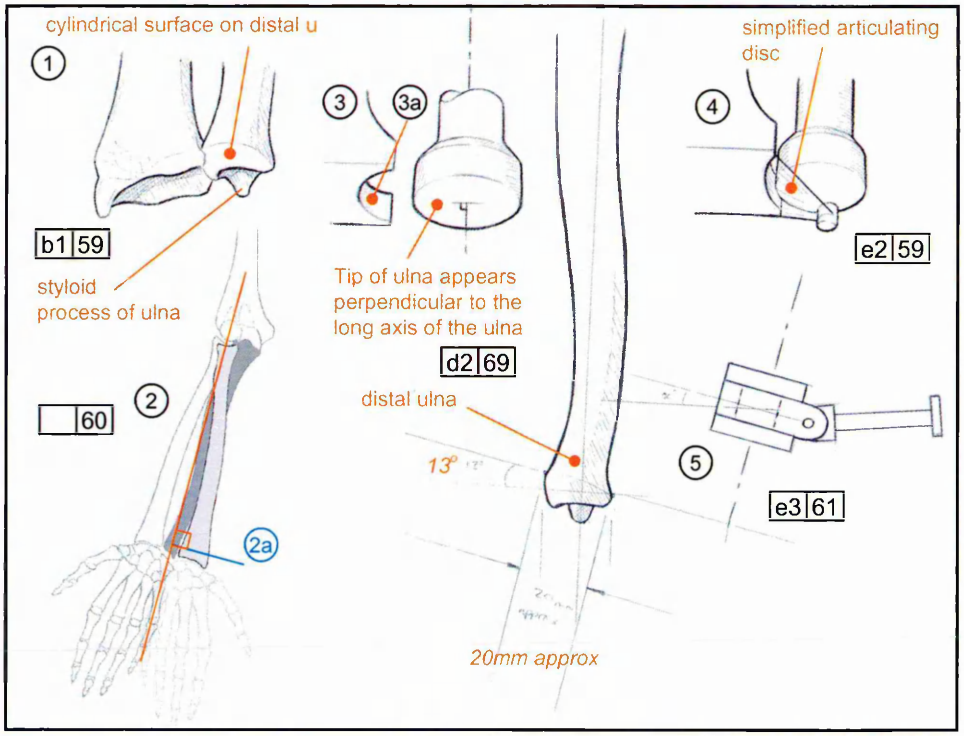


Fig 5.6 Observational Drawings of the Distal Radio-Ulnar Joint

The observational studies of the radius and ulna at the elbow were followed by studies of the distal radio-ulnar joint, as both these joints are stated as coupled during forearm rotation (Norkin and Levangie 1992). It was observed, and confirmed from the anatomical literature, that the distal radius possesses a concavity which articulates against a cylindrical surface on the distal ulna (1) (Kapandji 1982). From observational studies of this cylindrical surface, it did not appear to be orientated at an angle perpendicular to a line originating from the centre of the capitulum and extending to the centre of the head of the ulna (2a). Instead, the observed surface appeared angled either perpendicularly to the longitudinal axis of the ulna , or angled slightly proximally, medio-laterally. This apparent angle has been attributed to the truncation of the cylindical surface against the form of the distal ulna (Kapandji 1982). However, from observational drawing the whole cylindrical surface appears angled rather than truncated. Additionally, the distal tip of the ulna (3) was observed to be roughly perpendicular to the longitudinal axis of the ulna.

Further literature review indicated that the ligamentous structures between the radius and ulna are crucial in resisting translation of the radius relative to the ulna (Skahen et al 1997). Although these could not be observed on the skeletal models, it was reasoned that the role of the most distal radio-ulnar ligament, the articular disc (Norkin and Levangie 1992) might be deduced from observation of it's insertions and articulating surfaces. The articular disc inserts close to the ulnar styloid process (4) and onto the medial and frontal aspect of the of the radius (Kapandji 1982). It was reasoned that if this 'disc' is considered inextensible then the near perpendicular rim of the ulnar would guide the radius bone through a similar path, perpendicular to the long axis of the ulna (5).

It was noted that the concavity in the radius bone (3a) is larger in radius than that the radius of the ulna. Literature review indicated that radiographic research had found this in the intact distal radio-ulnar joint (Cone et al 1983).

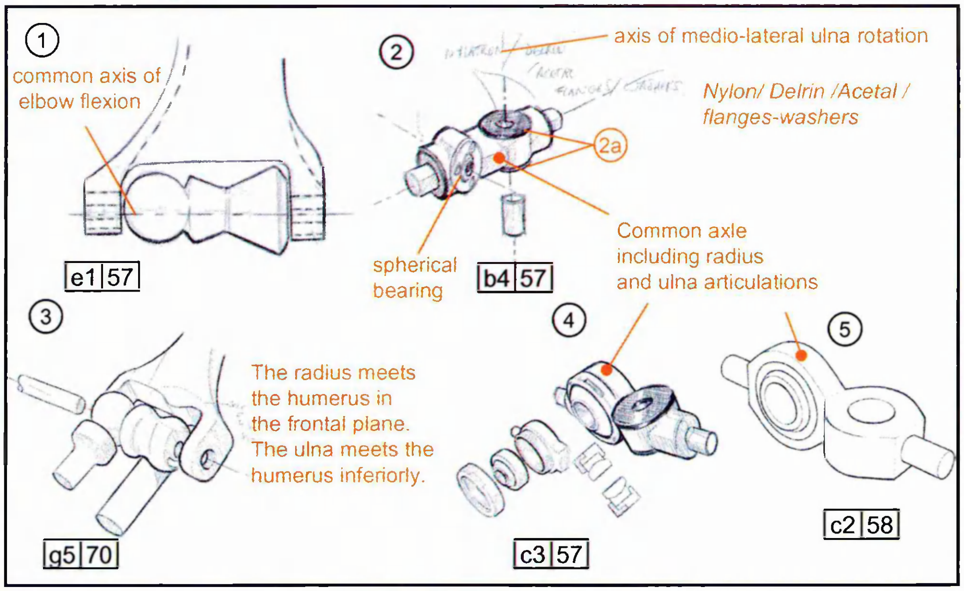


Fig 5.7 Development of Proximal Radio-Ulnar Joint

It was observed, and checked against the anatomical literature, that the elbow flexes on a common axis, that can be considered to run through the centre of the capitulum and the centre of the trochlea (Norkin and Levangie 1992). Therefore, an analogy was considered placing the spherical feature of the capitulum and grooved form of the trochlea onto a single axle (1) (see also chapter 6). Initially, the proximal capitulum to ulna joint was drawn as a ball and socket, however, this idea was superseded by ideas focussing on the use of a spherical bearing. The spherical bearing was chosen as it permits a mechanical connection between the two parts of the joint through the centre of the joint. Whereas, a ball and socket might require additional analogies of the radial collateral ligament and annular ligament that connect the radius to the humerus and ulna (Guyot 1990). Previous sketchbook idea development of the MCP joint had indicated that it might be difficult to realise a practical joint using an analogy of ligaments (concept development - chapter 4). It was reasoned that if the spherical bearing was connected to an axle common to the ulna, then it would only need to have a small range of rotation movement, permitting pronation and supination, as the major rotation of flexion and extension would be achieved by rotation of the whole axle (2) relative to the humeral fixture. It had previously been determined that the centre of the trochlea groove might be the site of medio-lateral humero-ulnar articulation. This articulation was proposed as a single axle (2). However, due to the size of the surfaces in contact, observed in the skeletal models, it was considered appropriate to provide two large thrust washers on both sides of the joint (2a) to limit further rotations. Observational drawing indicated the position the radius against the capitulum to be approximately perpendicular to that of the connection ulna to the trochlea (3). Therefore, sketch ideas for the axle proposed that the axle be machined to allow the spherical bearing to be fitted at 90 degrees to the axis of medio-lateral rotation of the ulna (2).

Several ideas to fix the spherical bearing within the axle were proposed. These included a using an internal circlip and a threaded cap (4). These ideas were discounted on the basis of adding complication to the design and compromising the strength of the axle. Existing mechanical fittings for hydraulic actuators show spherical bearings force fitted into their fixtures. This more simple approach has favoured and adopted for the final axle design(5).

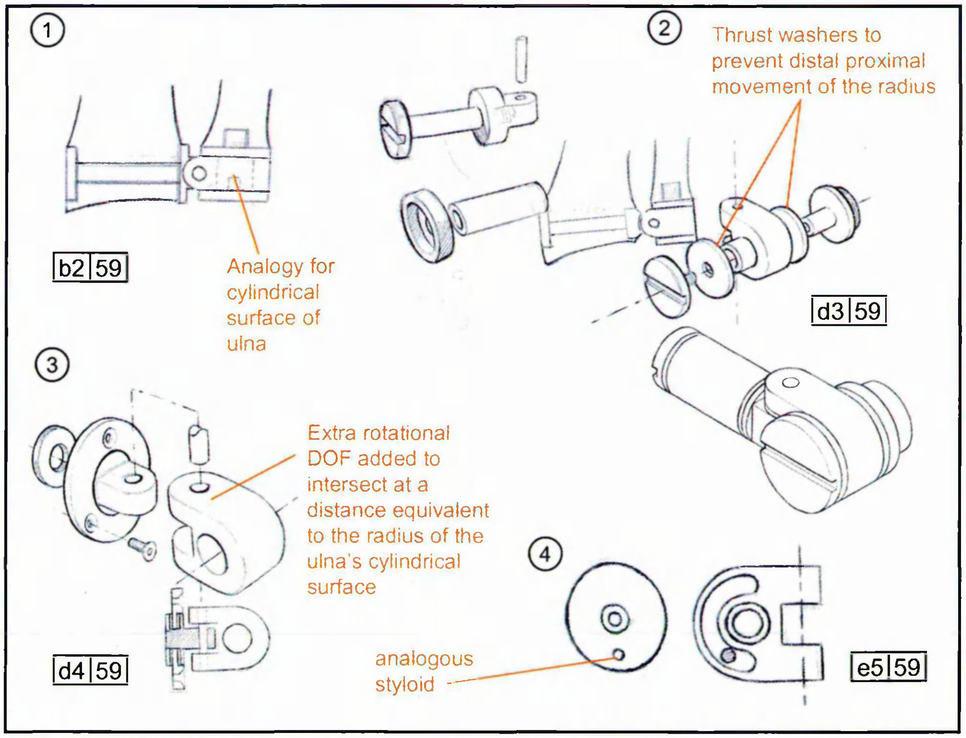


Fig 5.8 Development of the Distal Radio-Ulnar Joint

Observational drawing of the distal portion of the ulna indicated that movement of an articular disc against it this might act as a guide for the movement of the radius. As the distal surface of the ulna was observed to be perpendicular to the ulna's long axis, then this might guide the radius to rotate in a similar path. Sketchbook ideas were generated that would provide an analogy for the observed articulating cylindrical surface on the distal ulna (1). These ideas proposed the use of cylindrical bearings made from bearing plastic. A literature review indicated that 80 percent of the load on the hand is transmitted to the radius (Norkin and Levangie 1992). Consequently, plain thrust bearings were included into this joint design to design prevent uncontrolled distal or proximal movement of the radius relative to the ulna (2).

Observational drawing had highlighted the differences of curvature of the cylindrical surface of the distal ulna and the cylindrical segment from the distal radius. (Cone et al 1983) have reported relative movements between these surfaces during pronation and supination. It was reasoned that if relative angular movement must occurred, it would be at the interface of the two articulating surfaces; i.e.at a point on the radius of the curvature of the ulna head. Therefore, sketchbook ideas proposed adding additional orthogonal axes of movement to the distal radius, intersecting at a point equivalent to the radius of curvature of the distal ulna (3). Anatomical texts indicate that the range of movement of pronation and supination is effected both by the musculature of the arm but also by ligaments such as the quadrate, and anterior-posterior radio-ulnar ligaments becoming taut (Norkin and Levangie 1992). The form of the radius and area around the ulna styloid is also factor in limiting pronation and supination movement (Kapandji 1982). An analogy of the ulna styloid was proposed as means of limiting the angular movement of the model joint. This was proposed by to be a semicircular track in the rotating U component in which the analogous styloid would run (5).

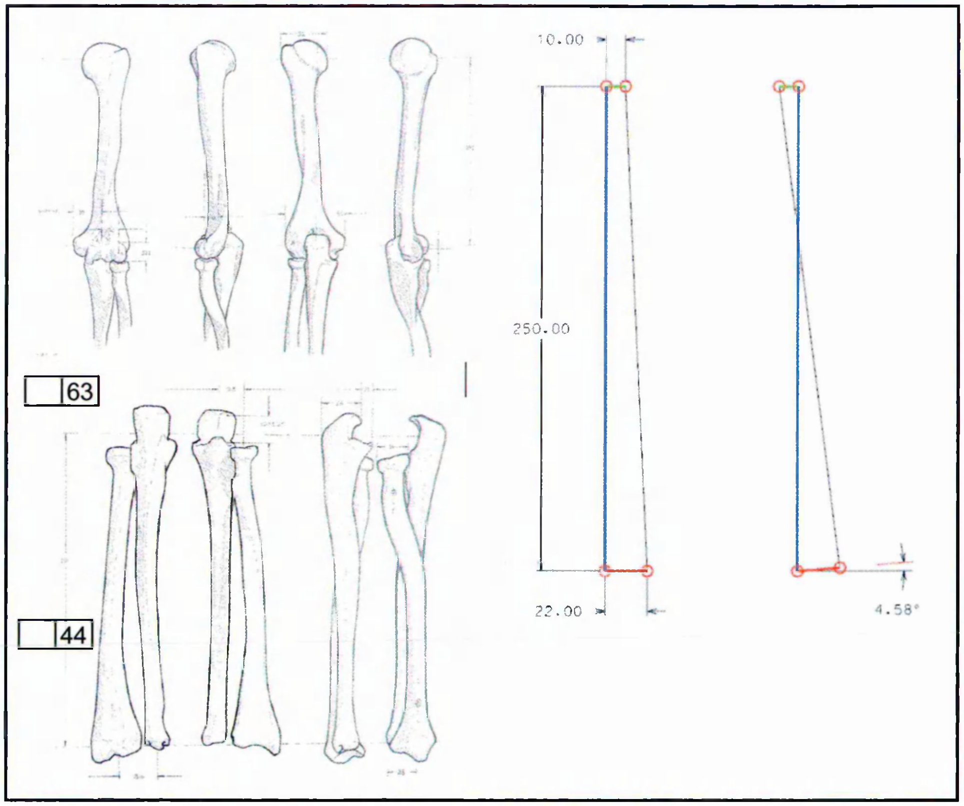


Fig 5.9 Observational Drawing

The observational drawing previously undertaken was used a basis for two dimensional trigonometric analysis to understand how the proposed joints would function when coupled together. During the observational drawing studies approximate measurements of anatomical features were recorded using a steel rule accurate to 0.5mm and annotated on these drawings. The distance from the centre of the trochlea notch to the distal centre of the ulna head (blue) was recorded as 250mm; the distance between the centre of the capitulum and the trochlea groove (red) estimated at 22mm, and the radius of the cylindrical surface on the distal ulna (green) estimated at 10mm. Two views of this set of links were draw, one in relating to the supinated position where the green link is to the right of the blue link, and a pronated view in which the green link has been rotated 180 degrees perpendicularly to the blue link to be to its left. As the bones of the forearm are not understood to deform under normal pronation-supination movements the links joining the articulations were considered of the same length in both cases. For ease of calculation the blue link was considered stationary to the remaining links rotating relative to that. Using simple trigonometry it was calculated that the red link would move through an angle of 4.6 degrees (counter clockwise) on full pronation. The red link represents the centre line on which ulna and radius rotations take place, however, these centres are colinear with the main axis of elbow flex in the model. In the initial measurements it was this axis that had been chosen as the datum from which parallel translations of the distal ulna had been measured. Therefore, considering the red link stationary a *clockwise* rotation of the ulna of 4.6 degrees represents a translation of Sin (4.58)*250mm = 20mm parallel to the red link. This was identical to the values recorded from the intact limb, and so the joins designs were detailed for prototype production.

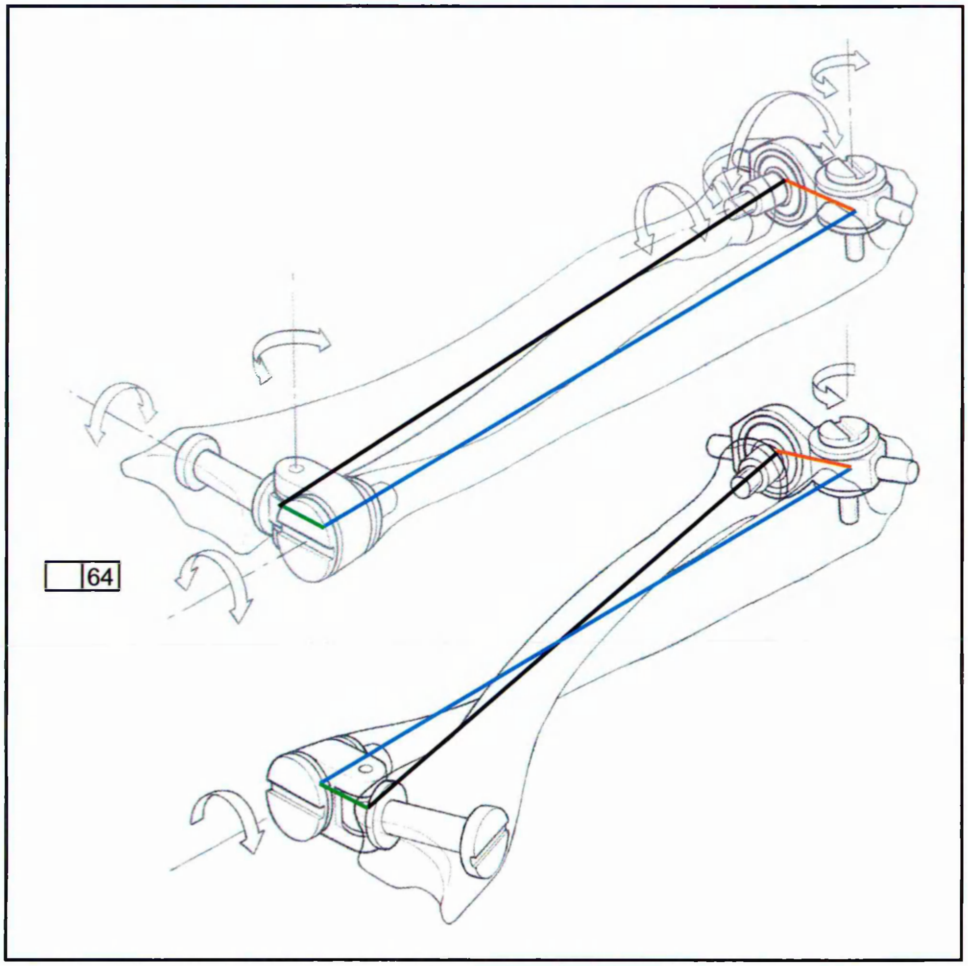
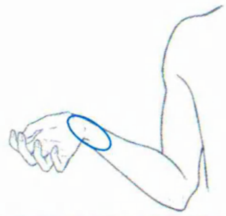


Fig. 5.10 Radius and Ulna Complete With Calculation Links

This figure shows how the intersection of the axes of rotation of the joint form the intersection of the links for the simple mathematical model used in the development of the joints.



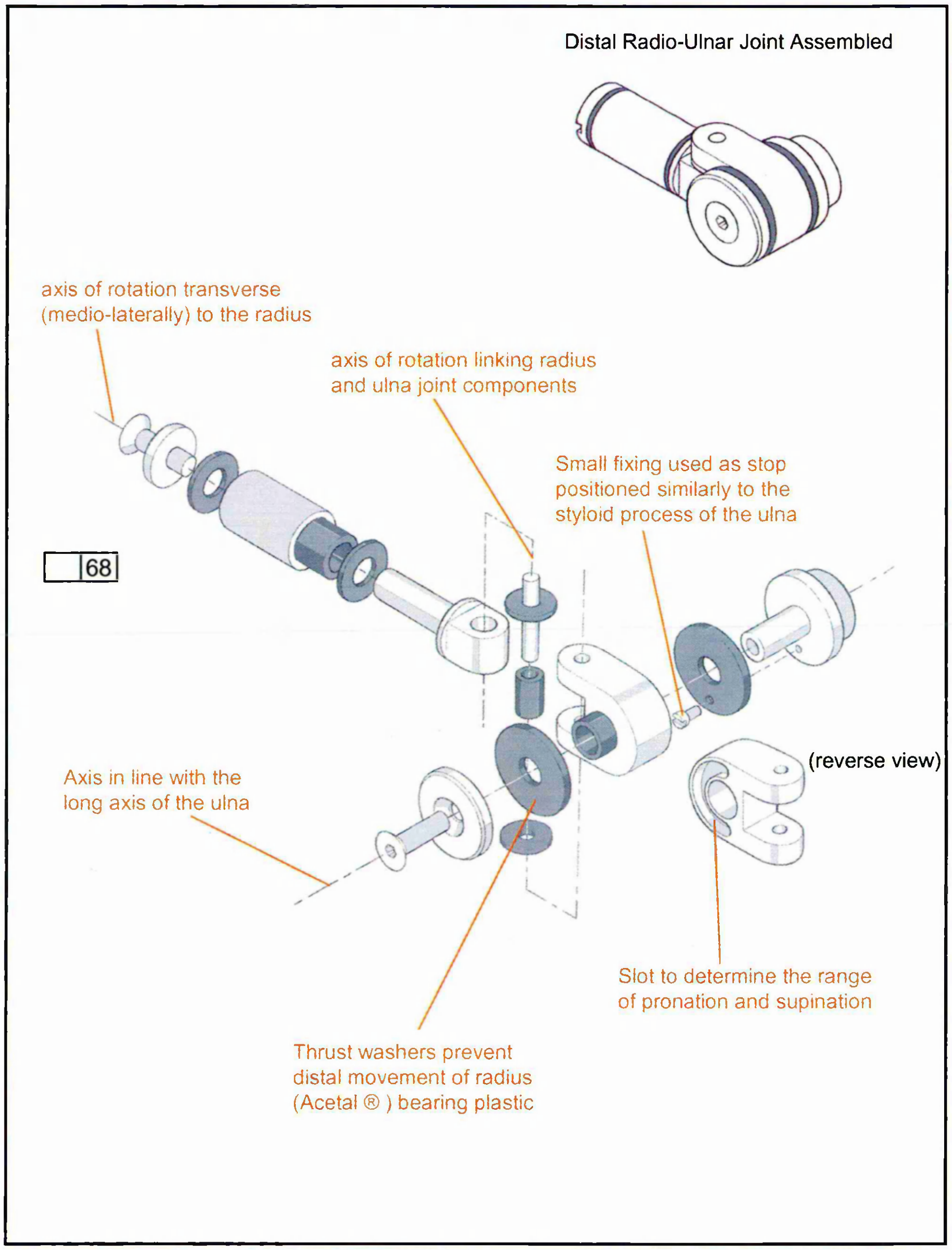


Fig. 5.11 Exploded View of the Distal Radio-Ulnar Joint

This figure shows the components of the model distal radio-ulnar joint, along with indications to the design principles embodied within the design.

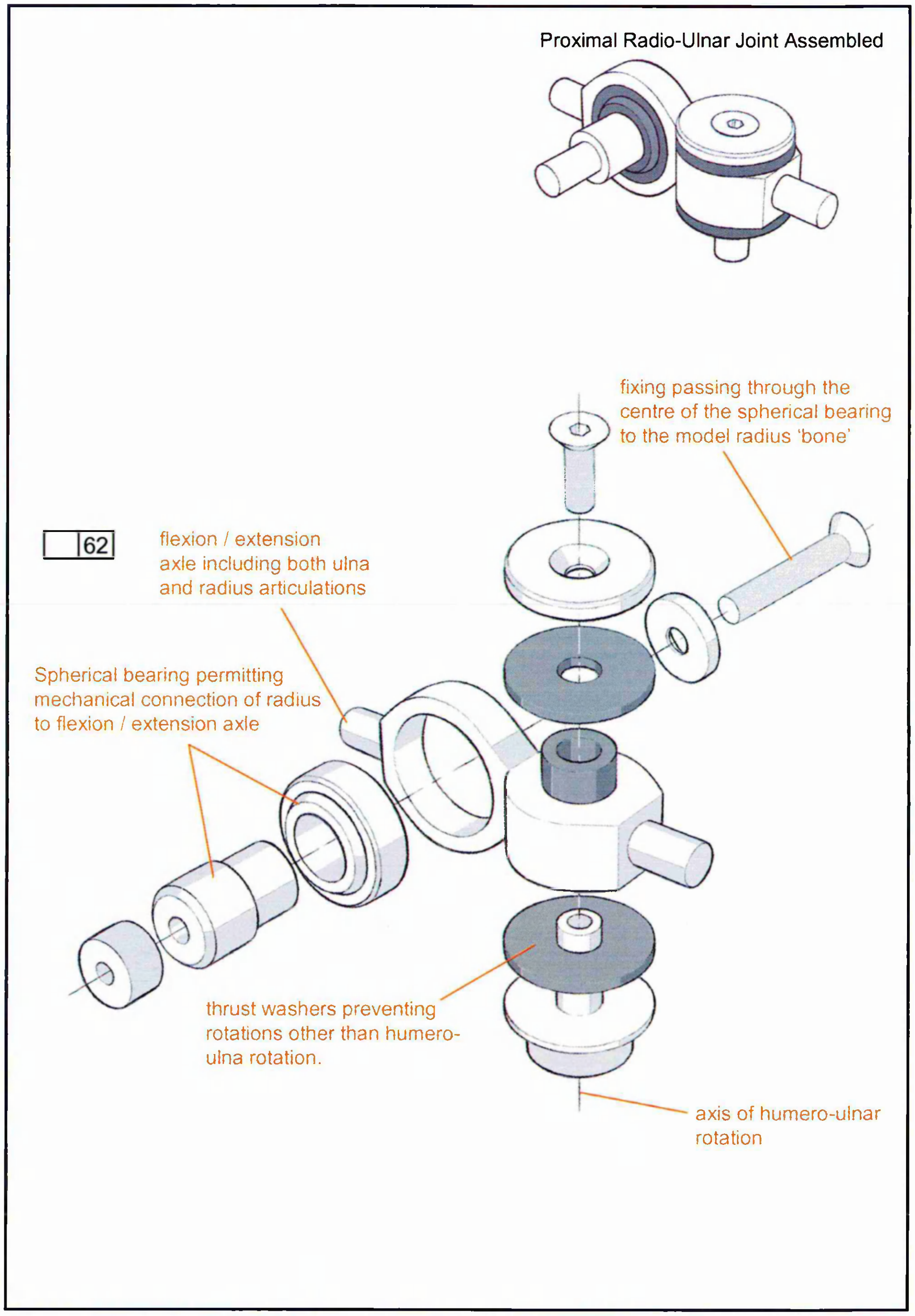
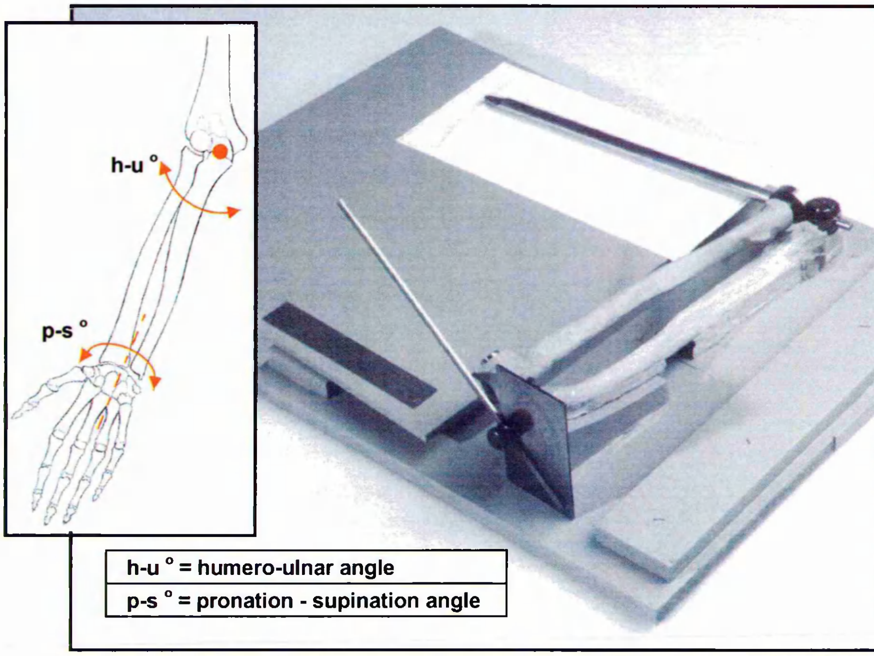


Fig 5.12 Exploded View of the Proximal Radio-Ulnar Joint

Similarly to the previous page this figure shows the model proximal radio-ulnar joint and along with indications of the functions of some of its components.



h-u °	p-s °
0.00	0
0.50	10
1.00	20
1.45	30
2.00	40
2.75	50
3.22	60
3.75	70
4.22	80
4.33	90
4.58	100
4.97	110
5.22	120
5.23	130
5.30	140
5.33	150
5.17	160
4.83	170
4.53	180

Fig 5.13 Joints Measured within Resin Casts of Human Radius and Ulna

The proposed articulations of the model joints, although requiring close tolerances, were all simple geometrical forms. Therefore, it was considered that conventional machine tool processes would be appropriate for prototyping. The structure of the joints was specified to be a 'freecutting' mild steel, whilst an Acetal ® copolymer was chosen as a suitable bearing plastic. As with the development of the wrist and finger joints many ancillary holding 'jigs' were required.

Once the joints were made, the skeletal model which had served as the subject of observational drawing, measurement and calculation, was used to make high definition silicone rubber moulds of the radius, ulna and humerus bones. Once these moulds were complete a low contracting rigid polyurethane casting resin was poured into the mould cavities. An MDF mounting board was made with a line scribed parallel to one of its edges.

The resin bones were then taken from the moulds and arranged in a posture with the ulna and radius flexed at approximately 90 degrees to the humerus, with the long axis of the ulna parallel to the scribed line on the mounting board. The radius and ulna were positioned in supinated posture, whilst a two part polyester resin of a contrasting colour was applied between them. Once this had cured the humerus was removed and the mounting board taken to a vertical milling machine. The scribed line on the board was aligned with one of the axes of the milling machine. The centre of the trochlea notch was approximated on the resin cast, and this was taken as a datum. Using this datum 'pockets' were machined into the casts to insert the joints at positions corresponding to the calculated link lengths. The joints were secured to the bones with more polyurethane resin. Subsequently, resin binding the bones together was removed and the model was pronated and supinated. A mark was placed on the styloid process of the model radius and a lightweight extension arm fixed to the flexion-extension axis proximal radio-ulnar joint. The model ulna remained firmly fixed to the mounting board with polyester resin. Measurements were then taken of the angular position of the proximal flexion extension axle with respect to changes in angle of pronation and supination.

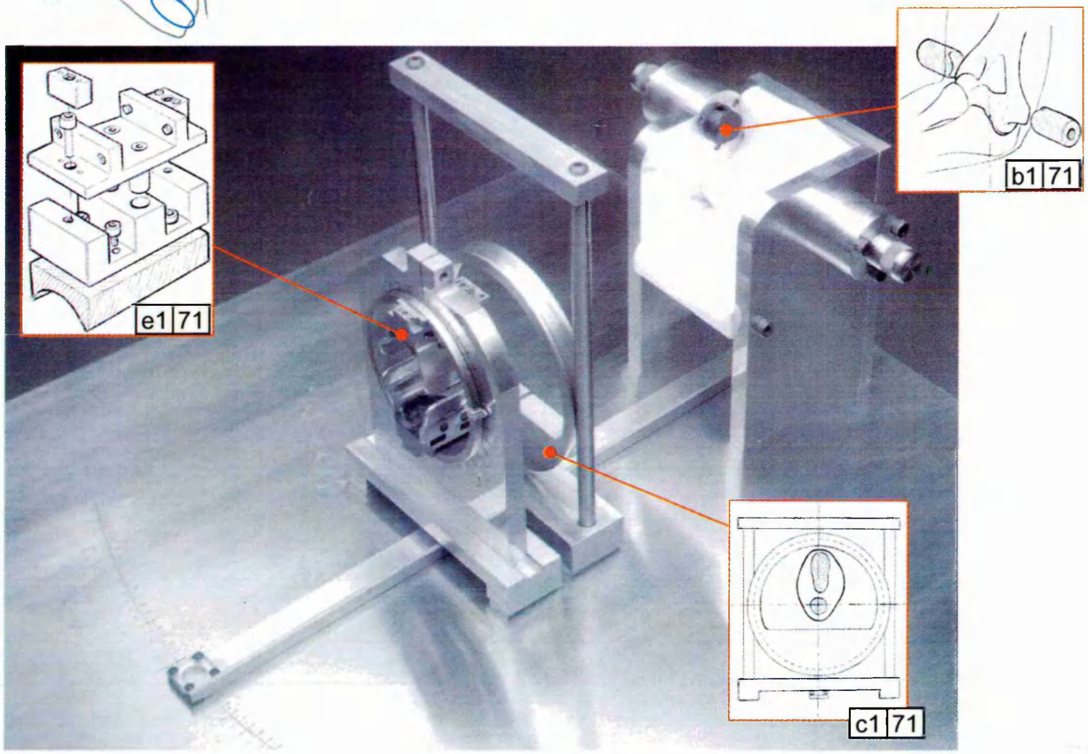


Fig 5.14 Pronation-Supination Splint

Previous studies on the pronation-supination movement of the human arm have been performed on cadaverous arms (Youm et al 1979). Principally this has been done so that rigid markers can be a fixed to the skeleton. Rigid mechanical connection is considered necessary as the majority of the radius and ulna lie deep within soft tissue (Kapit and Elson 1993). More recent studies (Nakamura et al 1994) have been performed using Magnetic Resonance Imaging. However, with these experiments it is unclear how the splints required to fix the arm within the imaging device constrain the movements of the arm. Conflicting results have been reported using radiographic methods: the research findings of (Cone et al 1983) report no evidence for a medio-lateral articulation at the humero-ulna joint whilst (Amis 1990) reports radio graphic evidence supporting a medio-lateral articulation up to 10 degrees.

To ascertain how closely the prototype joints were reproducing the movement of the ulna during forearm rotation it appeared appropriate to take measurements from an intact limb, where all the constraints of a mechanical splint were know. A male of normal build was chosen as the subject for these measurements. A close fitting splint was tailor made for the subject. A large plain annulus bearing (a) was manufactured with adjustable close fitting adjustable wrist clamps (b). This was housed in a fixture with increments of 10 degrees marked upon it. The wrist clamp for the ulna was mechanically connected to a grooved hollow disc (c) . Using an accurate vernier height gauge the disc was positioned so that the centre of the ulna was coincident with that of the disc. The grooved disc rotated between two parallel ground bars connected to a stand with a 'peg' projecting from its centre to line with one of the centre lines of the grooved disc. The Proximal part of the forearm was secured in a elbow fixture with two pegs securing the humeral medial and lateral epicondyles (d).

(1)

p-s °	h-u °
0	0.00
10	0.00
20	0.10
30	0.25
40	0.58
50	1.08
60	1.58
70	2.08
80	2.34
90	2.83
100	3.67
110	3.92
120	4.34
130	4.67
140	5.00
150	5.50
160	6.17

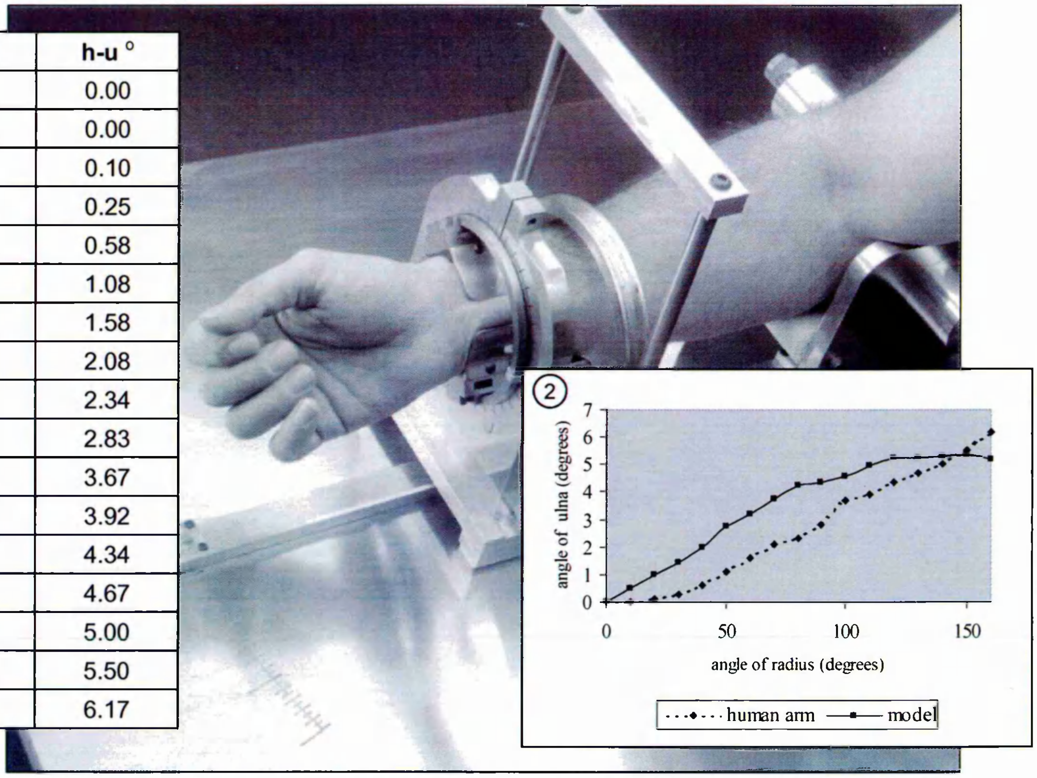
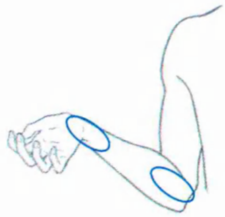


Fig 5.15 Pronation-Supination Splint

Vertically beneath the elbow fixture aligned with the approximate centre of the olercranon was a peg onto which indicating bar (a) rotated. The peg aligned with the grooved disc was also connected to rotate with a slot within the indicating bar. Both the fixture for the wrist and grooved disc were manufactured with to slide on PTFE (polytetrafloroethylene) blocks. The mounting board was made from polished aluminium sheet, onto which additional low surface tension lubricant was sprayed to further reduce friction between the mounting board and the distal clamping fixtures.
The subject was firmly secured in the jig and the forearm rotated in 10 degree increments, whilst the angular position of the ulna was recorded from the indicator bar. The experiment was repeated three times, the mean values being recorded on table (1).

The graph (2) shows the difference between the movement of the model ulna and that of a human ulna during pronation-supination movements. It evident that rotation of the bones was occurring before being indicated by the scale on the annulus bearing, due to relative movement of soft tissue within the wrist clamps, thus supporting the need for direct connection to the skeleton (Youm et al 1979) . This was estimated by twisting the clamp wrist retaining the wrist in full supination. Although the clamps were tight around the wrist it was found that this movement accounted for an intial estimated error of 10-20 degrees due to the skin becomming taut before movement was recorded. All measurements were taken using 0 degrees (full supination) as the start position. Therefore, although currently there is a wide discrepancy between the angular positions in the mid range, this can slightly offset by soft tissue errors, if the maximum estimated error of 20 is used this bringing the maximum discrepancy down to less than 1 degree, or less than 4mm of ulna translation.



Discussion

The process of creative reasoning has been used again in the development of the linked forearm joints. Using observational drawing from three dimensional anatomical models it was found that details of the anatomy could be elucidated that proved important in the design of the analogous joints.

In the development of the forearm joints it has been found necessary to supplement the creative reasoning process with a stage of mathematical analysis. As it was found that exploring the effects of the linked the distal and proximal joints was too complex using purely sketch book idea development.

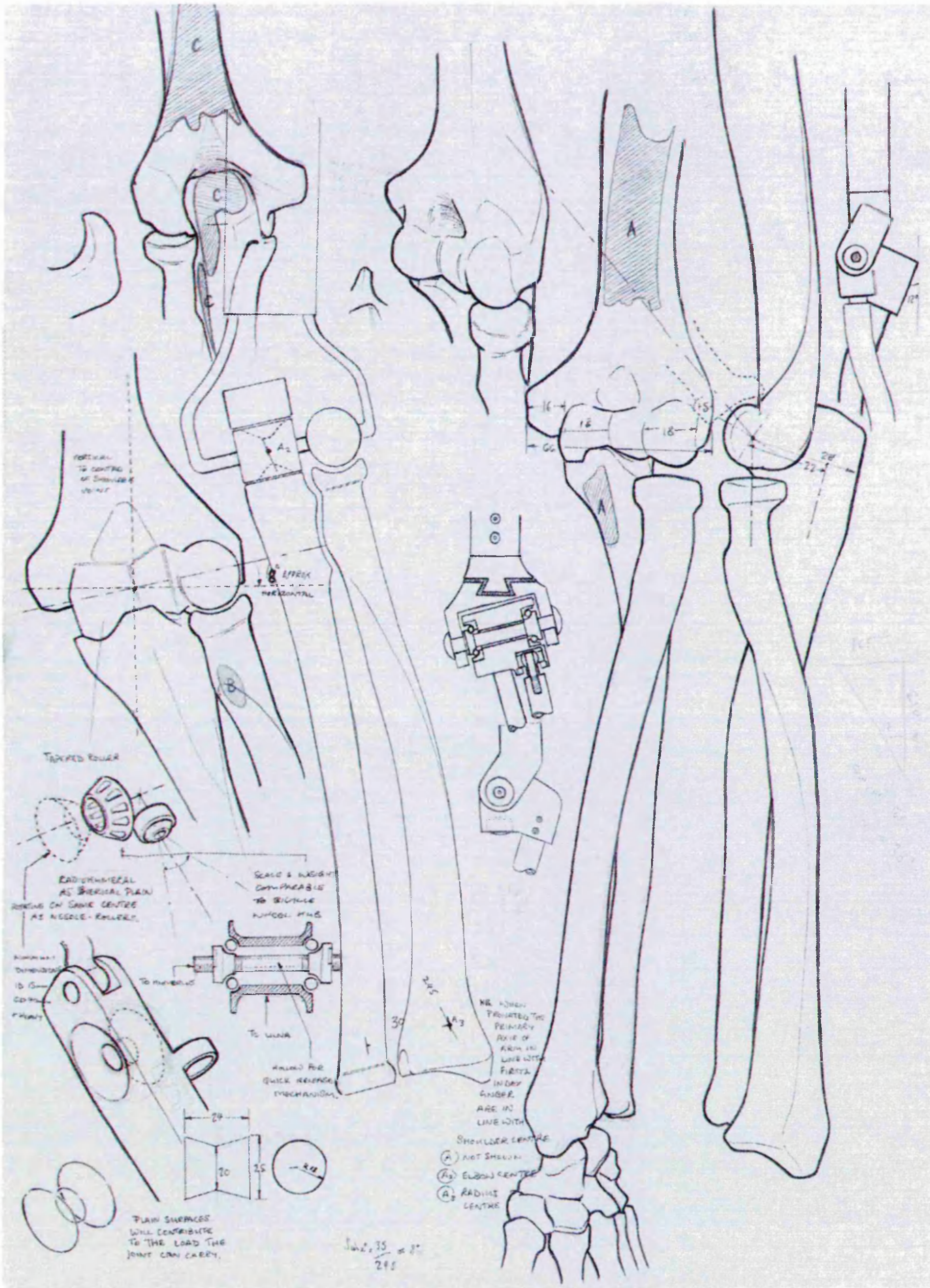
Conventional machining techniques were considered appropriate for the prototyping of these joints. Unlike the finger joints these joints have individual forms requiring machining from many directions. Additionally, some of the joint components have relatively simple forms, again suiting conventional machining techniques.

It was considered appropriate to use resin casts of the human radius and ulna bones to connect the joints to initially test the movement of the joints. However, this may suggest possible 'strut' forms suitable for an eventual prosthesis using the appropriate choice of material.

Specially designed splints were constructed to compare the movements permitted by the joint designs against those of the human forearm. This was done as from the literature it was evident that there were uncertainties about the nature of forearm pronation / supination movements in the intact arm. However, using the splint method significant error was found due to the effects of soft tissue.

It was considered that for a meaningful qualitative evaluation of the movement permitted by the forearm joints it was necessary to first develop an elbow fixture. The development of the elbow is detailed in the following chapter.

6. Development of an Anatomically Analogous Elbow Joint



A Sketch Sheet Used in the Development of the Model Elbow

The previous chapter showed the development of analogous joints permitting pronation and supination movements of a model forearm. Due to the combined nature of the articulation of the forearm and elbow flexion many of the principles elucidated in the development of the proximal radio-ulnar joint pertained to principles applicable for a model elbow joint. Therefore, it was considered that to successfully evaluate these principles a model combining elbow joint and forearm joints was needed.

To add to the anatomical analogy emphasis was placed on the production of a model elbow form that was close to the form of the distal humerus. Consequently, more complex prototyping methods methods were required than had previously been used.

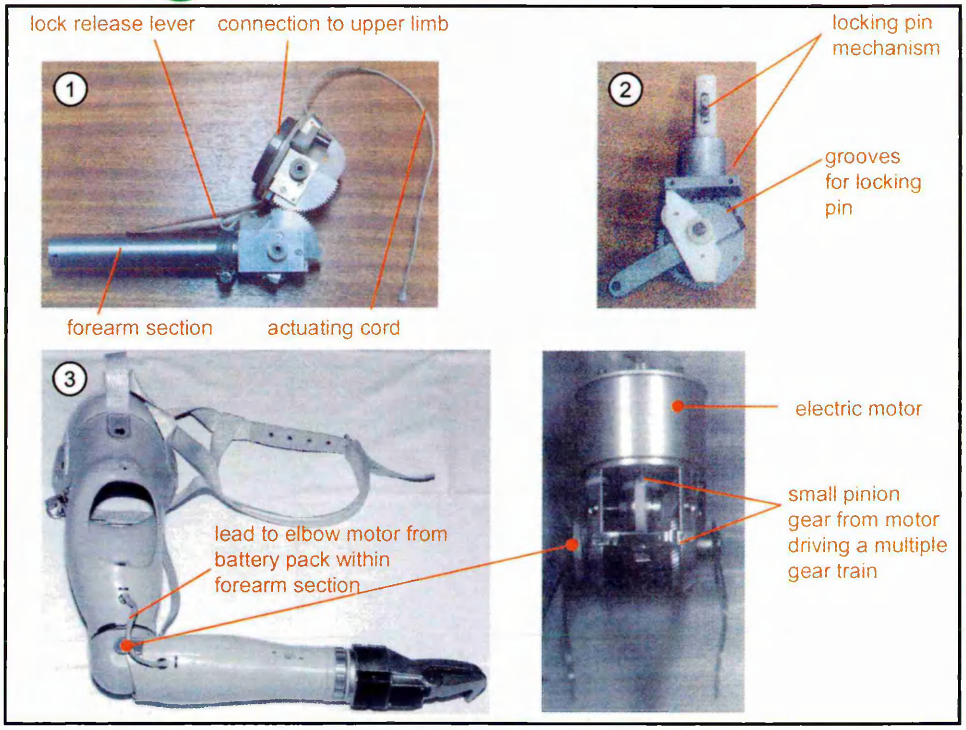
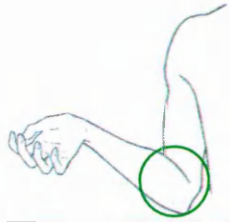


Fig 6.1 Prosthetic Elbow Components

Prosthetic replacement elbows are essential to the amputee, as the function of the elbow is crucial for feeding feeding activities (Kapandji 1982). The loss of the function of the elbow joint rather than any other joint has been indicated as jeopardising independent living through making it impossible to carry out activities of daily living (Stanley and Kay 1998).

Figures 6.1(1) and (2) show two components from body-powered elbows. Figure 6.1 (1) shows two gears where the movement is controlled by a chord. This arrangement of the gears allows a range of movement of around 180 degrees flexion, whilst minimising the amount of excursion needed from the actuating cord (Banerjee 1982). Minimal actuating cord excursion is necessary as the motivating movement of bi-scapula adduction only produces limited cord excursion, part of which may also be required to operate the jaws of the split hook (Banerjee 1982). Figure 6.1 (2) shows a locking mechanism used in prosthetic elbows. 'Locks' are used to maintain levels of flexion of the elbow whilst requiring no further physical effort from the amputee to maintain this position. The lock shown achieves this function through a pin falling into groves machined around a gear. Once locked, the mechanism (1) requires the contralateral arm to operate a release lever on the forearm section of the prosthesis. Powered locking mechanisms have been developed for electrically powered elbows, working on a similar to the mechanism of (2) (Jacobsen et al 1982).

Powered components such as (3) commonly consist of an electric motor in the humeral section, with a gear assembly at elbow level that reduces the high speed low torque rotations of an electric motor to lower speed higher torque movements suitable for flexion of the prosthetic elbow. These devices are assembled to minimise their bulk and so allow for a range of humeral lengths to be accommodated in a single modular design (Ibbotson 1999). However, the large amount of gearing required make these components comparatively heavy at around 2/3 kg (Otto Bock 2000).



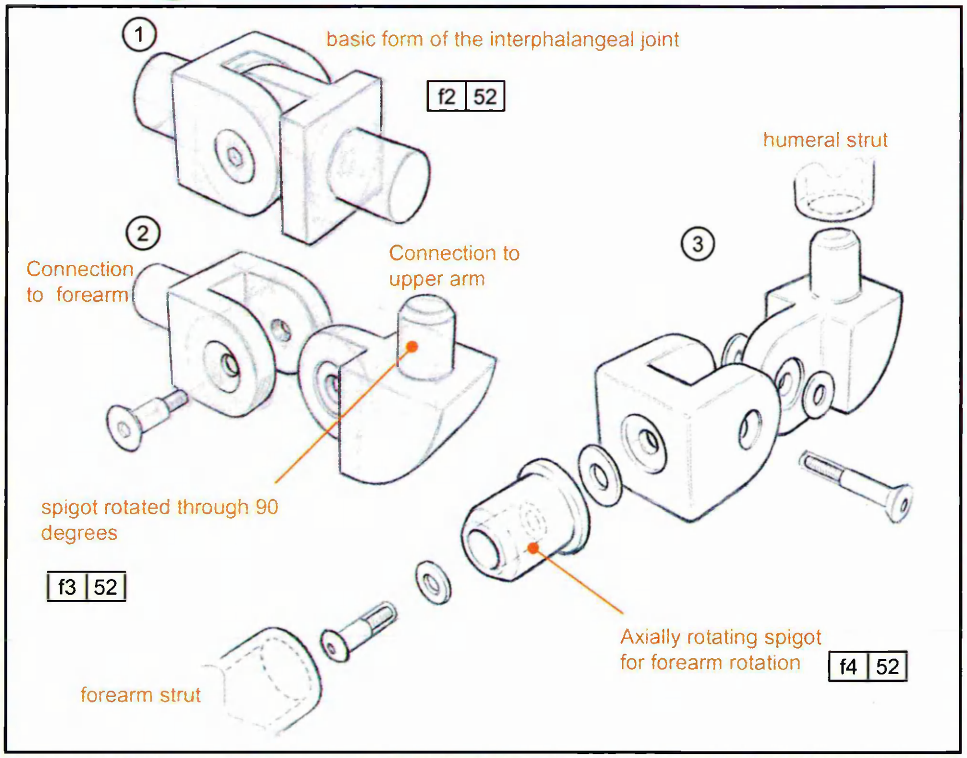
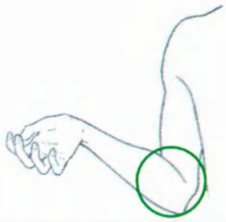


Fig. 6.2 Translating Design Principles from the IP Joints to the Elbow

It was found that the development of the elbow could not be separated from the development of the articulations of the forearm. Therefore, sketchbook idea development focussing on the elbow also includes ideas for the articulations of the elbow that include flexion / extension of the forearm.

Initially articulations for the elbow were considered using mechanical principles that had already been elucidated in the development of the interphalangeal joints (chapter 3). This was considered appropriate since initial observation of the motion of the intact human elbow suggested that the articulation of the elbow was similar to that of a simple uniaxial rotation. Additionally, the rotary movement of the forearm appeared to be similar to that of an axial rotation about a central spigot. Consequently, the initial sketch ideas above focused on implementing the simple IP joint principles of articulation to the articulations of the forearm and elbow. Figure 6.2 (2). shows how the form of the basic interphalangeal joint (1) might be changed by rotating one of the spigots through 90 degrees to enable this type of joint to possess the to correct range of movement for an elbow joint.

Comparison of the form of these ideas to that of the anatomy, showed that they differed considerably from the original anatomy. The most obvious deviation being that the human forearm contains two bones, whereas the proposed forearm articulation consists of a single strut. Additionally, whilst a single axially rotating strut might approximate the range of movement of the forearm anatomically the arrangement of struts and joints is quite different (chapter 5). Therefore, to obtain a closer mechanical analogy of these joints observational drawing studies were undertaken; firstly, for the forearm joints and subsequently for the junction of the forearm joints with the humerus which is discussed in the following pages.



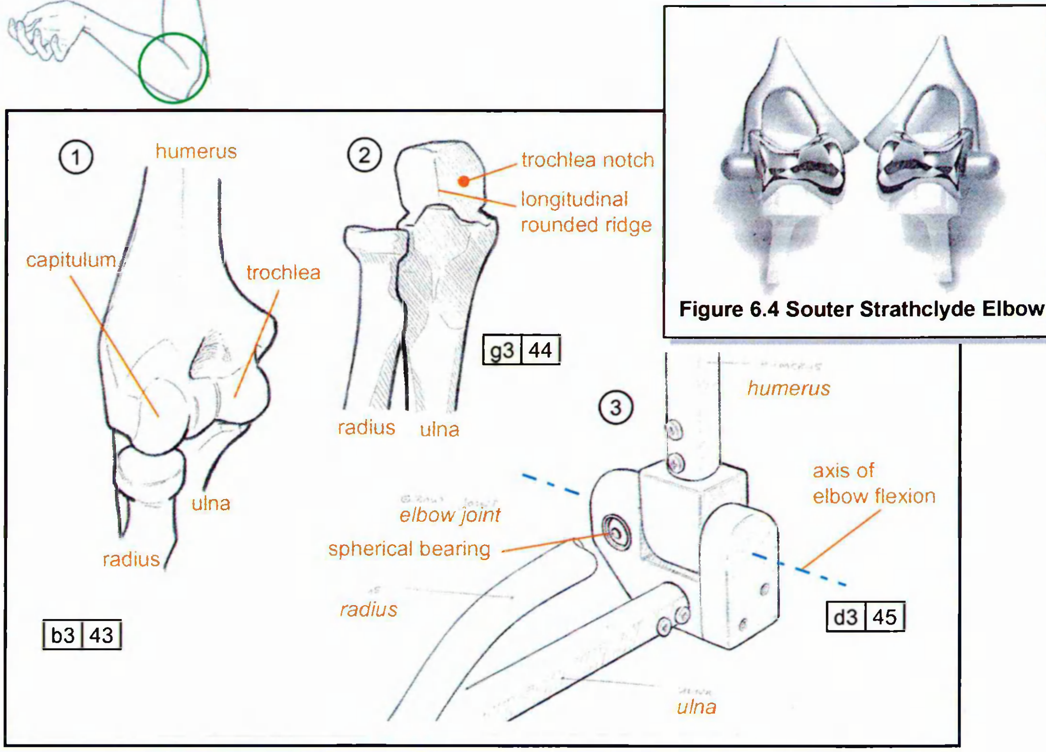


Figure 6.4 Souter Strathclyde Elbow

Fig 6.3 Drawings Focussing on the Capitulum and Trochlea

Figure 6.3 (1) shows an observational drawing of a skeletal right arm. This can be determined from the position of the capitulum and trochlea on the humerus. The capitulum is a partial spherical surface (Kapandji 1982) on which the radius bone articulates. The capitulum is lateral to the trochlea when the humerus is facing anteriorly (facing front).

At this stage a review of implantable elbow prostheses was undertaken to ascertain their appropriateness for an analogous model. It was found that all commercially available components focus on the trochlea to ulna articulation (Betts 1998). The Boimet Ltd Kudo Elbow and Souter Strathclyde Elbow (figure 6.4) closely reproduce the form of the trochlea from biocompatible metals such as titanium (Biomet 1990, Howmedica 1990). The form of the ulna's trochlea notch in the Souter Strathclyde Elbow is moulded in high density polyethylene (Howmedica 1990). The bones of the elbow are connected within the body by ligaments (Guyot 1990). To the sides of the elbow joint, are medial lateral ligaments and to the front and reverse an anterior ligament and posterior fibres, as well as additional oblique ligaments (Guyot 1990). Both the implants discussed require that the ligaments remain intact, as the articulating surfaces of the implant's ulna trochlea notch and trochlea do not not extend far enough around one another to support loads (Betts 1998). There are elbow implants that are linked together, such as the Alivium Stanmore Total Elbow Replacement (Zimmer 1990). This component possesses a convoluted form, but kinematically it is a simple uniaxial articulation (Betts 1998). However, it is made of solid steel components and was therefore considered too heavy for an analogous model. Additionally, a joint for the capitulum to radius articulation was also needed.

Experience in the development of the MCP joint (figure 4.3) showed that sketch ideas using an analogy for ligaments surrounding the joint may be overcomplicated (figure 4.3 (4a)). Consequently, sketch ideas were developed focussing on mechanically connecting the trochlea and ulna, initially by a simple hinge (3). Sketch (3) shows a spherical bearing as analogy of radius to capitulum articulation and ulna to trochlea.

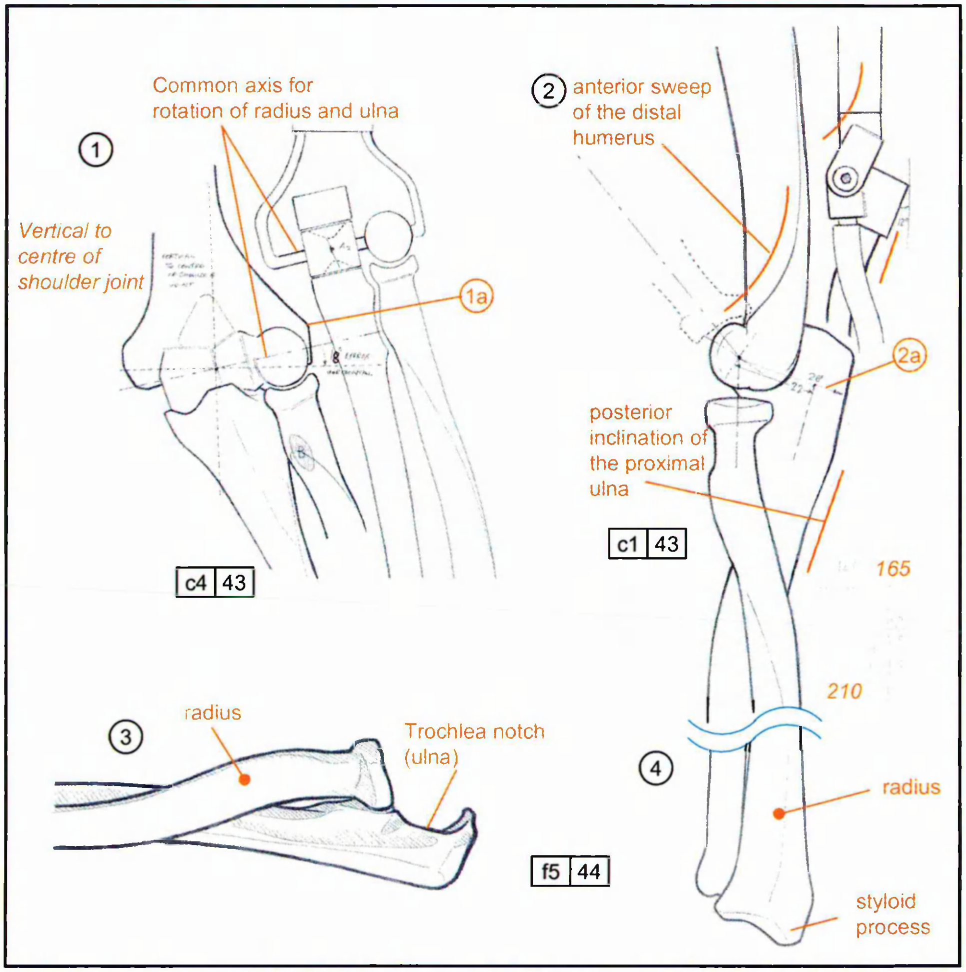
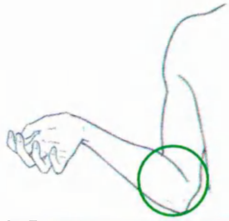


Fig 6.4 Observational Drawings of the Distal Humerus

Continued observational drawing highlighted that the rotation of the ulna and radius appear to be lie on a similar axis across the humerus (1), a finding supported by anatomical literature (Kapandji 1982). The process of observational drawing also indicated that the distal portion of the humerus sweeps anteriorly (2). The humeral sweep appears matched by a posterior inclination of the proximal ulna (2). The trochlea notch on the anterior surface of the ulna (3), offsets the main shaft of the ulna (2a), enabling the unimpeded range of movement of the elbow to typically 145 degrees (Smith et al 1996). To determine the range of elbow flexion of an average male, approximate measurements of ultimate flexion angle were taken from one of the researchers whom had been used as the basis of measurements in previous joint development. Several points were chosen on the arm that were both easily determined from palpation, and also appeared relatively unchanged during flexion and extension movements of the elbow. The styloid process (4), lateral epicondyle (1a) and a position where the deltoid meets the humeral shaft were determined from palpation and marked on the skin. Measurements were then taken between these points with a rule accurate to 0.5mm. A measurement was then taken on full flexion of the arm between the styloid process and the insertion of the deltoid. Simple trigonometry revealed estimated an acute angle of 34 degrees. As no hyperextension of the elbow could be seen, the range of movement of the researchers elbow was estimated as 180-34 = 146 degrees.



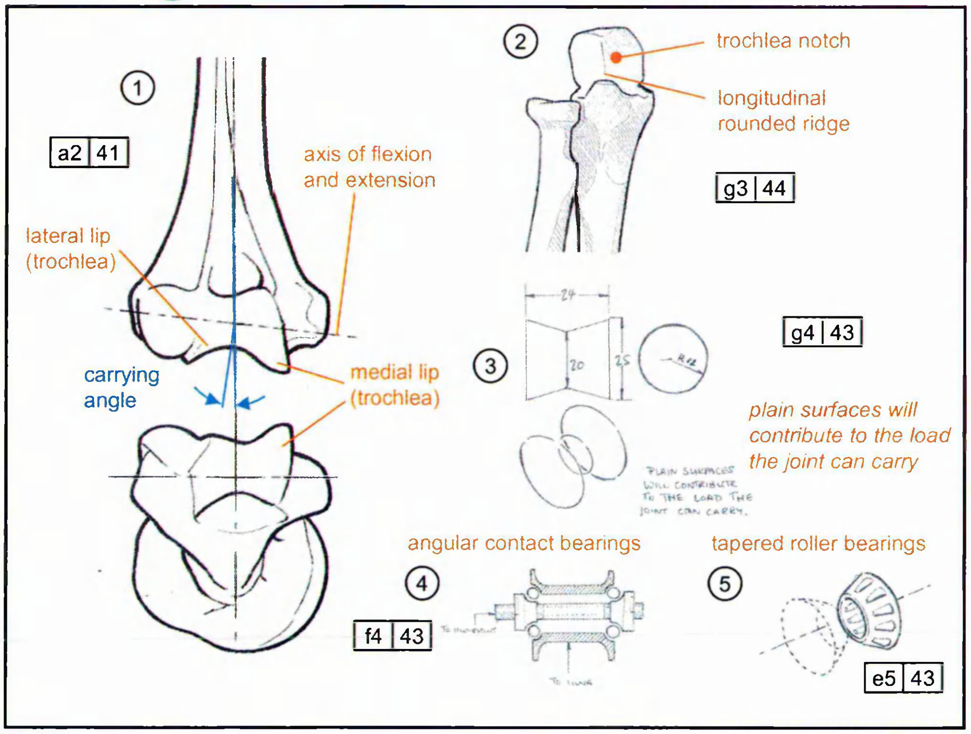


Fig 6.5 Observational Studies of the Trochlea

Further drawing studies of the trochlea indicated that the medial lip of the trochlea appeared lower than the lateral lip. Literature review states that this is an indication of the 'carrying angle' (Smith et al 1996). The carrying angle has been defined as the acute angle measured between the extended forearm and a line extrapolated from the long axis of the humeral bone (Smith et al 1996). There is wide variation in the magnitude of the carrying angle in individuals, with the carrying angle reported greater in women than in men, ranging between 5 and 19 degrees (Smith et al 1996). The carrying angle of one of the male researchers was measured by extending the arm onto a piece of card. Straight edges were then aligned against the medial edges of the lower and upper arm and lines scribed against the straight edges. These lines were subsequently measured using a protractor accurate to 1 degree, and the carrying angle estimated at 13 degrees. No clear function has been identified for the carrying angle (Smith et al 1996), however, cosmetically the possession of a carrying angle may be significant as it can observed in the extended arm of females. The carrying angle is not reproduced in current prosthetic elbows, as flexion occurs along an axis perpendicular to both the long axes of the upper and lower arm sections.

Observational studies of the trochlea notch highlighted, what is referred to as, a longitudinal rounded ridge (Kapandji 1982). Initially, it was considered that the form of the trochlea and trochlea notch function to resist both axial and thrust forces. Therefore, the trochlea was considered analogous to angular contact bearing races (4) or tapered roller bearings (5), which are arranged to resist similar loading. The observational studies were followed by palpation of skeletal anatomical models. It was found that the ulna could be palpated laterally against humerus. This was initially considered due to absence of the cartiligeous tissue in the model, however, literature review indicated that a lateral movement at this joint may occur during pronation and supination (Amis 1990) (Chapter 5).

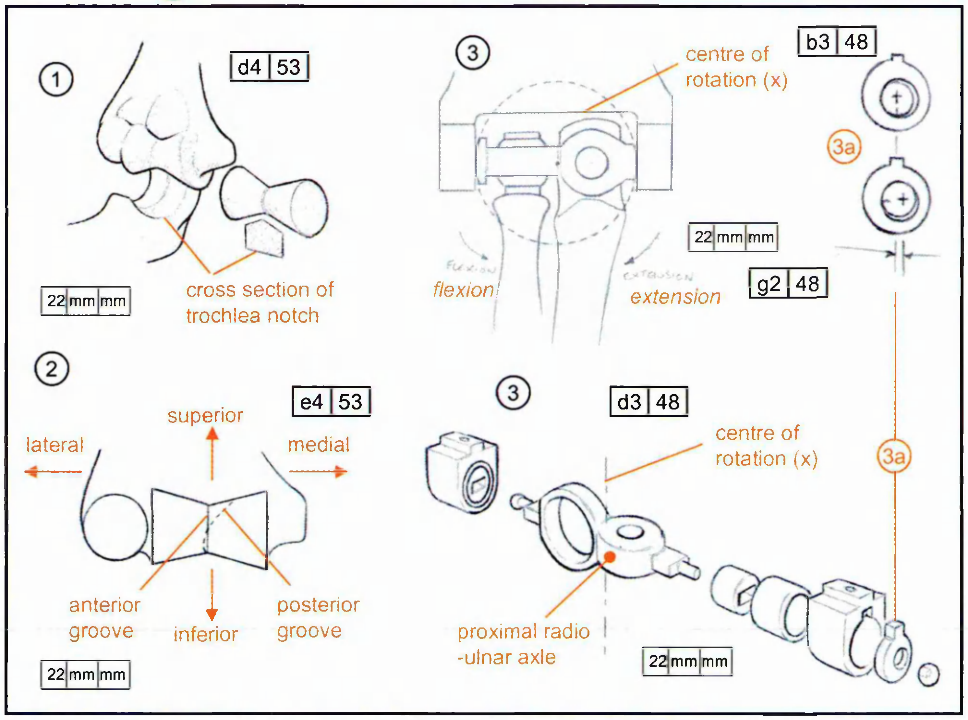
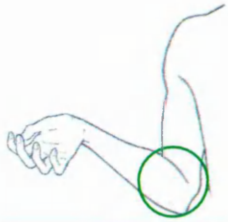


Fig 6.6 Initial Sketch Ideas for Carrying Angle Mechanisms

More extensive review of anatomical literature indicated that the carrying angle may vary with angle of flexion of the elbow (Kapandji 1982). Kapandji's theory states the mechanism for carrying angle change is by the close contiguity of the trochlea notch to the trochlea (Kapandji 1982). Sketch (1) shows how a pointed section of the trochlea notch could be imagined being guided by the bobbin section of the trochlea. Kapandji states that the trochlea instead of the of possessing simple groove, most commonly possesses a groove running directly superiorly to inferiorly (top to bottom) on anterior view (front) and helically, superior-medially, to inferior-laterally on the posterior view (Kapandji 1982). Kapandji indicates this has the effect of causing a lateral carrying angle in the extended arm, whilst when the elbow is flexed the forearm aligns with the upper arm eliminating the carrying angle.

The possession of a clear carrying angle might have cosmetic benefit when viewing the extended arm. However, the cosmetic and functional significance of a changing carrying angle is unclear (Smith et al 1996). More recent anatomical literature report different methods of measuring the carrying angle indicating that uncertainties as to whether the carrying angles diminishes during flexion, or remains constant (Stanley and Kay 1998). It was considered from this evidence combined with reported individual variations of carrying angle (Kapandji 1982); that a first model elbow should possess a constant carrying angle. However, further iterations of the model might include the mechanism for a changing carrying angle if evaluation of the model joint indicated its absence detrimentally effected appearance or function.

At this stage in the development of the analogous elbow the parallel investigation into pronation and supination of the forearm (Chapter 5) had resulted in a proximal radio-ulna axle. A mechanism (3) was proposed to permit this axle to rotate about a centre (x) using cams (3a) to cause a lateral rotation on extension and medial rotation on flexion. This complexity of the mechanism made it undesirable of for model prototyping.



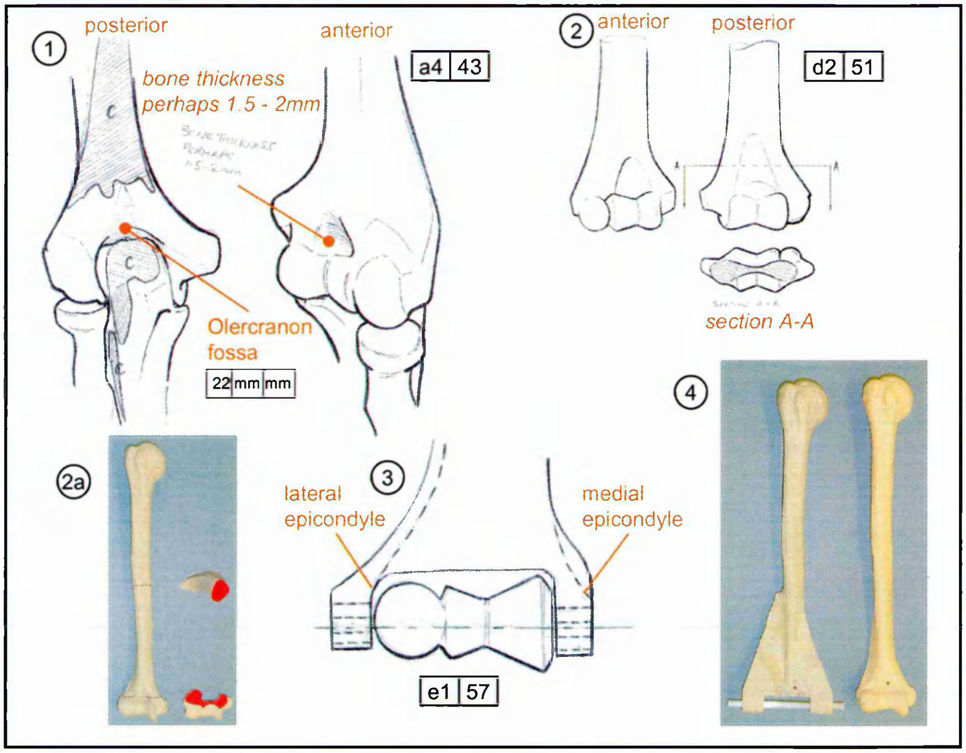


Fig 6.7 Observational Drawing of the Distal Humerus

Observational drawing was combined with moulding techniques to further investigate the form of the distal humerus. Observational drawing indicated that the distal humerus flares outwards becoming wider rather than deeper in anterior view. Drawing studies indicated depressions immediately above the trochlea on both anterior and posterior surfaces (a). Anatomical literature refers to these depressions as the olercranon fossa (Kapit and Elson 1993).

To determine the thickness of the humerus at this point a resin copy of a humeral bone was cross sectioned. To make he resin copy a silicone rubber mould was made from a skeletal model humeral bone. A resin copy of the humerus was then taken from the mould and cut transversely to determine its cross section at different points along its length (2a). Towards the middle of the humerus it's section is approximately circular, towards the capitulum and trochlea the form divides into two over the trochlea (2). As it was considered that an analogy of the trochlea and capitulum should rotate on a common axle, the indication of the division in the form was 'exaggerated' in development sketches (3) to 'fork' like forms to hold the common axle. Another resin humerus was taken from the mould and a shaft fitted through it at the approximate centre of the capitulum and trochlea. Further resin was added to to visually ascertain the effect of using the medial and lateral sides of the distal humerus as supports for the proposed shaft (4). It was found that little resin was needed to build up an adequate support for a 6mm shaft on the medial side, as this corresponded with the medial epicondyle (d). However, more material was needed on the lateral side, as this epicondyle is much less prominent from the articulating face of the capitulum (3). Despite this prominence the approach was still considered appropriate, as from observation of the intact arm the medial epicondyle appeared much closer to the outer profile of the arm. Whereas, a slight prominence on the lateral epicondyle might be 'masked' by the bulk of the brachioradialis and extensor carpi radialis longus muscles.

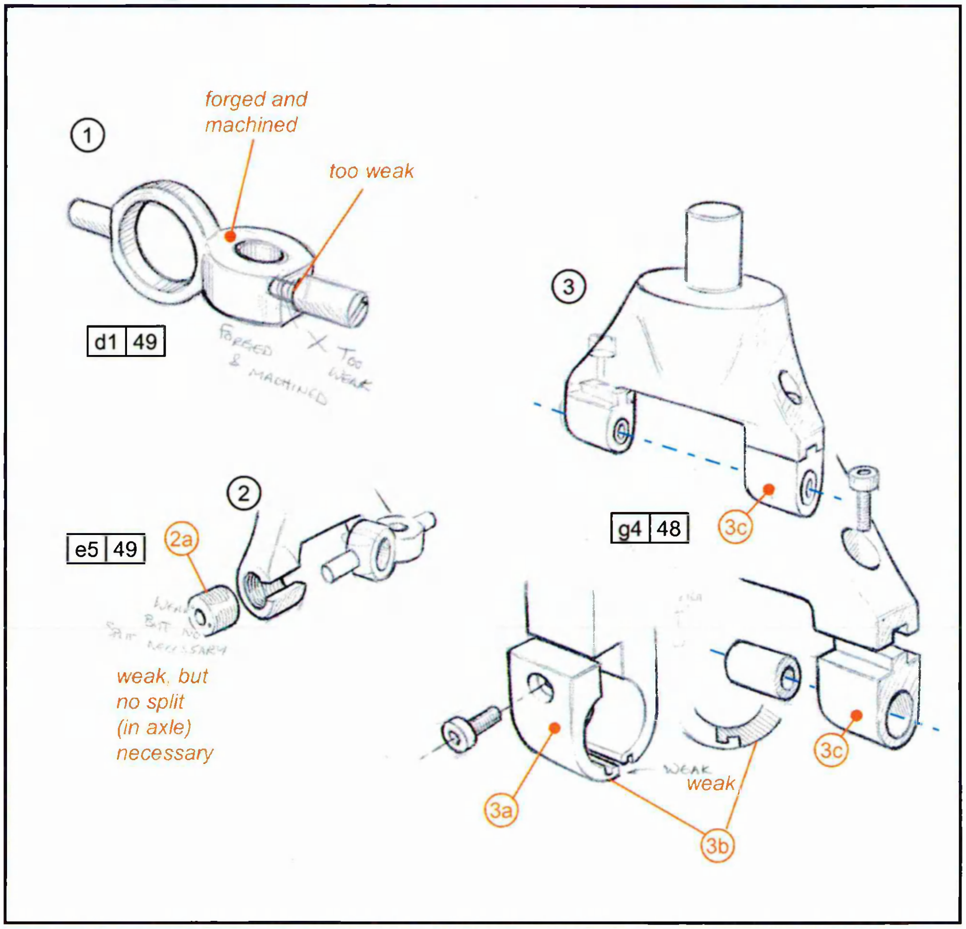


Fig 6.8 Inserting the Proximal Radio-Ulnar Axle

Continued development of the humeral component focussed on a means of inserting the radio-ulna axle. It was considered that the axle component should be machined from a single forged steel billet for strength. Initially, splitting the axle had been considered to insert it into the elbow fixture, however, latterly splitting the axle was thought to compromise its strength (1). Instead, sketch (2) shows a how a split in the humeral component might permit access for the axle shafts. Plain axle bearings might then be threaded into the humeral component to fix the axle in place (2a). Having an incomplete cylinder to hold the axle bearing was considered too weak. Sketch (3a) shows how the split might be configured using a separate screw fixed component (3a), incorporating a mating joint to increase strength. Both sketch ideas (2) and (3a) were considered to compromise strength; instead sketch (3c) shows the favoured solution, separating the component along the axis of elbow flexion.

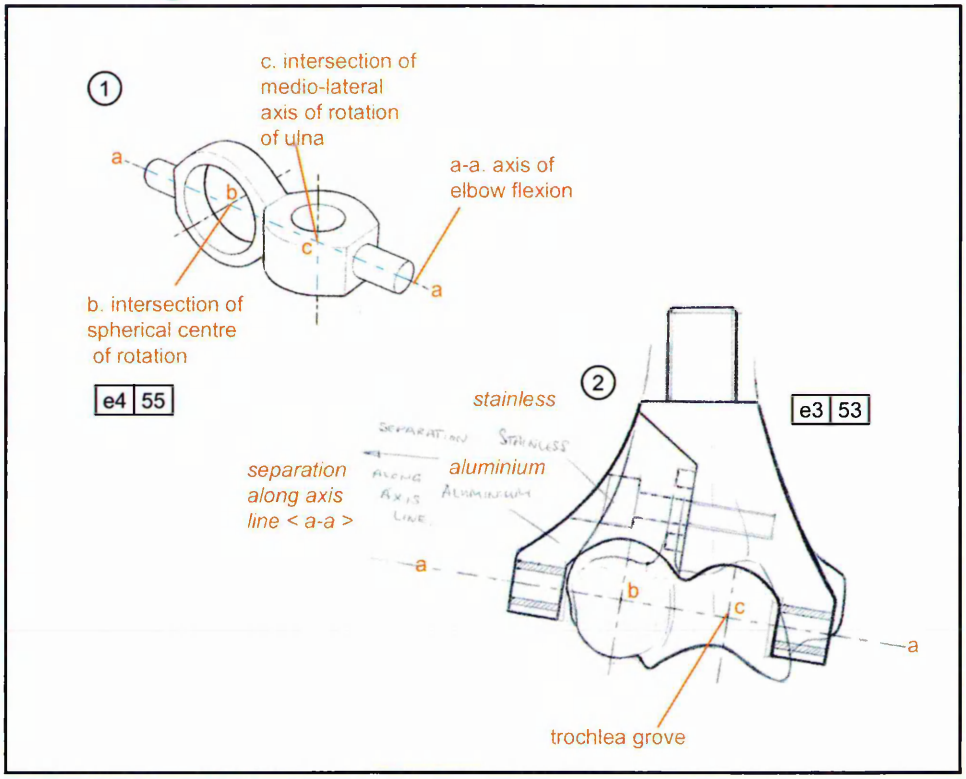


Fig 6.9 Location of the of Elbow Components

In the development of the proximal radio-ulna axle the ulna to capitulum articulation was considered a spherical articulation, equivalent to that permitted by a spherical bearing. This was found consistent with existing anatomical literature (Kapandji 1982, Smith et al 1996, Kapit and Elson 1993). More speculatively, the trochlea to tochlea notch was considered to posses a medio-lateral articulation (1) (Chapter 5). Subsequent designs for the humeral section of the elbow were developed using an observational drawing of the humerus as an underlay (2). During this process care was taken to position the proximal radio-ulna axle where intersections of the axes of rotation appeared close to those on the distal humerus. As the capitulum is considered a partial spherical surface, an approximation of the centre of rotation was found by matching a circle with similar diameter and known centre to the periphery of the capitulum (2 - b). The medio-lateral articulation of the trochlea to trochlea notch articulation was estimated at the centre of what is referred to as the trochlea groove (Kapit and Elson 1993) (2 - c). The positioning of the proximal radio-ulnar axle provided further resolution of the proximal aspect of the elbow component and indicated that further resolution of the form of the proximal aspect of the elbow component was necessary.

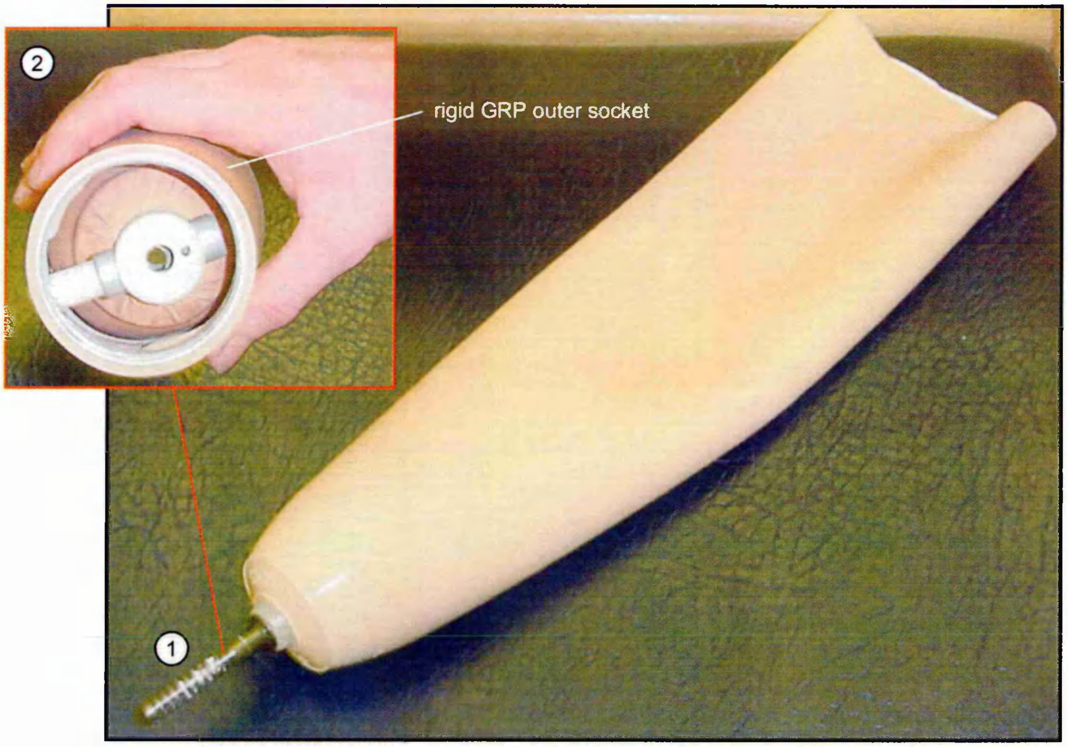
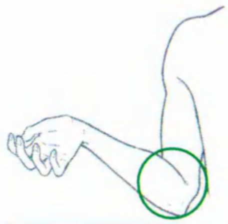


Fig 6.10 The Commercial ICEROSS Prosthetic Suspension System

The proximal end of the elbow component required a fixture that permitted the elbow to be attached to a suspension mechanism. Review of some of the existing suspension devices for upper-limb prostheses was done at the Centre of Mobility and Specialised Rehabilitation at the Northern General Hospital, Sheffield. An interview with V. Ibbotson a Senior Occupational Therapist at this centre indicated that the more successful suspension methods relied on donning of the suspension system separately to the prosthesis (Ibbotson 1998). Figure 8.10 shows the ICEROSS suspension socket. In this method of suspension an air tight soft silicone socket is first rolled on by the amputee. Moulded into the distal end of the socket is either a bayonet fitting (1) or piece of cord. The rigid glass reinforced plastic (GRP) prosthetic socket is then pushed onto the silicone socket. The GRP is secured to the silicone either by the mating of the bayonet with a clip (2), or by the cord being wrapped around a capstan on the exterior of the GRP shell. Using the cord method the silicone socket is pulled into the GRP socket protecting the distal end of the remaining limb (Ibbotson 1998).

All the observed suspension systems rely on a rigid prosthetic shell to stabilise the prosthesis. The aspects of the existing devices that appeared of benefit to a future mid-humeral prosthetic device were; donning the suspension system separately, and protecting the distal section of the amputees arm. Connecting the prosthesis to the suspension system was observed to be easier with the bayonet clip when carried out with only a single arm. Reported less favourable features of existing suspension systems were; the lack of circulation of air around the socket requiring high levels of hygiene of the amputee (McCurdie et al 1997) and the rigidity of the GRP socket (Ibbotson 1998).



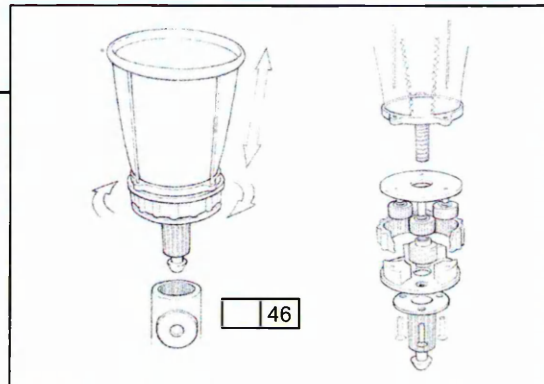


Fig 8.12 Speculative Suspension Method

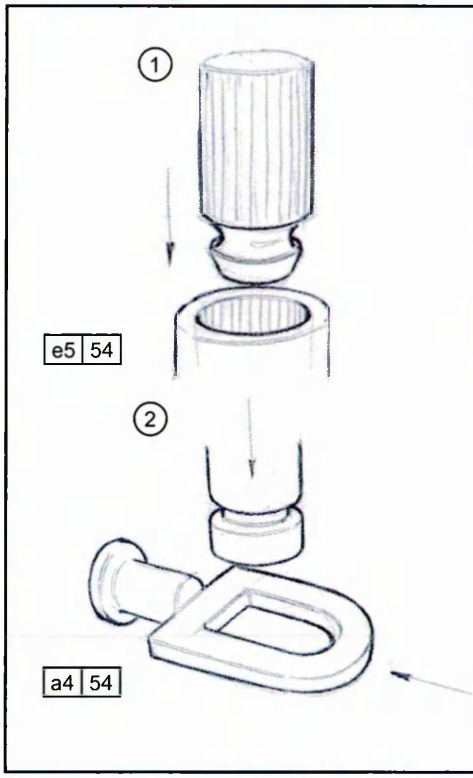
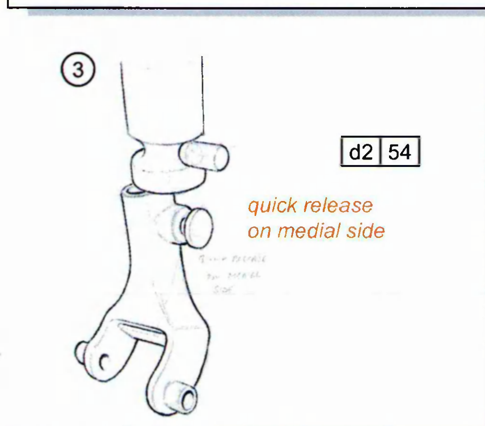
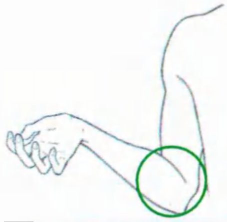



Fig 6.11 Consideration of Suspension Methods

In view of earlier finding of the focus group the integration of a rigid exoskeletal shell suspension method into the design principles of a future prosthesis was inappropriate. Additionally, it was thought that an exoskeletal approach would significantly divert from the method of design by analogy to the human anatomy. Instead what were considered to be the most beneficial aspects of existing suspension methods were used. The interview with V. Ibbotson indicated that donning of a separate suspension system was preferable to the amputee. Consequently, a peg projecting from a future suspension was considered a simple means of mating a suspension system to the elbow component (1).

From attendance at many amputee meetings it has been observed that it was difficult for the amputee to consistently ensure the suspension system has the orientation with respect to the long axis of their remaining limb. Therefore, angular adjustment was incorporated into the elbow fixture through splines on in the bore of the elbow component (1). Connection of existing prostheses onto the silicone socket was reported as most easily achieved through a bayonet and sprung quick release similar to sketch (3). Therefore, a bayonet form was applied the distal end of the peg, and a sprung quick release was fitted to the medial side of the casting. The medial side was chosen as it was considered less vulnerable to accidental release than placement on the lateral side (4). A future suspension system was sketched purely to visually explore the consistency of securing the endoskeletal model arm by a 'soft' exoskeletal method to the amputee. The design speculates that a socket might be made from an inextensible braid and three corset type ribs. The sketch proposes the braid be secured to the limb by extending the braid along its long axis once the limb is inside the braid. However, the detail of this design is not the subject of this research.



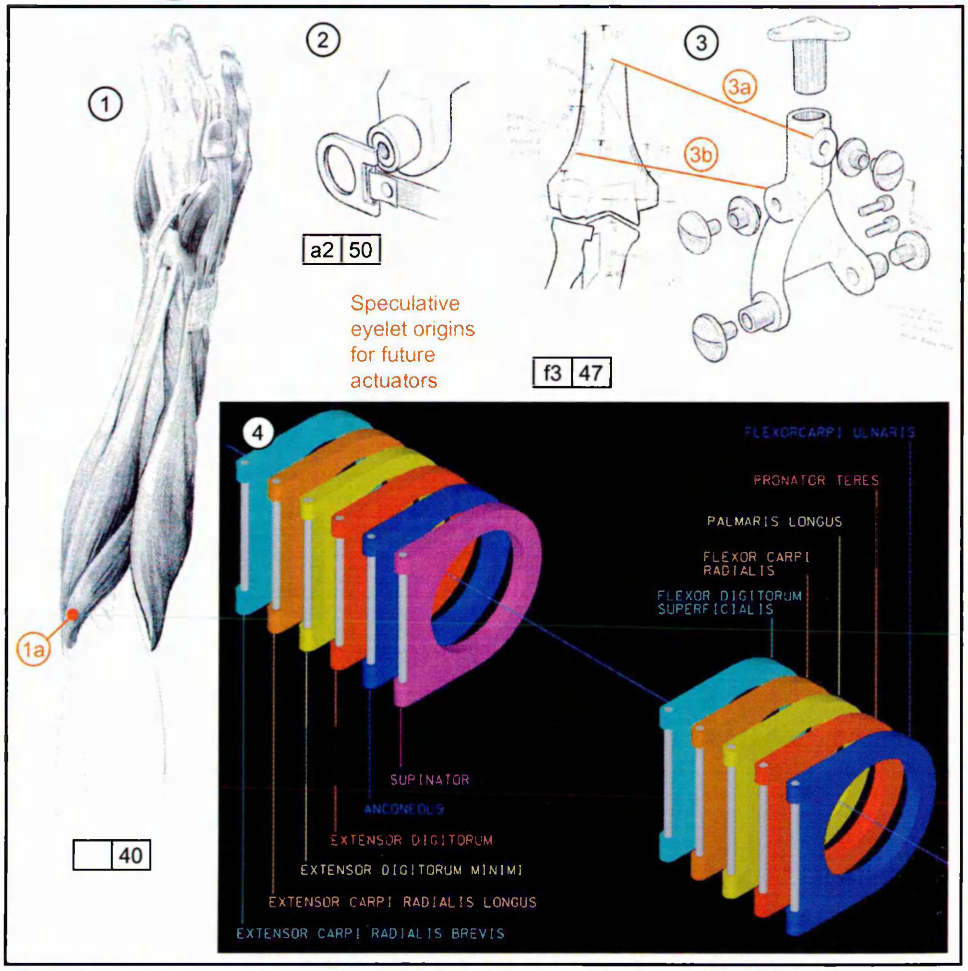


Fig. 6.12 Extrinsic Muscle 'Origins'

Wire 'tendons' were used to activate the digits of the model hand. A literate review on the elbow suggested that many of these extrinsic tendons 'originate' at the elbow (Kapit and Elson 1993). Further observational drawing from anatomical models marked with muscular attachment points elucidated that many of the extrinsic flexor muscles of the hand originate from the medial epicondyle of the humerus, whilst the extrinsic extensor muscles originate from the lateral epicondyle; an observation supported by the anatomical literature (Kapit and Elson 1993). It was thought appropriate that an anatomically analogous model elbow should closely reproduce these 'origins'; just as many of the 'insertions' had been reproduced on the model hand. Observation of the extrinsic musculature of cadavers combined with observation of muscular anatomical models (1) show these muscles to overlap one another as they approach their origin on the distal humerus (1a). Consequently, simple eyelet-type origins were designed to fit onto cylindrical bearings (2), concentrically arranged with the main axis of elbow flexion on the medial and lateral sides (3). Observational drawing also highlighted that origins for the muscles of brachialis (3a) and brachioradialis (3b) are within the space occupied by the elbow component, therefore, two further similar 'origins' were provided. The suspension peg prompted questions of future suspension methods, similarly this stage focussed questions about the appropriate actuation strategies. Consequently, researchers working in the field of novel actuators were contacted (Della Santa 1997).

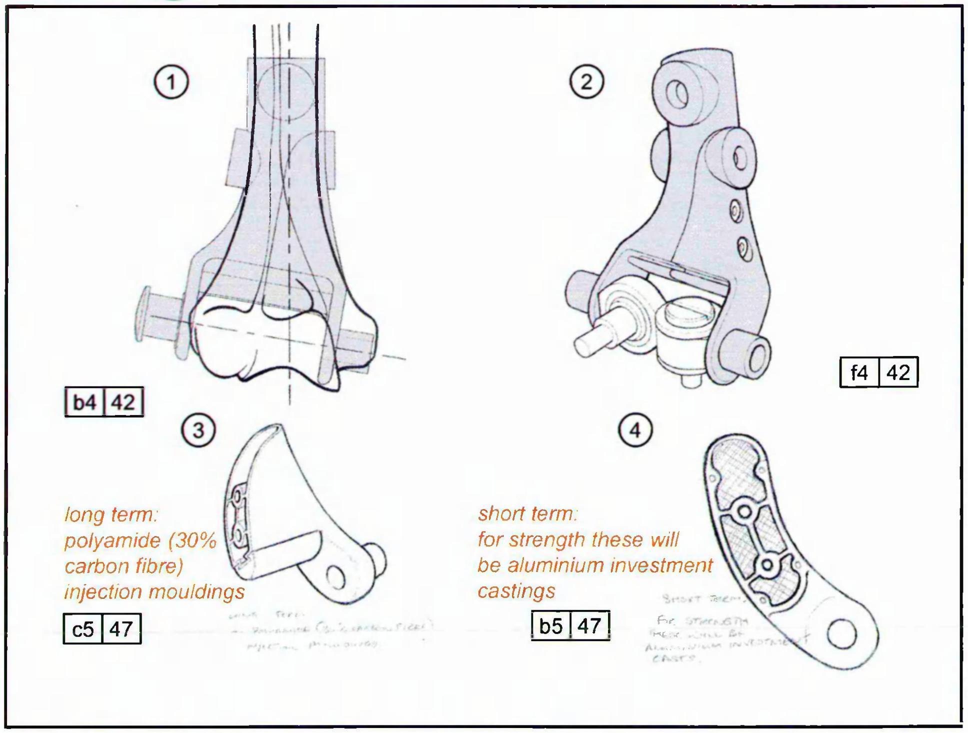


Fig 6.13 Proposed Design

Following the evaluation of the form of the model finger joints (Evalaution by Dr. Williams chapter 6) the form of the analogous elbow was designed to be much more complex and contoured than previous joint designs. Approximating the contours of the distal humerus resulted in a design of relatively large volume (1, 2). The comparatively large weight of existing myoelectric prostheses is indicated as a major factor in their indiscomfort (Kejlaa 1993). Consequently, to reduce weight but both retain these contours and retain comparative strength it was thought the components form should be a shell or skin form (Gordon 1978) (3, 4).

Findings from separate US research using pneumatic muscles to flex a model elbow show that friction against these actuators, when arranged in an anatomical manner, severely limits their efficiency (Hannaford et al 1995). Therefore, a smooth outer surface was proposed for the elbow component to reduce friction against devices used for actuation. Materials were chosen that had good bearing properties whilst retaining rigidity (3).

The proposed design includes two securing machine screws. Two screws were proposed both to increase clamping force between the two forms but additionally, to ensure the correct alignment of the two bores that permit articulation of the proximal radio-ulna axle.

Features such as lightness of weight and a smooth contoured form through the production of a 'skin' were prioritised in the production of the model. It was considered that a casting technique would be the most appropriate for prototype production, as the chosen plastic requires injection moulding equipment, unsuited to prototyping. Consequently aluminium was considered a suitable substitute material for a lightweight rigid form that could be highly finished.

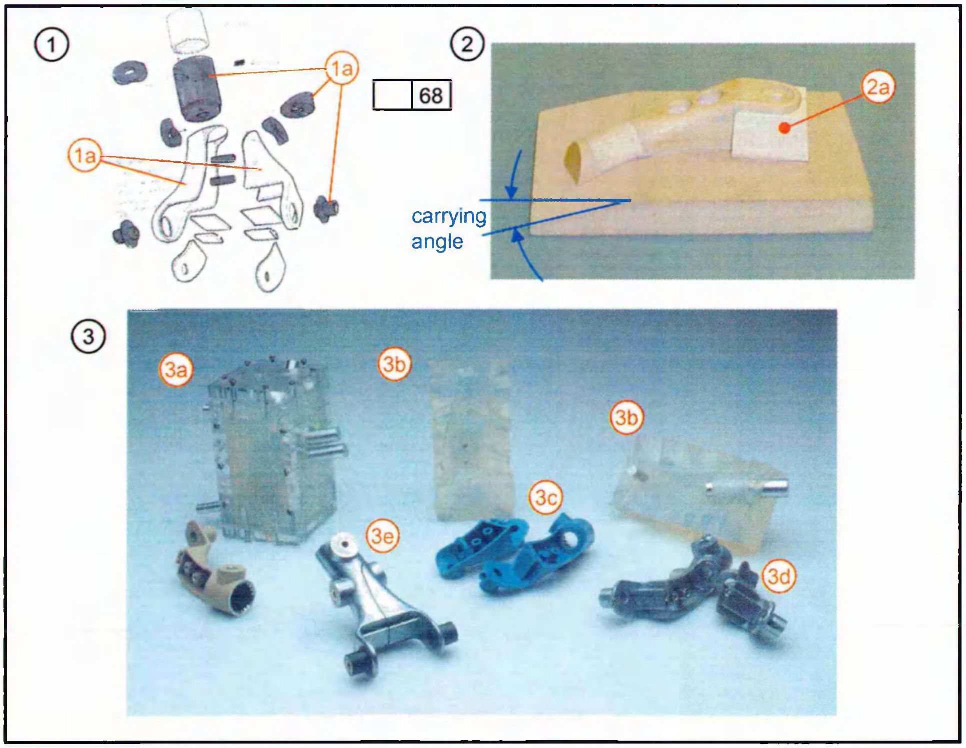


Fig 6.14 Prototype Manufacture

Using a casting method requires the production of a master 'pattern'. The highly complex form of the elbow appeared unsuitable to conventional or CNC machining processes used in the production of previous designs. Consultation with a skilled pattern maker indicated that the desired forms could be created using a fabrication process (1). It was indicated that vacuum formed polystyrene 'skins' could be used for the majority of the form of the design(1a); whilst conventionally machined components might be inserted for the areas serving as an articulating surfaces (1b). Gelutong wood was selected as an appropriate material to make the patterns (2). These patterns were created using established pattern making techniques. 'Core prints' (2a) were added to these intermediate patterns to indicate subsequent cutting lines. The final patterns were assembled using a dichloromethane solvent to weld the polystyrene parts together and an epoxy resin to adhere the machined parts.

Subsequently, the patterns were taken to the Castings Advisory Service, Sheffield for advice on reproducing the patterns in aluminium. Lost wax casting was offered as the most suitable, with the production of the necessary wax components from soft silicone mould tools. Further advice on appropriate materials and methods needed in the manufacture of soft silicone mould tools was sought from an expert model maker at a local cutlery factory. At this stage it became apparent that room temperature vulcanising silicone rubber required a powerful 'degassing' vacuum chamber which had to be constructed. Acrylic mould boxes were made complete with aluminium cores (3a), the boxes were then filled with the silicone rubber. These moulds (3b) were subsequently injected with wax at 1.5bar 70°C. The wax parts (3c) were taken for investment at a local casting firm in low melting point aluminium alloy. The resulting castings (3d) required some subsequent machining and hand finishing (3e).

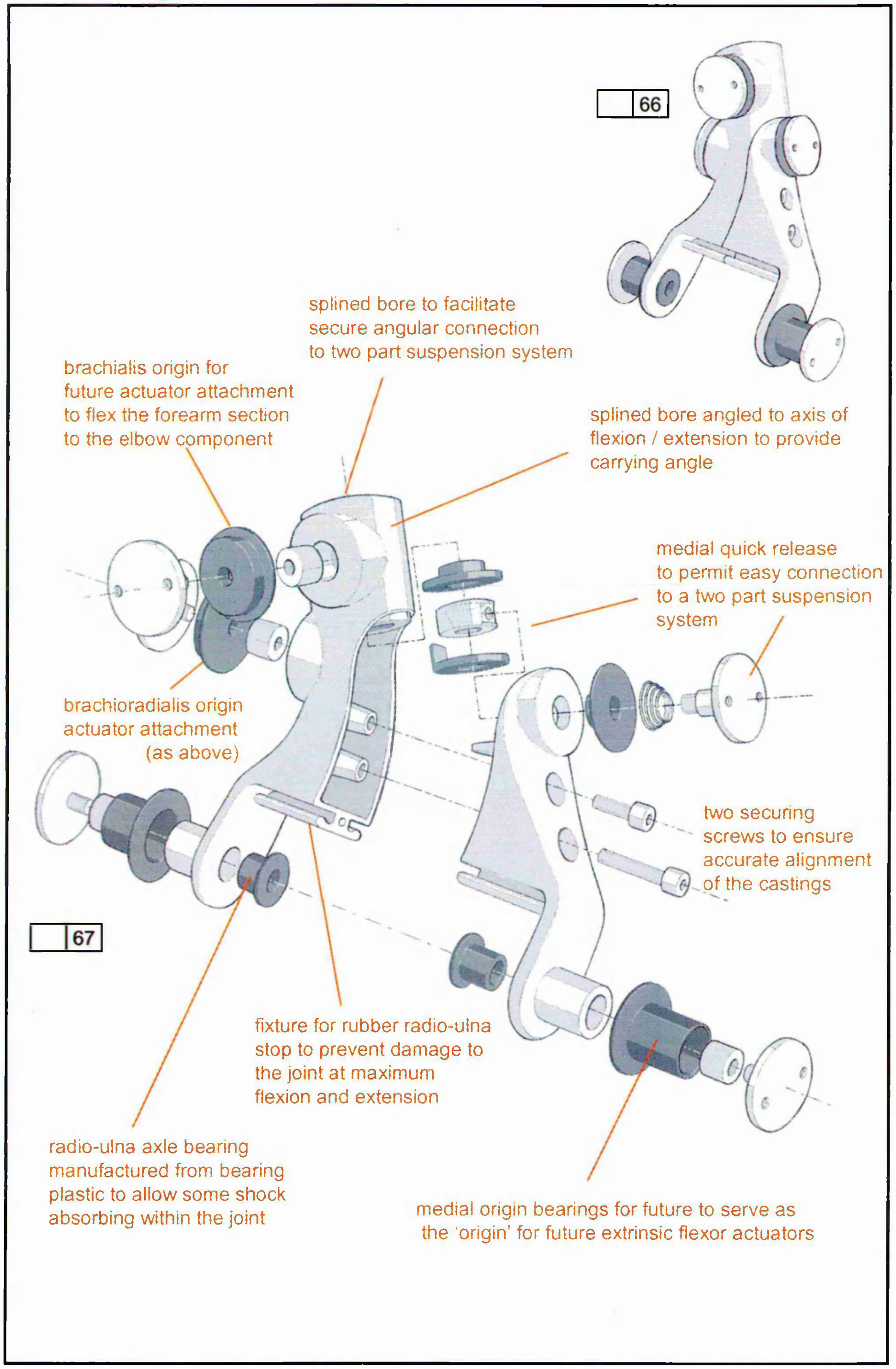
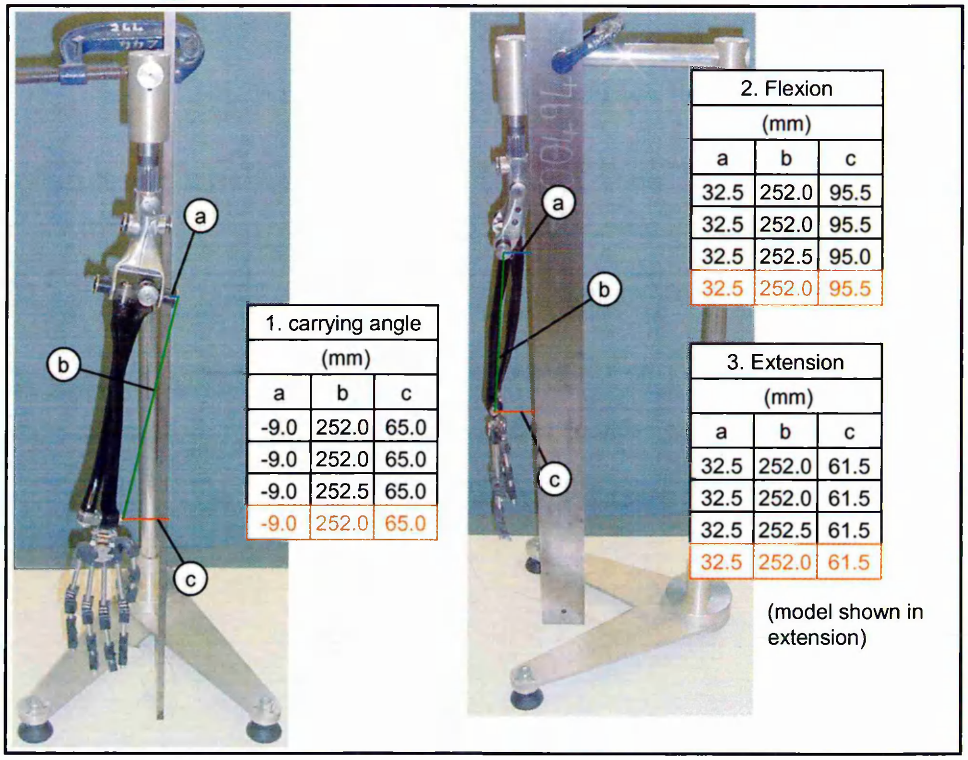


Fig 6.15 Design Principles Embodied Within the Elbow Component



1. carrying angle (mm)		
a	b	c
-9.0	252.0	65.0
-9.0	252.0	65.0
-9.0	252.5	65.0
-9.0	252.0	65.0

2. Flexion (mm)		
a	b	c
32.5	252.0	95.5
32.5	252.0	95.5
32.5	252.5	95.0
32.5	252.0	95.5

3. Extension (mm)		
a	b	c
32.5	252.0	61.5
32.5	252.0	61.5
32.5	252.5	61.5
32.5	252.0	61.5

Fig 6.16 Quantitative evaluation

The model arm was secured to a specially made stand through an appropriate splined peg to fit within the splined bore of the elbow component. The peg was aligned with the vertical support of the stand, as was a ground straight edge. Measurements were taken perpendicularly to this edge to determine both the carrying angle of the model in with the model arm in extended position, and the range of flexion and extension of the model.

Using simple trigonometry the carrying angle as defined by Smith et al 1996 was calculated to be:

Carrying angle

Sin-1((65.0-9.0)/252.0) = 12.8°

Range of carrying angle reported in humans 5-19° (Smith et al 1996)

Calculated range of Movement in flexion / extension

Angle to ground edge at full extension

Sin-1((61.5-32.5)/252.0) = 6.6°

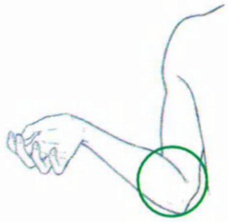
Angle to ground edge at full extension

Sin-1((95.5-32.5)/252) = 14.5°

Therefore, the range of movement in flexion and extension

180-(6.6+14.5) = 159°

Range of movement in intact human arm 145° (Smith et al 1996)



Qualitative Evaluation of the Model by D. Stanley, Orthopaedic Surgeon

The literature review on the anatomy of the elbow indicates that individual variations in anatomy effect the articulation of the elbow (Kapandji 1982). Additionally, there is uncertainty surrounding whether the elbow possesses fixed or changing carrying angle (Stanley and Kay 1998). Consequently, it was thought appropriate to select a professional with an expert knowledge of the anatomy of the elbow to review the model.

An expert in the field of elbow surgery was identified as D. Stanley an orthopaedic surgeon at the Northern General Hospital, Sheffield. D. Stanley is the co-editor of Surgery of the Elbow: Practical and Scientific Aspects, Arnold 1998 and has an interest in the development of new implantable elbow prostheses.

The forearm and elbow model was taken to the D. Stanley's office at the Northern General Hospital for his review. Present at the evaluation, apart from D. Stanley, were C. Rust and G. Whiteley. D. Stanley's review of the model was documented through notes taken at the time of the evaluation. The evaluation lasted approximately 20 minutes.

Initially, a brief outline of the research aims was given by G. Whiteley. Then the model was presented to D. Stanley for palpation

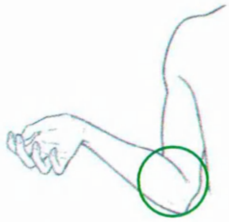
D. Stanley proceeded to palpate the model and view it from multiple angles. His first comments were on the lightness of the model and he inquired as to the materials of its manufacture. From palpation he was content that the range of movement of the model forearm was comparable with that of the human forearm. He indicated that the range of movement in flexion / extension appeared to be greater than normal, however, he added that range of movement at the elbow was also a function of soft tissue, which was absent on the model. He remarked on the possession of a carrying angle in the model, and was content that the single centre of rotation of the model in flexion / extension appeared to feel similar to that of the human elbow.

The remainder of the evaluation indicated he was considering the design as a potential implantable device, although this had not been stated as an aim by G. Whiteley at the start of the evaluation.

On viewing the model from the posterior view he indicated that the linking of the radius and ulna to the humeral (elbow) component was novel. He indicated the principle of linking the radius to the elbow component might have a practical benefit in a future implantable prosthesis. He reported that currently linked prostheses only link the ulna to the humerus, and that common surgical procedure is to excise (remove) the head of the radius. D. Stanley indicated the method of securing the radius to the elbow component through a pin projecting through the centre of the spherical bearing showed a potential principle for an implant using an intermedullary fixing into the radius.

He indicated that if the model elbow was to be used as an implant its form would need to be altered. D. Stanley indicated that 'spaces' that were evident in the model at full extension and were non-existent at full flexion were not appropriate as these 'voids' would eventually be filled by tissue in the body, ultimately limiting the articulation of the joint. Additionally, he indicated that the materials that model was made from were also incompatible with a device fitted inside the body.

The review concluded with D. Stanley expressing an interest to be kept informed on the progress of the research



Discussion

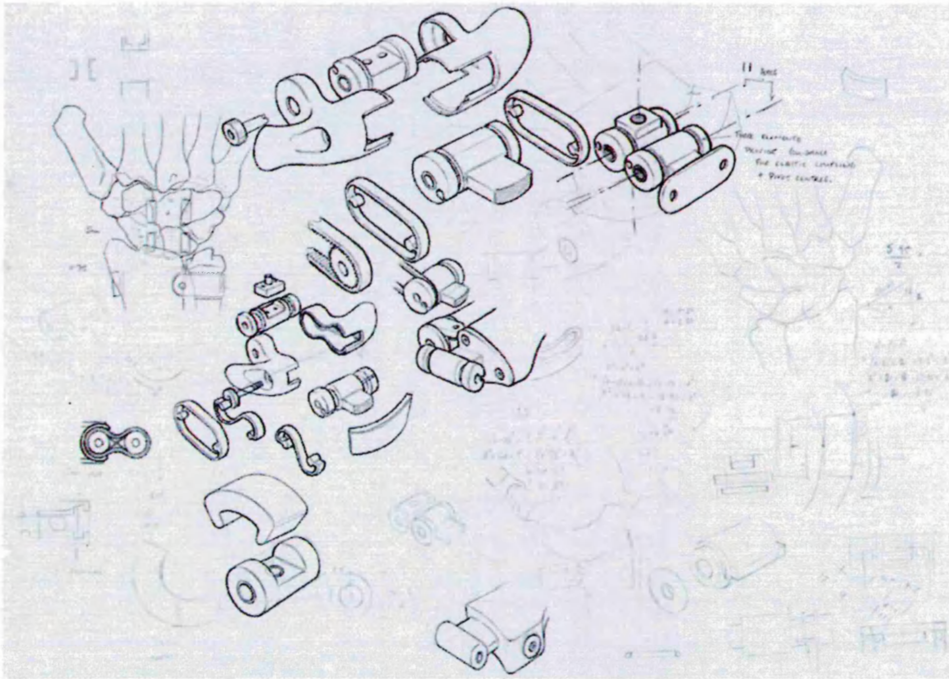
This chapter is distinct from other stages in the design of anatomically analogous joints as it demonstrates that to construct some of the principles for the anatomically analogous model 'speculative reasoning' was needed.

This was necessary in detailing the proximal aspect of the elbow component where suspension of the component from the amputees remaining limb was a factor. Therefore, to develop the proximal form of the component the most successful features of existing suspension systems were considered, resulting in the incorporation of a quick release clip. Additionally, to continue the use of analogy on the distal aspect of the component actuator 'origins' were developed that required communication with specialists involved in the development of novel actuators.

The prototyping methods used were more complex than those used in the development of the finger joints. The use of these methods resulted in a complex model elbow form with a high surface finish. The combination of craft and precision machining processes enabled a complex form to be made that also permitted the articulation of flexion and extension.

The model was reviewed by an elbow surgeon who indicated that the range of movement of the model forearm was what he would expect in a human limb, however, the absence of soft tissue made the comparison of the range of flexion / extension of the model more difficult to assess. Additionally, his evaluation indicated an unexpected potential application for the design principles within the model in the field of elbow implants.

7. Development of an Anatomically Analogous Wrist Joint and the Evaluation of the Skeletal Model Arm



A Sketch Sheet in the Development of the Model Wrist

To complete the model limb to mid humeral level for further evaluation it was considered that another wrist design was necessary that could be used to connect the previously developed hand to the model arm.

The initial wrist design was developed as part of the hand model principally to serve as a tool for the evaluation of the finger joints. The first model wrist was not developed using the same creative reasoning processes that had been used in the development of the model finger joints. It was found that the model wrist appeared less successful than some of the design principles embodied in the model finger joints, indicating that a second wrist model developed using creative reasoning processes may be more successful.

This chapter starts with a comparison of the articulations of prosthetic wrists and those of the human wrist. It then details the initial sketch book idea development that was completed trying to match the articulations of the wrist using principles elucidated in the development of the MCP joint. Conclusions form this exercise are then presented with Dr. Williams's evaluation of the first wrist (evaluations -chapter 4) to shown how this led to the next cycle of creative reasoning.

This is followed by a description of how model making and measurements taken from the intact wrist formed additoinal inputs into the creative reasoning process. The generation of a final design also highlights the extensive use of CAD / CAM techniques in the production of a complex form with a complex embedded mechanism.

As was the wrist was the final component necessary to link the model hand and arm this chapter finishes with the evaluation of the whole model arm including the wrist.

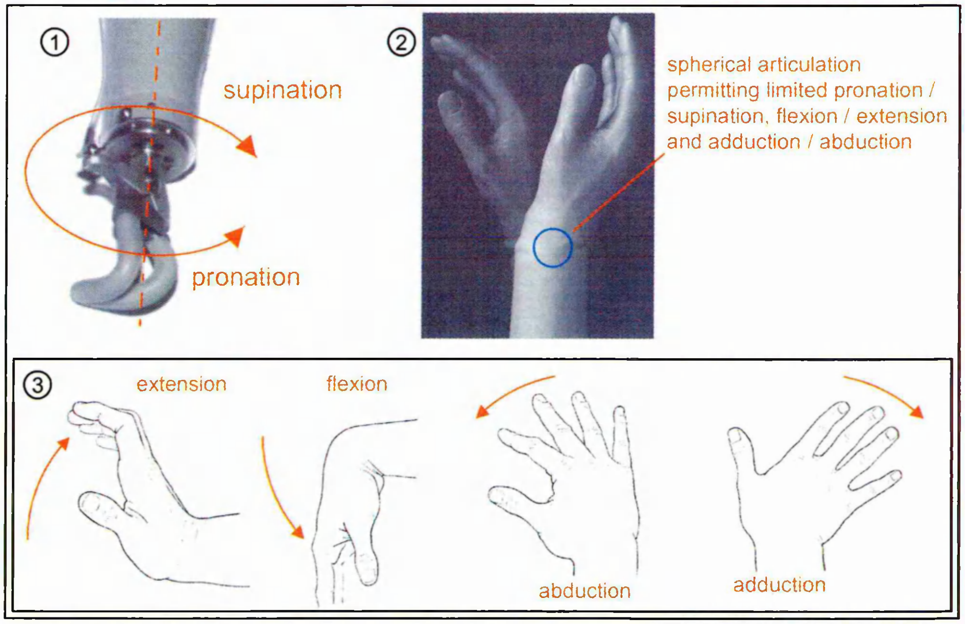


Fig 7.1 Prosthetic wrists and movements of the Human Wrist

As described in the forearm section (prosthetic components - chapter 5) prosthetic wrist components commonly only provide pronation / supination movements (1). However, the human wrist possess articulations for adduction / abduction and flexion extension movements (3) whilst movement of the whole of the forearm provides pronation and supination at the wrist (fig 5.2 (1,2)). Figure 7.1 (2) shows a passive fiction wrist available from Vessa Ltd. (No. 0010 Vessa Multiaxial Wrist Housing), that provides all three degrees of rotational freedom at the wrist. This component is only for the unilateral amputee as it must be positioned by the contralateral hand. The articulating mechanism used in this wrist can only provide part of the range of movement of the normal human wrist and is unlike the structure of the human wrist.

Evidence has shown (evaluation - chapter 4) that the absence of movement in the wrist section of a prosthesis is key in betraying the limbs artificiality. Therefore, it was deemed appropriate to devise articulations that were able to closely replicate the movement of the human wrist joint.

The wrist joint of the first model hand was quickly developed to enable a whole hand form to be created, principally for evaluation of the finger joints. During the development of the first wrist, measurements were taken to estimate the width of the wrist, and it's centres of rotation in flexion / extension, adduction / abduction. This was done by palpating the wrists of the researcher. From the palpation, marks were placed on the skin where visually it appeared that the centres of rotation occurred. The hand was photocopied to provide a two dimensional underlay from which an elementary articulated wrist was developed. Ranges of movement were visually assessed and appropriate stops placed in the mechanical design of the wrist.

The concepts that had been deduced from the observational drawing and sketchbook development of the IP joints were transferred to the mechanical design of the wrist. Like the IP joints, rotations were considered to occur about a single centre, and so simple hinge joints were made (translation of joint principles - chapter 4).

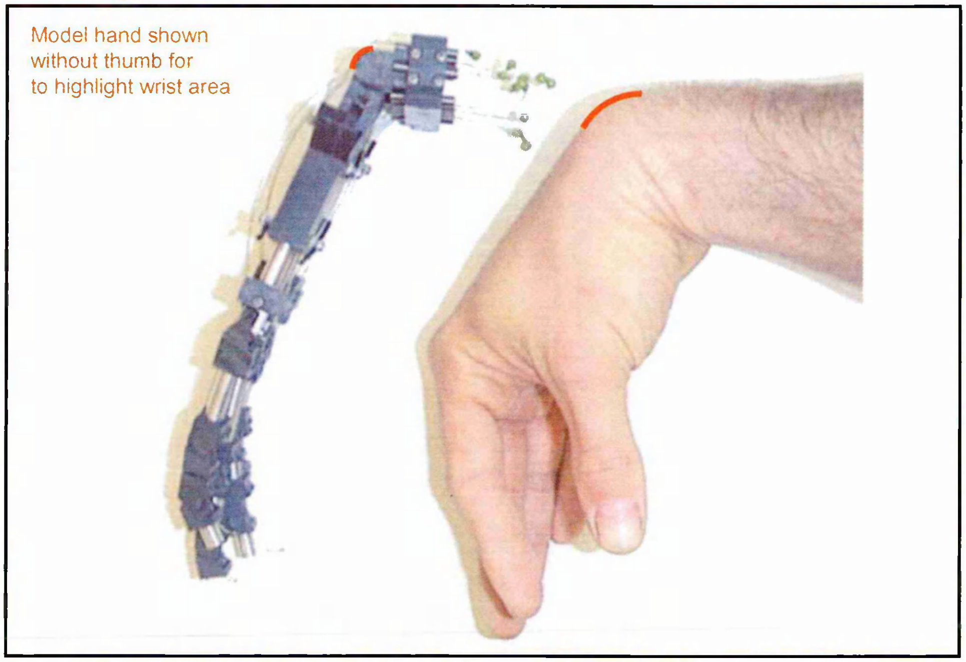


Fig 7.2 Flexion of the Human Wrist and the First Model Wrist

The evaluation of the prototype first model wrist identified several areas where the model wrist appeared to not to be a close analogy to the human wrist (evaluation - chapter 4).

The model wrist was palpated in the plane of flexion / extension by the researcher and compared to the palpated movement of a human wrist. This process highlighted a different 'quality' to the movement of the human wrist. It was also observed that the radius of curvature of the dorsal surface of the model wrist appeared to be different from that of the human wrist. The human wrist possesses a curvature with a much larger radius than that of the model for a similar angle of flexion. This didn't appear to be completely explained by the depth of the skeletal wrist components within the human hand (figure 7.2).

Observations from experiments using the pretensioning rig (evaluation - chapter 4) identified problems at the wrist when the model wire tendons were pretensioned. It was found that the movement of these tendons across the centre of rotation on the wrist in the plane of adduction / abduction resulted in an unstable wrist. Where the wrist would not remain in a neutral position, instead, tending either to latch towards maximal adduction or abduction.

Additionally, the attachment of analogous tendons for the digits highlighted coupling problems associated with flexion and extension movements of the wrist. It was found that extension of the model wrist effectively shortened the flexion tendons to the digits, consequently flexing the fingers. The reverse was found to occur in flexion of the wrist.

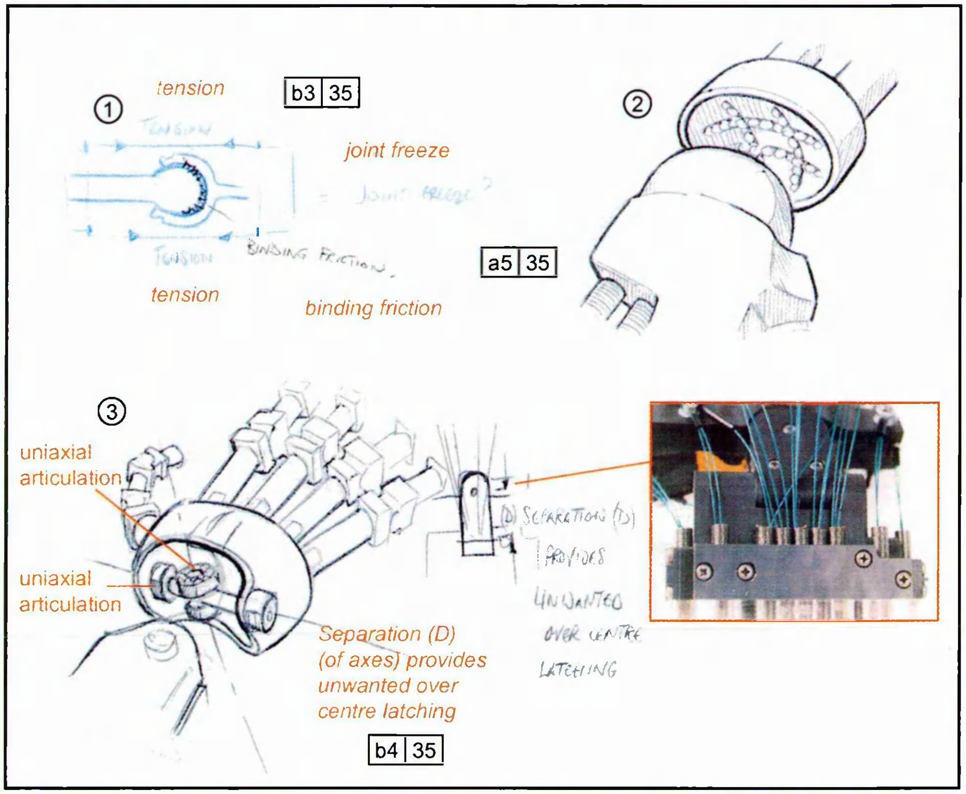


Fig 7.3 Wrist Sketches Using Principles from MCP Joint Development

Initially, for the second wrist design joint principles that had been identified in the development of the MCP joint were considered to solve some of the problems highlighted in the evaluation (evaluation - chapter 4)
To address the problem of the tendency of the model wrist to latch, ideas were considered that unified the centres of rotation of the model wrist in the planes of flexion / extension and adduction / abduction. Eliminating the distance between the centres of rotation would mean that the tendon guides could be much closer to them both . Therefore the analogous tendons would not be able to translate across the joint centre, which had been identified as the major cause of latching.
Sketch (1) shows a spherical design. Like early sketches in the development of the MCP joint this was considered as it possesses a single centre of rotation yet it can be configured to permit only two degrees of freedom. Initially, materials such as bearing plastic for the cup and socket were considered for prototyping this joint (1). However, it was thought that due to the number of tensioned analogous tendons running across the joint in combination with the large surface areas in contact this joint might have a tendency to bind or display a 'jerky' movement due to friction in a plain bearing of this size (1). Therefore, to reduce the areas of contact, rows of ball bearings were sketched within the socket. However, a constrained path for these ball bearings that also allowed fiction free wrist movement could not be adequately resolved (2).
Again to minimise surfaces areas in contact, universal joint ideas were sketched, similar to those sketched in the development of the MCP joint. These depict orthogonally placed uniaxial joints running on frictionless roller bearings (3).

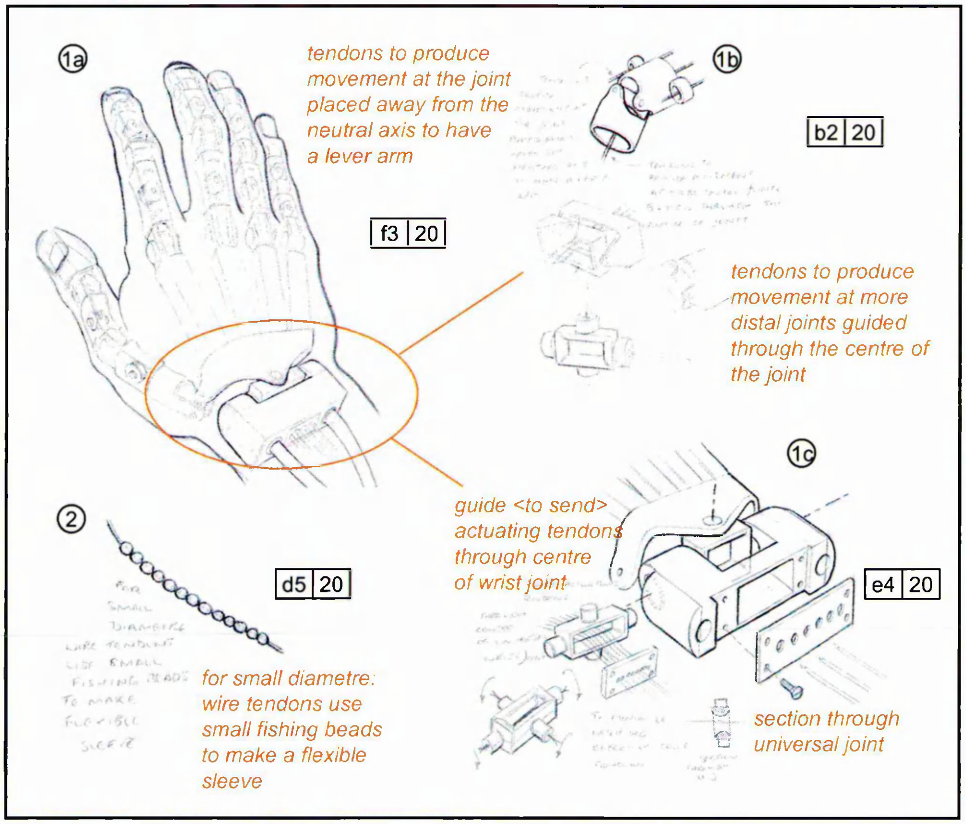


Fig 7.4 Sketch Ideas for Wrist limiting Coupling

The previous ideas appeared only a partial solution to the problems of the first model wrist. Examination of the first model wrist within the tendon test-rig had showed that movement of the wrist joint produced undesired movements of the fingers, due to the mechanical coupling of the wrist to the finger by the analogies of the extrinsic to flexor / extensor tendons (evaluation - chapter 4).

Subsequent sketch ideas were produced that expanded on the universal joint ideas previously developed. The universal joint was sketched as a hollow design (1 a-c) which would guide the extrinsic tendons as closely as possible through its centres of rotation. It was considered that if the extrinsic tendons could pass as close to the centres of rotation as possible the effect of wrist position on finger position would be minimised.

Other ideas to minimise mechanical wrist-finger coupling included guiding analogous extrinsic tendons around the wrist using Bowden cables. However, it was found that commerically available Bowden cables were unsuitable for passage around the tight radii produced by a flexed wrist due to bending of the close wound metal springs within the sleeve of the cable. Ideas for sleeve designs capable of passage around such tight radii were considered using small fishing beads (2). However, simple tests showed that this arrangement produced too much friction when the cable was tensioned within the beads.

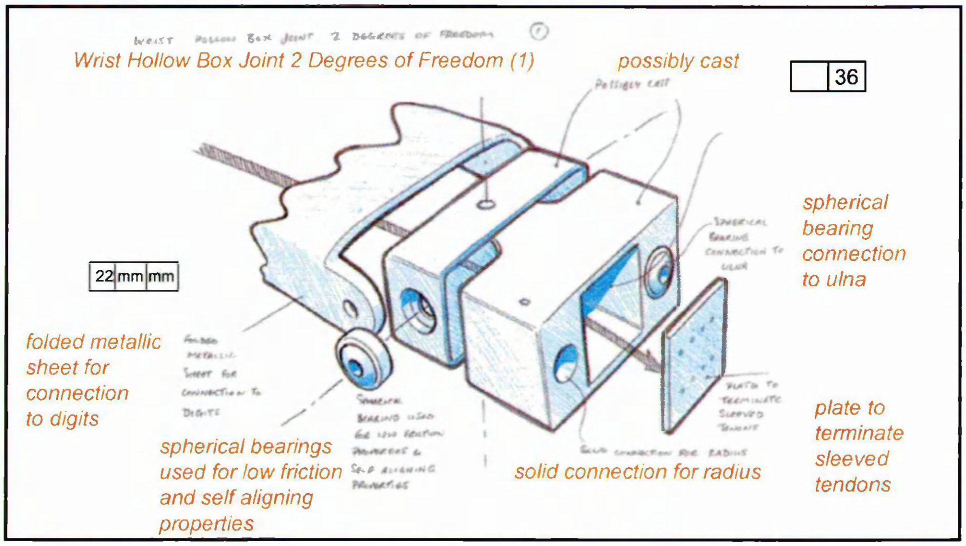


Fig 7.5 Sketch Idea for a Mechanical Solution to Wrist - Finger Coupling

The previous sketch ideas were not considered ideal solutions to the coupling problems. Guiding the tendons as close to the centre of a hollow universal joint was considered the more favourable, however, friction problems were foreseen with cables rubbing against one another.

Review of the first model wrist by hand surgeon Dr. N. Williams, highlighted that the guidance of the tendons around the model wrist did not represent a close analogy of the human anatomy. He considered that the guidance channels in the model were too proximal and that the carpal tunnel and extensor retiniculi that guide the extrinsic tendons around the wrist needed to be much closer to the centres of rotation of the wrist joint (evaluation -chapter 6). Dr. Williams comments also indicated that further observation may point to mechanical refinements of the guidance of the tendons though the wrist to lessen latching in the plane of adduction / abduction. However, as the tendons do not pass through the centre of the human wrist in the plane of flexion and extension (Armstrong and Chaffin 1978) it was unclear how a close mechanical analogy of the human wrist could eliminate undesired movements of the fingers caused by movement of the wrist.

Reference to anatomical literature (Fox 1993) showed that the independent movement of the wrist and the fingers, despite their extrinsic tendon coupling, was managed through low level nervous system interconnections made through the spinal cord (Fox 1993). These interconnections enable the extrinsic agonist and antagonist muscles responsible for finger movement to compensate for movements of the wrist (Armstrong and Chaffin 1978). Consequently, it was considered that a mechanical solution to the coupling problem might not be appropriate. A review of advanced robotics literature indicated research into possible actuator control strategies that might permit a control system analogy of the nervous system connections of the human body (Hannaford et al 1995).

The early wrist sketch ideas showed that a mechanical design may not be able to solve all of the coupling difficulties of the first model wrist. However, it was thought that further observational drawing studies were required to inform the next cycle of wrist joint design. It was anticipated that observational drawing might elucidate more subtle kinematic principles that could be used in the next wrist design.

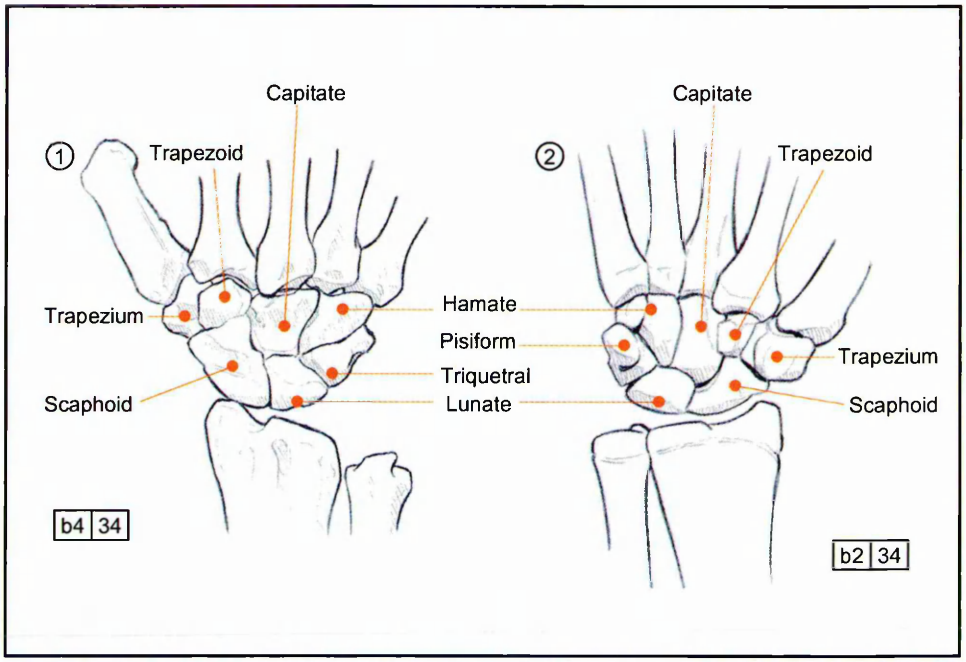


Fig 7.6 Observational Drawings of the Human Wrist

Observational drawings were produced of the human wrist from an anatomical skeletal model arm to gain an understanding of the three-dimensional form of this joint. The figures above show dorsal (1) (palm down) and volar (palm up) (2) views of the skeleton of the human wrist.

It can be seen that the human wrist is composed of numerous small bones called carpal bones. These bones are formed so that they can move relative to one another (Berger et al 1982) and in the intact human arm they are connected together by numerous ligaments (Youm and Flatt 1982). The form of the carpal bones is such that in the neutral position the fit between the bones is highly congruent allowing relatively large loads to be supported by the wrist (Kapandji 1982).

As the following pages will include a discussion of the boney anatomy of the wrist it is appropriate to become familiar with this nomenclature.

The labels of the carpal bones reflects the form of these bones. Carpal is derived from carpus indicating that the wrist is divided into many pieces (Lewis and Short 1962.). The individual names of the carpal bones are also descriptive of their form. The carpal bone at the base of the thumb, the trapezium indicates that it has a roughly quadrilateral shape with two sides parallel (Lewis and Short 1962). The neighbouring trapezoid carpal indicates that it is of quadrilateral shape with no sides parallel. The label capitate indicates that this bone possess a large 'head' (Lewis and Short 1962). The hamate carpal is derived from the Latin - hook and alludes to its hooked form (Lewis and Short 1962) that provides part of the support for the 'carpal tunnel' (Kapandji1982). The scaphoid carpal is derived from the Latin for vessel or boat (Lewis and Short 1962), and describes the concave and convex elements of this bone. The title lunate describes the crescent moon shape of this bone. The carpal labelled triquetral described the three sided form of this bone (Lewis and Short 1962), whilst the label pisiform indicates that this bone is of round and of a small size (Lewis and Short 1962).

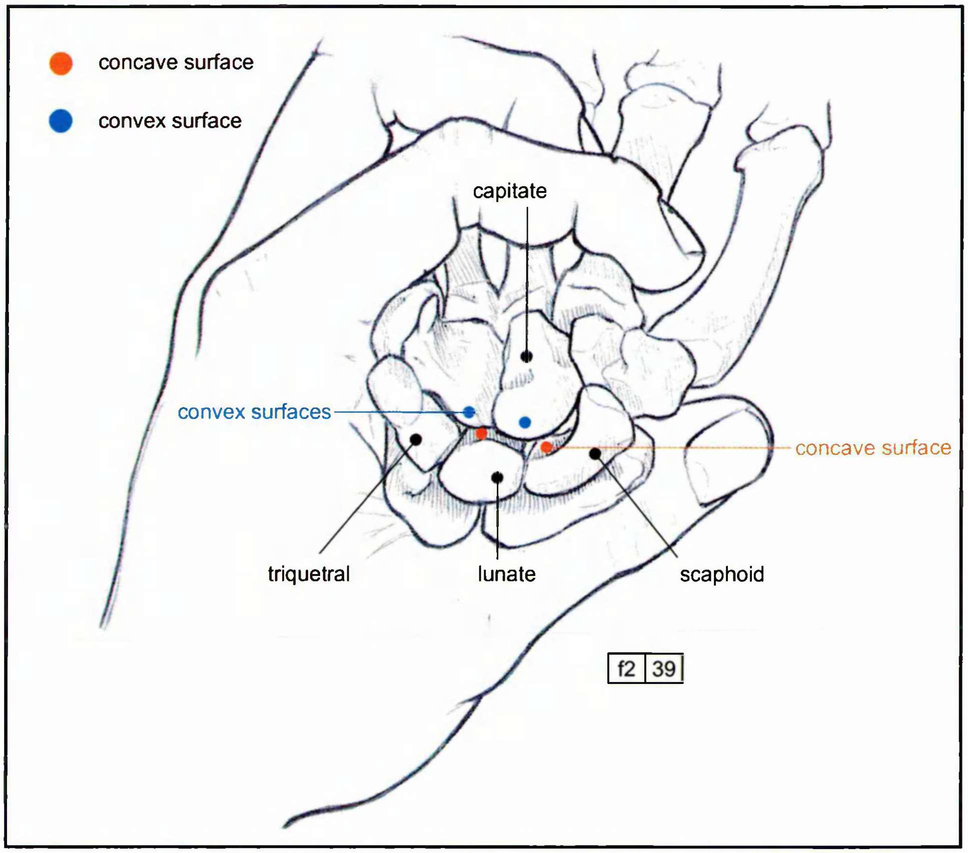


Fig 7.7 Observational drawing of the Midcarpal Joint

Observational drawing highlighted several areas on the carpel bones that were smooth and appeared to possess portions of simple geometric forms, such as partial spheres and cylinders. It was reasoned that these may indicate possible articulating surfaces. Such surfaces were observed on the head of the capitate and hamate, and that these appeared to be part of a line of articulating surfaces, transversely dividing the carpal bones into two rows.

Further observational drawing was performed with the skeletal wrist 'hyperextended' to reveal the form of the articulating surfaces between the two rows of carpals. The exercise showed that the convex head of the capitate rotates with a concavity of the lunate. Additionally, it showed that the capitate similarly rotated within the saphoid, whilst towards the thumb side of the saphoid, the saphoid itself presented a convex face for rotation within the trapezium. This appeared mirrored on the triquetral side with the hamate presenting a convex face to the lunate and part of the triquetral, then reversing, so the triquetral presents a convex face to the hamate.

It was considered that further literature review was required to verify the presence of a mid-carpal articulation during actions of the intact wrist.

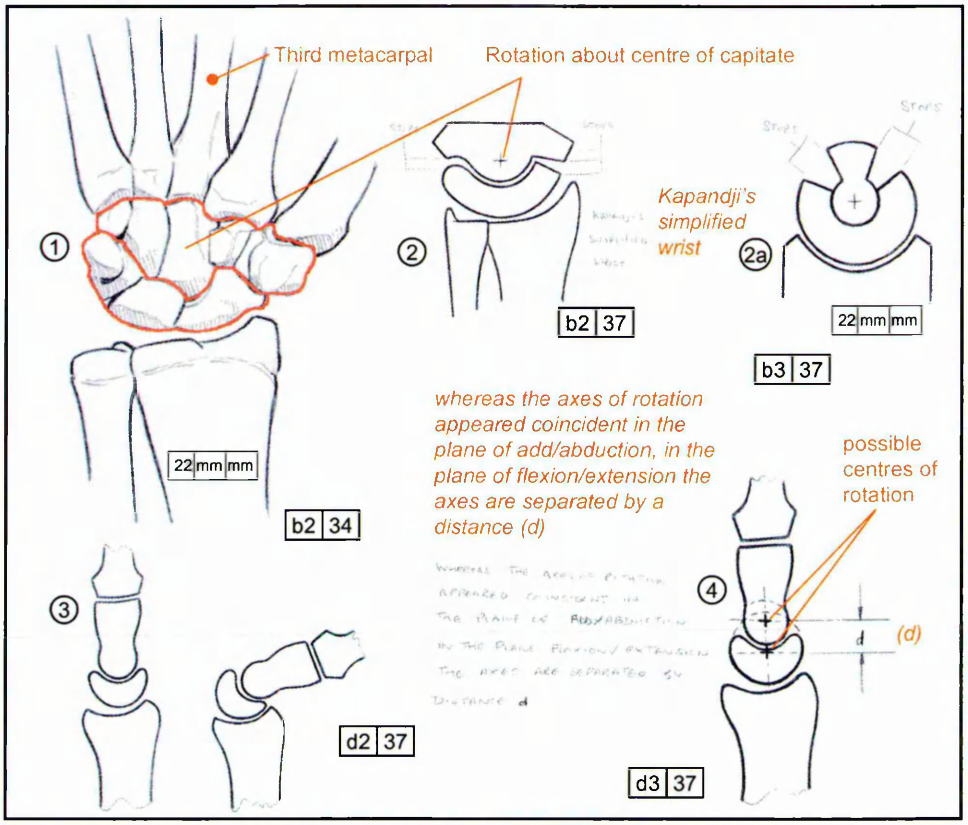


Fig 7.8 Articulations of the Wrist

The literature review indicated that two theories have been put forward for the action of the carpal bones within the intact wrist. One theory attaches significance to a 'rigid' the connection of the lunate, capitate and third metacarpal. This is referred to as the 'capitate column' theory, where little transverse movement occurs between these bones to provide maximum stability to the third metacarpal (Berger et al 1982). The second theory divides the carpal bones into distal and proximal rows (Kapandji 1982). The distal row includes the trapezium, trapezoid, capitate and hamate, whilst the proximal row includes the triquetral, lunate and scaphoid (Kapandji 1982) (1). During flexion / extension and adduction / abduction movements of the wrist it is stated that the distal and proximal rows of carpal bones rotate relative to one another (Kapandji 1982). From observational drawing studies of the articulating surfaces between the capitate and lunate it appeared that the form of these bones would allow movement rather than stop it. Therefore, the carpal row theory was followed as the carpal column theory supports no movement between these carpals.

Simplified drawings produced by Kapandji were reproduced (2), and further 'mechanised' (2a). Figure 7.7(2) shows Kapandji's contention that adduction and abduction movements of the wrist occur about a point approximately at the centre of the head of the capitate (Kapandji 1982). The distal carpal row rotates relatively to the proximal row, however, the rows have roughly concentric articulating surfaces resulting in rotations about a single centre (2a). During flexion and extension of the wrist Kapandji states that rotations occur between the distal and proximal carpal rows, as can be seen in the cross sections (3). A simplified cross section (4) shows how if the articulating surfaces are considered to be radii of circles then this motion might be considered as occurring between to separate distinct centres.

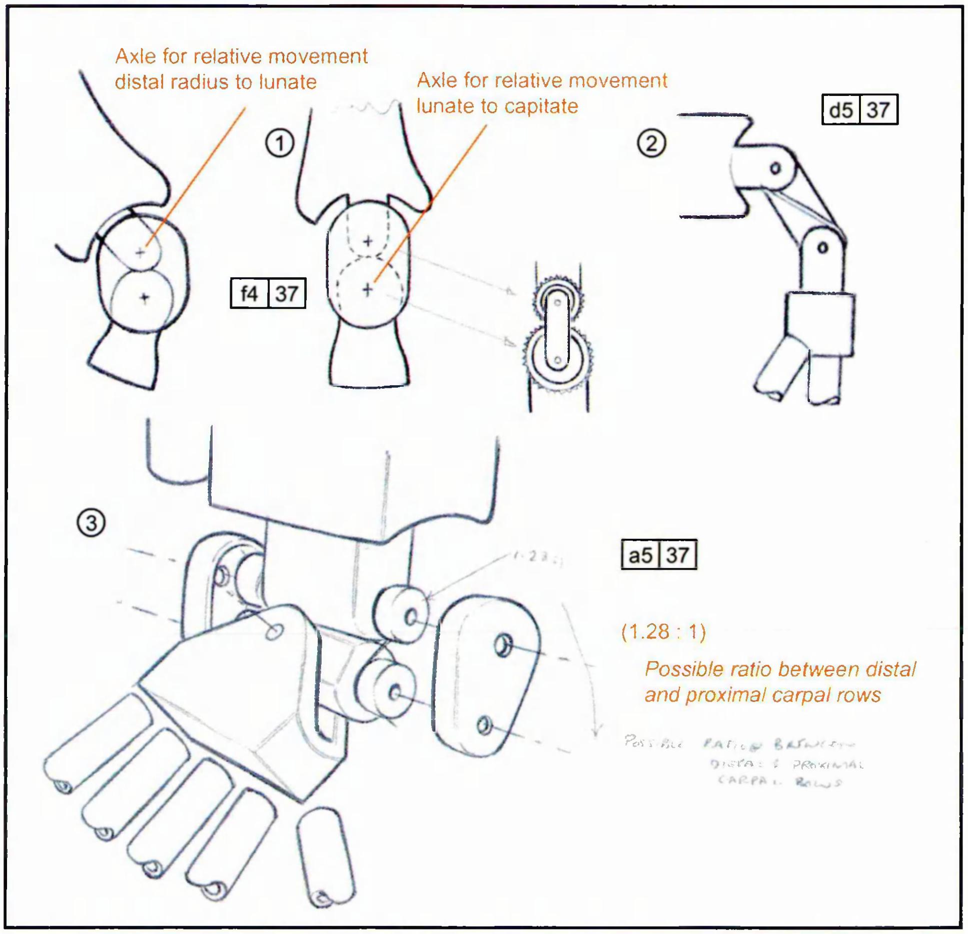


Fig 7.9 Sketches for Distal and Proximal Carpal Row Wrists

Focussing on the articulation of the wrist in flexion and extension; several means of coupling analogous distal and proximal rows were sketched. Based on the simplified cross section shown in figure 7.8 (4).

Initial sketches explored the use of gear teeth to connect the axles (1). Whilst sketches (2) and (3) explored connecting the axles using a pulley belt.

From literature review an approximate ratio of 1.28:1 was determined as the ratio between movement of the capitate to lunate compared to the movement of the lunate to the distal head of the radius during flexion and extension movements (Berger et al 1982). To achieve a similar ratio between the axles different sized gears and pulley wheels were considered. This approach was subsequently rejected as it was thought that a serrated gear would not be an appropriate surface for analogous tendons to run over. Consequently, further sketch book development centred on a pulley connection.

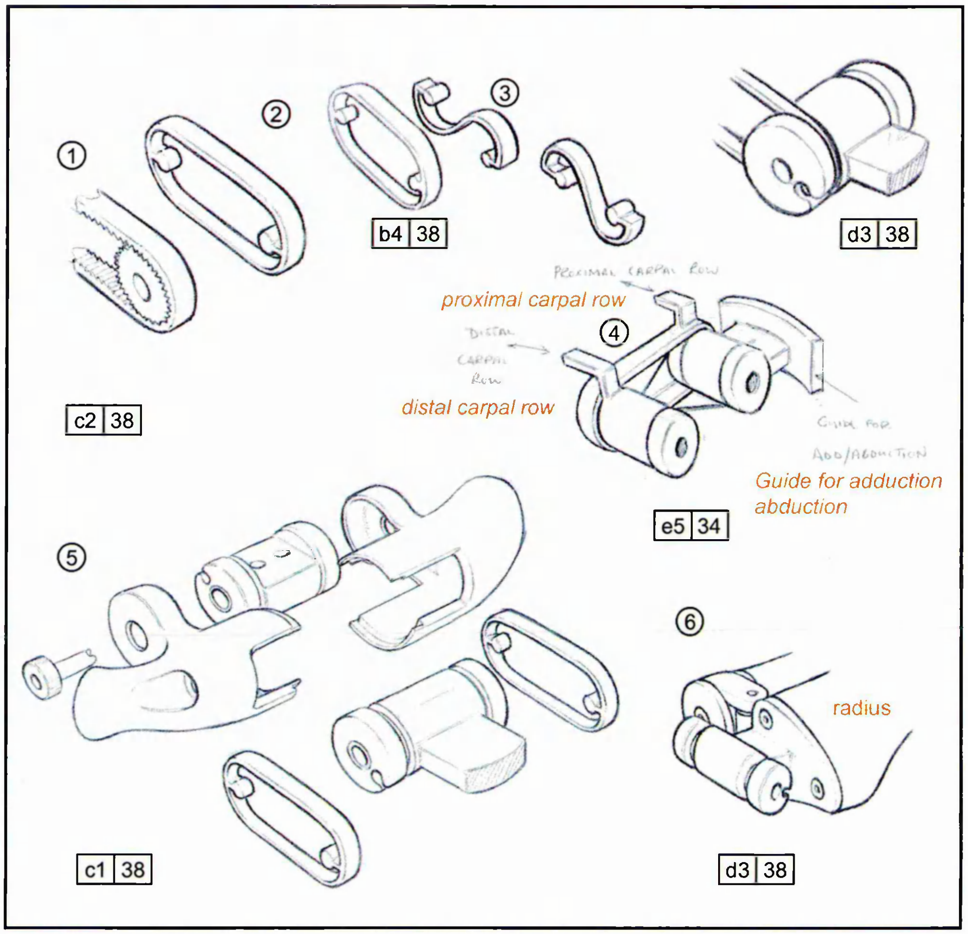


Fig 7.10 Sketches for Distal and Proximal Row Coupled by Pulleys

Different pulley belt types were considered, such as miniature geared belts (1) and belts with two lugs fitting into corresponding holes within the pulley wheels (2). Crossed belts were also sketched (3), however, these were rejected on the grounds of introducing possible assembly errors. It was considered that a simple continuous belt, such as that shown in sketch (2) would be the most appropriate for prototype manufacture.

Sketch (4) shows projections from each axle labelled distal and proximal carpal row. This sketch and sketch (5) investigate the possibility of producing axle covers to the rotating sections corresponding to the outline form of the proximal and distal rows. Axle covers were proposed to present a smooth face for the passage of tendons over the wrist mechanism. Sketch (6) indicates that in a similar way to the anatomy the main connection between the wrist and forearm should be through the analogous radius bone (Norkin and Levangie 1992).

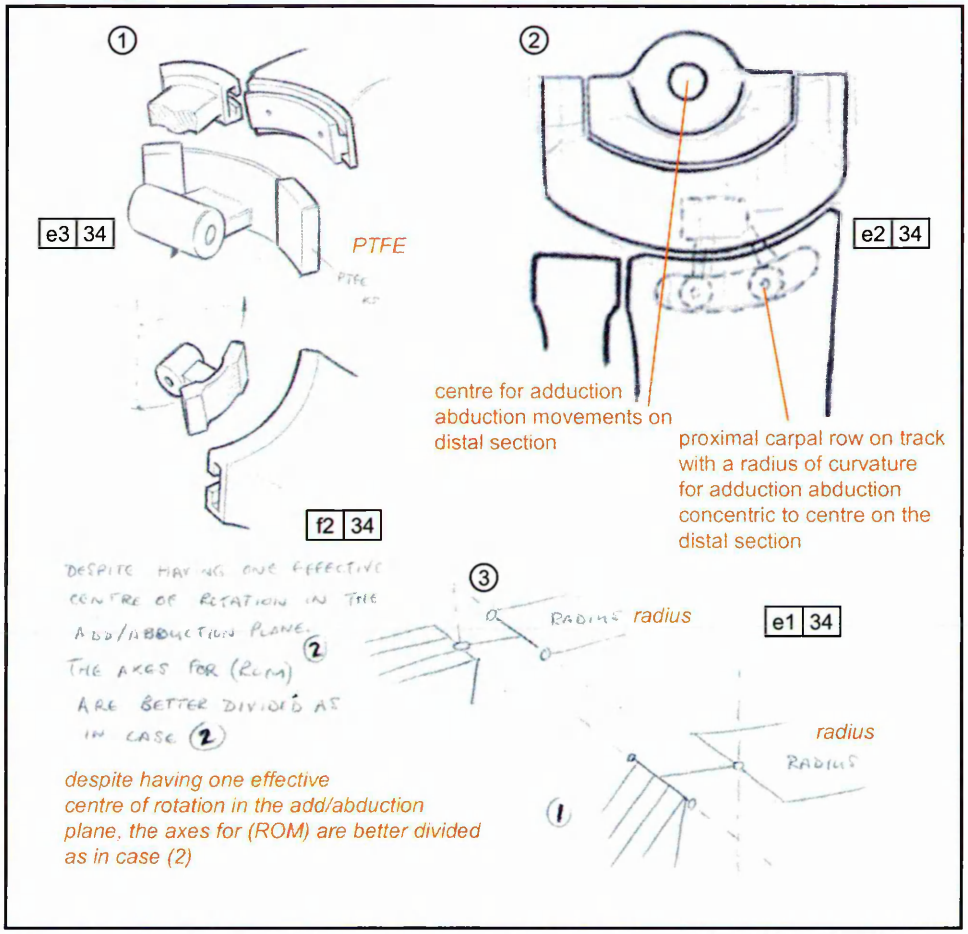
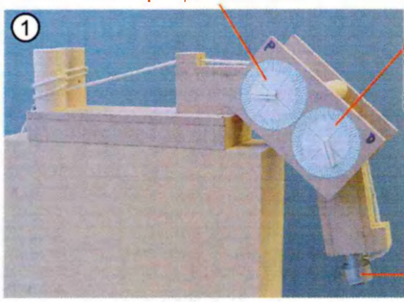
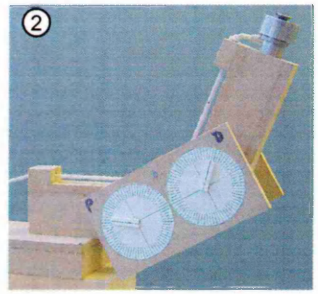


Fig 7.11 Initial Design Ideas for Adduction and Abduction Movements

Progressing from Kapandji's theories of wrist flexion / extension, ideas were developed for mechanical structures combining these articulations with articulations that would permit movement in the plane of adduction / abduction. The simplified sketch depicted in figure 7.8 (2a) indicates that whilst the distal and proximal rows may move independently during adduction and abduction, they still appear to rotate about a single point at the centre of the capitate, a view supported in the literature (Kapandji 1982, Youm and Flatt 1980). Therefore, sketch ideas were produced of mechanical arrangements permitting the fixture of the proximal axle to rotate about this point (1, 2). It was initially proposed that this would be achieved using a curved track possessing a radius of curvature concentric with centre point on the distal carpal row (1, 2). However, further sketch investigation indicated that such a mechanism would allow adduction and abduction of the wrist when it was maximally flexed or extended (3). From palpation this did not appear to occur. Instead it appeared that the plane of adduction abduction, although diminishing, appeared to follow the frontal plane of the hand as it is flexed and extended. Literature on the tendon routing corresponding to the muscles chiefly involved in wrist movement (flexor carpi ulnaris, flexor carpi radialis, extensor carpi ulnaris and extensor carpi radialis longus and brevis) (Smith et al 1996, Lamb et al 1989) appeared to support this reasoning. Therefore, it was concluded that the distal carpal section, following the frontal plane of the hand, should be the only section with an articulation for adduction / abduction movements.





1. no added mass		2. 62g mass		3. 612g mass	
p (deg)	d (deg)	p (deg)	d (deg)	p (deg)	d (deg)
5.0	5.0	5.0	5.0	5	2.5
10.0	10.0	10.0	10.0	10	2.5
15.0	15.0	15.0	15.0	15	2.5
20.0	20.0	20.0	20.0	20	2.5
25.0	25.0	25.0	22.5	25	2.5
30.0	30.0	30.0	27.5	30	2.5
35.0	35.0	35.0	32.5	35	2.5
40.0	40.0	40.0	37.5	40	2.5
45.0	45.0	45.0	42.5	45	5.0

Fig 7.12 Testing the Linkage of Distal and Proximal Wrist Axles

At this stage it was considered that mechanical joint principles had been derived for both flexion / extension and abduction / adduction movements. However, it was unclear how the proposed coupled flexion / extension mechanism would behave during actuation from extrinsic tendons; and supporting weight on its distal section. Therefore, a scale model of the mechanism was made with angle indicators connected to each axle. The proposed coupling mechanism worked on equally sized pulleys, therefore similar rotations were expected on each dial as the tendon was pulled.

The test-rig was made from wood. The pulley belts were stout elastic bands, and the tendons were cotton string.

On pulling the tendon, with no mass attached to the distal section, the dials read approximately similar rotations. However, on increasing mass, rotations on the distal section became greater. It was observed that this was occurring due to extension of the elastic band pulley belt. It was reasoned that this was due to the moment between the mass and the distal axle being less than the moment to the proximal axle. It was thought that an analogous wrist exhibiting this behaviour may not be advantageous from both functional and cosmetic perspectives.

It was evident at this stage that to produce a suitable coupled mechanism for wrist flexion and extension movements would require significant further development. Therefore, it was thought appropriate to review the movements of the intact human wrist to ensure that a simple uniaxial articulation was not in fact appropriate.

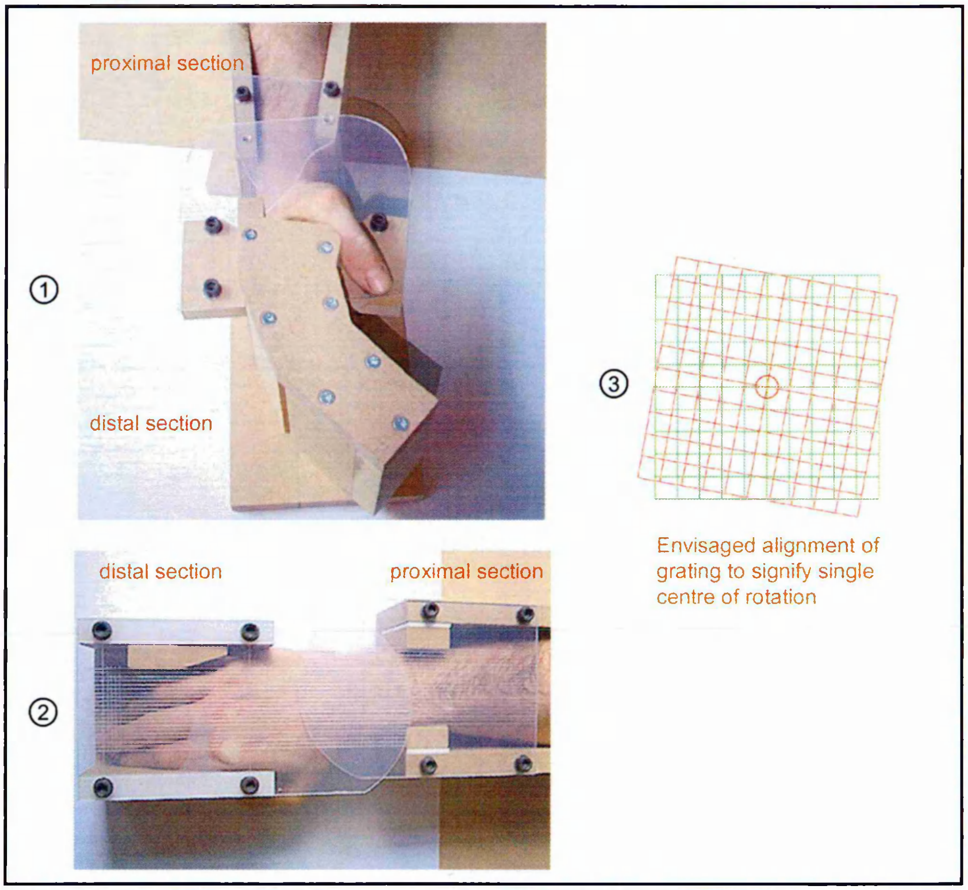


Fig 7.13 Splint Tests to Examine the Movement of a Human Wrist

To examine the movement of an intact wrist, closely fitting wooden splints were made to fit onto one of the researcher's hands. The splints were devised to have a flat base through which the proximal splint was rigidly attached to a wooden board, whilst the distal section could be freely translate on the board. This was done to limit the movement of the joint to a single plane for analysis. Two sets of splints were devised. One to capture movement of the wrist in the plane of flexion/ extension(1), and a second to capture movement in the plane of adduction / abduction (2).

Initial tests were performed to determine whether a single centre of rotation could be located during movements of the wrist. This was done by fixing transparent acrylic sheets marked with grid lines to the proximal and distal sections. It was envisaged that if a single centre of rotation existed for either movement then this could be seen in alignment of grid lines (3). The researcher slowly moved his wrist from maximum adduction to maximum abduction, while an observer looked for apparent alignment of the grids. It was found that the grids did appear to align on a single point in the mid-range of adduction and abduction movements. This apparent centre was marked on the proximal arcylic grid. However it was found towards the extents of movement this marked centre would change.

Although in the mid-range of adduction / abduction movements an apparent single centre could be found, no single centre of rotation could be determined in any part of the wrist movement in the plane of flexion and extension.

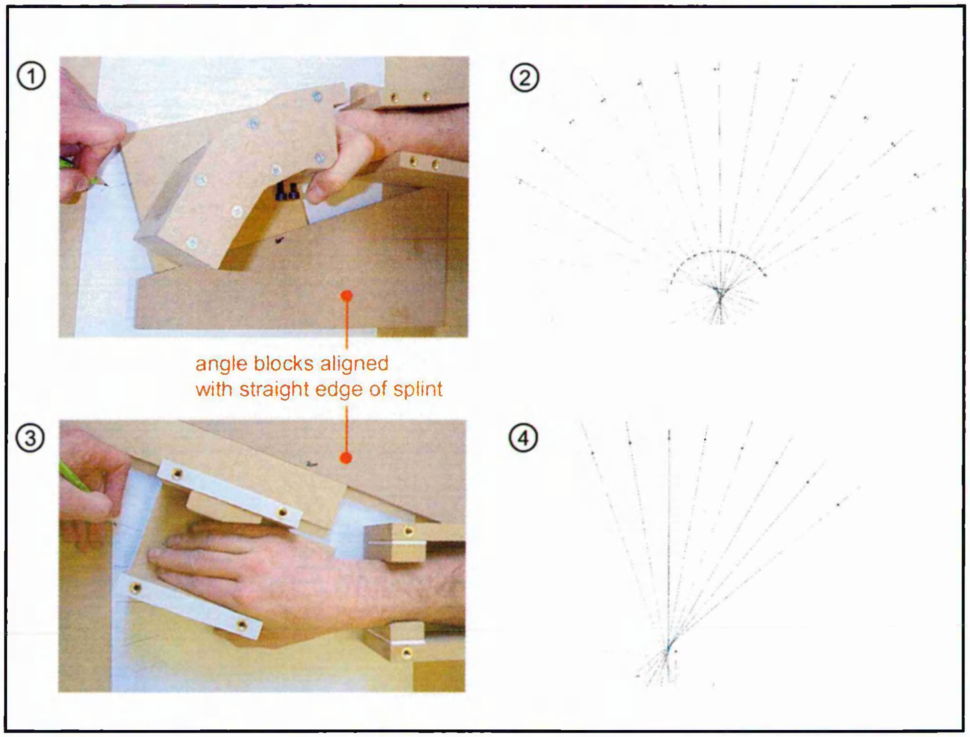


Fig 7.14 Wrist Adduction Abduction Articulation

The absence of a single centre of rotation indicated that the articulation of the wrist in this plane was more complex than a simple uniaxial joint. To ascertain what type of articulation was being demonstrated it was thought appropriate to use a visual method.

Reference marks were placed on the distal splints (1 and 3) and cartridge paper placed under them. Using blocks angled at 10 degree increments marks were made on the cartridge paper corresponding to the reference mark on each distal splint. This procedure was followed multiple times for both the flexion / extension and adduction / abduction splints.

The marks on the cartridge were then scribed through with an adjustable set square. The resulting loci (2 and 4) produced were then examined.

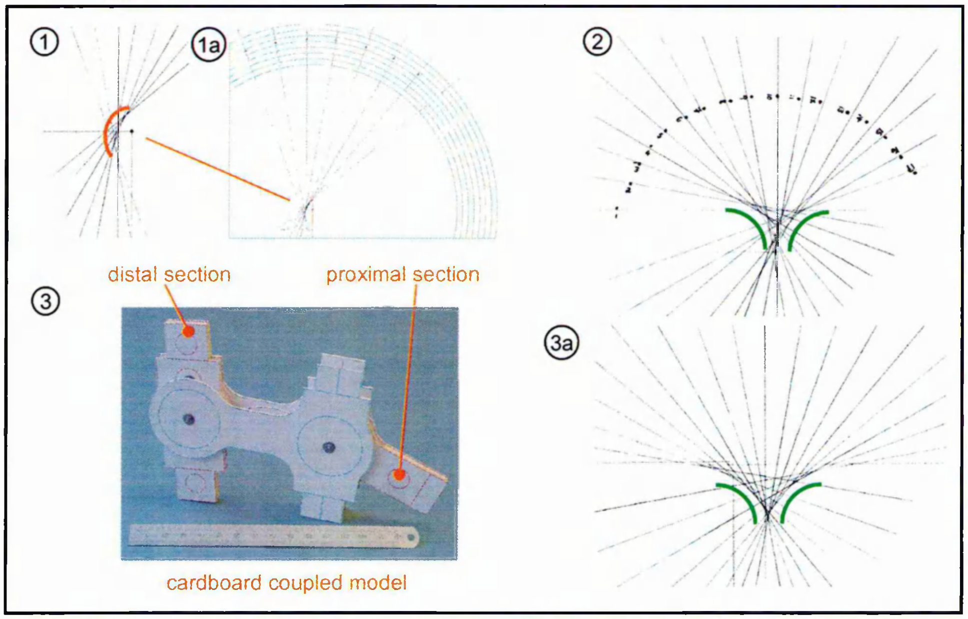


Fig 7.15 Analysis of the Splint Produced Loci

The loci of points that was produced by the splint in the plane of adduction / abduction is shown in figure 7.14 (1). It was expected that the scribed lines would all terminate at a single point indicating a single centre of rotation movement in this plane. However, figure 7.14 (1) shows that the lines do not terminate in a single point. It was reasoned that these lines still indicate a single centre of rotation, only the reference mark on the splint was slightly to the left of the true centre of the joint. This evident as a single arc loci was produced (1). The approximate centre of the marked points was found using a transparent overlay marked with a centre point together with corresponding narrowly spaced concentric arcs (1a). The overlay was manoeuvred over the sheet of recordings to ensure the best fit of the arc of points between the narrow lines. The position of the centre was then marked on the sheet of recordings. The position of these marked centres appeared similar between recordings. Subsequently, this centre position was marked on the board relative to the proximal splint.

Similar recording were taken for flexion / extension movements (2). Unlike the recordings for the plane of flexion / extension, the absence of a single termination of the scribed lines didn't appear consistent with splint misalignment. It was reasoned that for the near 180 degree movement constant misalignment from a single centre would be evident as a single arc, similar but with a more complete circumference to that seen in the previous recordings (1a). However, the recordings showed two mirrored arcs (2).

Concurrently, measurements were taken from anatomical skeletal models to develop a simple scale model of a possible mechanism to approximate the coupled movements of the distal and proximal carpal rows (3). The proximal part of this was secured to a board whilst a straight edge was fixed to the mobile distal section. A procedure was followed similar to that used with the splints to record the locus shown in figure 9.14 (4). It clearly shows the characteristic mirrored arcs that was evident in the flexion / extension splint recordings.

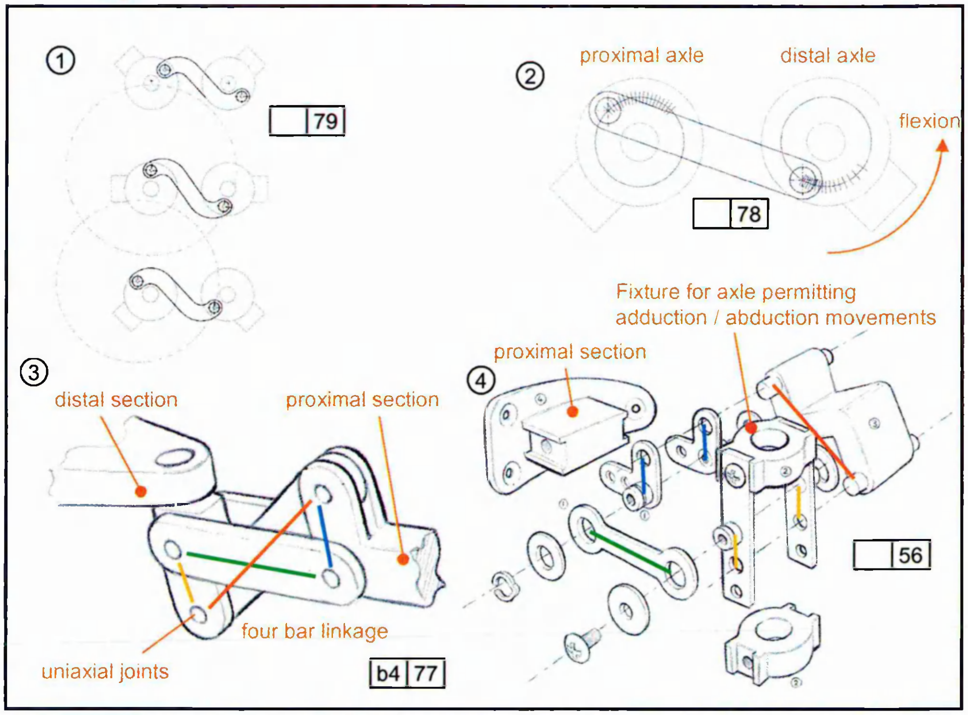


Fig 7.16 Initial Sketches for Rigid Axle Coupling

The comparison of the loci recorded in the plane of flexion / extension for both the human wrist and the coupled cardboard model indicated that a coupled twin axle design might be appropriate.

Initially, couplings had been considered that relied on miniature pulley belts. However, it had been found that these might be vulnerable to stretching with an added distal load. Consequently, it was thought that the coupling of the axles should be simpler and more robust. The simplest coupling of the axles was considered to be a single rigid link (1). Initially, sketch ideas (1) were proposed that retained the historical cylindrical forms that had been necessary for the function of the the pulley system. Using CAD software the proposed coupling of the distal and proximal axles via this link were investigated (1). It was found that by using a scrolled link the distal section could be made to rotate the necessary 180 degrees to approximate the range of movement of a wrist in flexion / extension (Kapandji 1982). However, during this process it was found that rotation of the distal and proximal axles did not appear to be exactly matched unlike the pulley system. This was further investigated by marking the necessary arc of movement on the proximal section in 5 degree increments. The corresponding position of the link on the distal axle was then marked. It was evident from this exercise that the relative increment of movement on the distal section increased as flexion increases (2). The simple model that had been used to produce the recordings that were compared with the recordings of human wrist had been linked in this simple manner. Therefore, it was reasoned that this type of coupling might in fact be appropriate.

It was realised at this stage that the essence of the proposed mechanism relied on four bars being linked through simple uniaxial joints (3). Therefore, designs were proposed that dispensed with the previous cylindrical forms. Focus shifted to combining the four bar link mechanism with an axle on the distal section that would permit adduction / abduction movements of the hand (4).

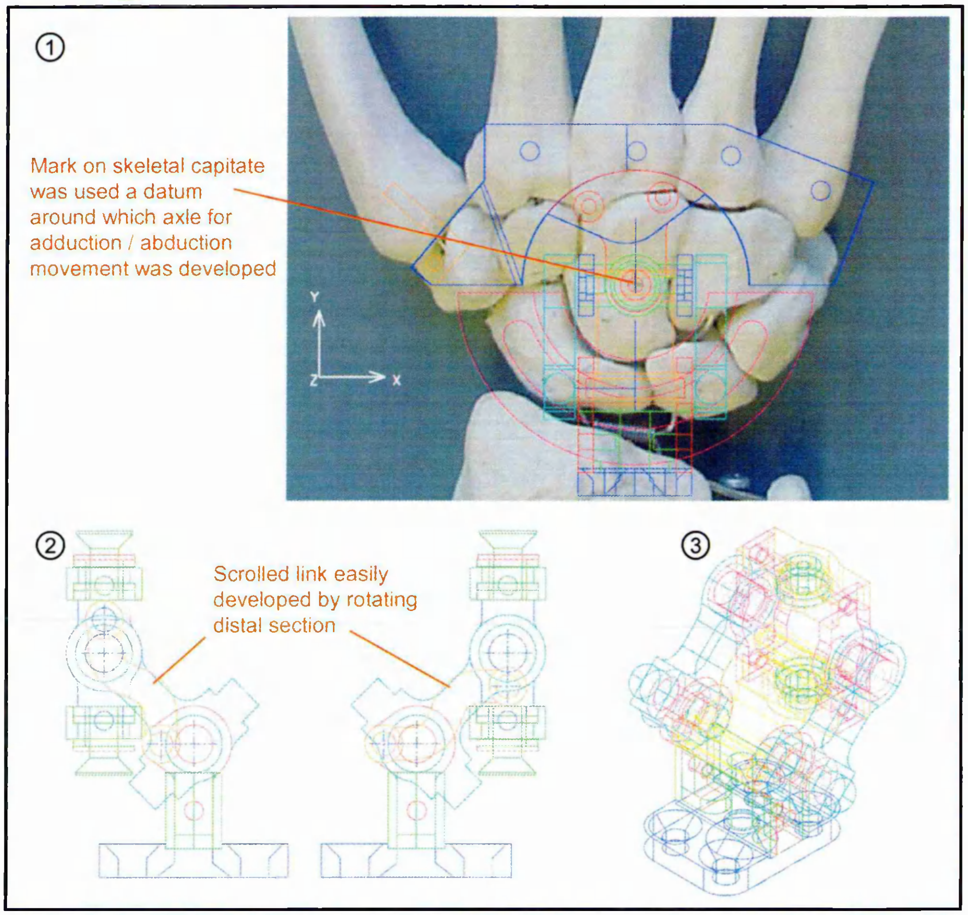


Fig 7.17 CAD joint development

Much of the previous joint development had progressed through sketchbook idea development. However, it was considered that both due to the small scale and the multi-articulate nature of the proposed design that further development would be more appropriate using CAD software.

Although the simple model had shown similar characteristics to those of the wrist, the four bar link mechanism is quite unlike the boney and ligamentous structures of the human carpus (Kapandji 1982). Therefore, extensive development work was needed to detail the dimensions of the mechanism to fit within the volume of the human skeletal carpus. As an aid to development, photographs of the skeletal carpus were used as backgrounds on the CAD screen (1). Using CAD software it was found easier to develop the forms of the links necessary and ensure the correct interference free range of movement of the mechanism. Figure 7.18 (2) shows the scrolled link in gold, the development of the shape of this link was aided by being able to easily rotate the distal section. The dimensions used for the links involved in the flexion / extension mechanism came from measurements of the diameters of the lunate and capitate from skeletal anatomical models.

Anatomical literature indicated wrist movements could be considered as occurring about a centre approximately at the middle of the capitate (Youm and Flatt 1980, Kapandji 1982). This appeared consistent with the recordings from the splints. Therefore, a mark was placed on the skeletal capitate (used as the CAD background) and this was used as the datum around which the articulation for the adduction / abduction mechanism was developed (1).

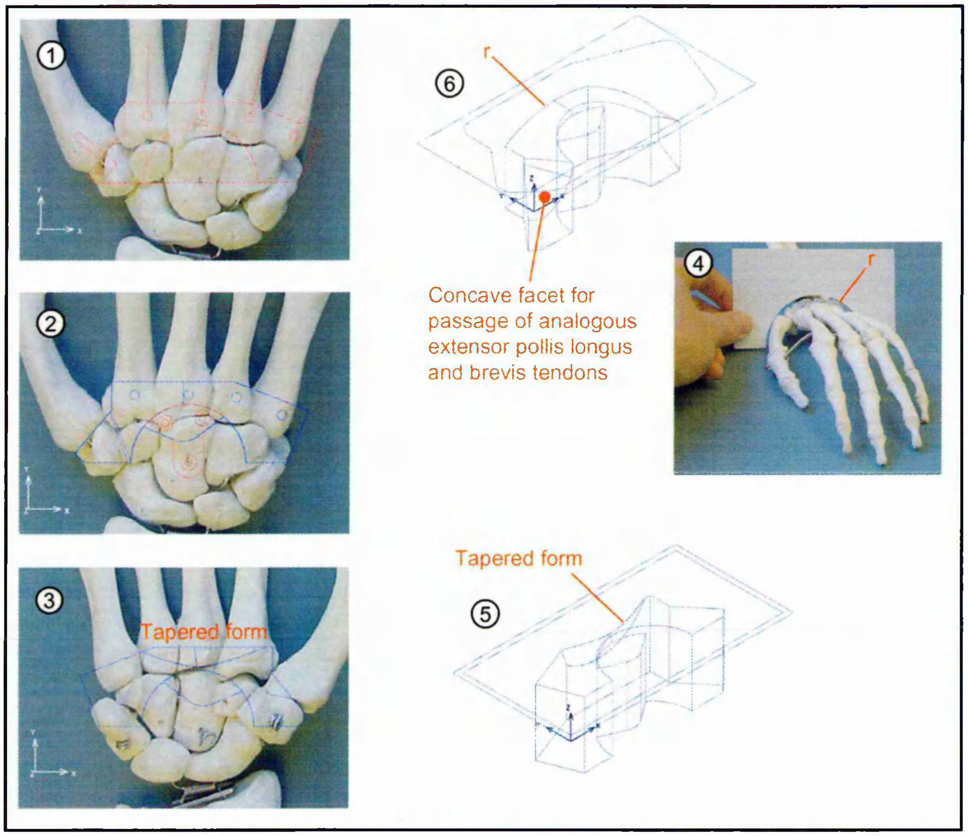


Fig 7.18 Development and Investigation of Joint Form

In the development of the linkage mechanism the carpal bones were treated as distal and proximal rows. The carpal bones were similarly treated as fused 'rows' in developing a form suitable to act as an anchors for the digits. The distal row needs to secure the metacarpal shafts at the correct angle and spacing. The angles and spacings were determined using CAD software underlayed with a photograph of a skeletal hand (1).

The outline plan of the model distal carpal row was determined by simplifying the outline of the trapezium, trapezoid, capitate and hamate carpal bones. Additionally, the proximal face of the form was shaped to allow a range of movement in adduction/abduction for the linkage mechanism similar to that determined using the splints (2). This was achieved by rotating the previously designed linkage mechanism about the centre of the capitate. Kapandji suggests that this can be considered as the centre of wrist rotation in the plane of adduction and abduction (Kapandji 1982), which appeared consistent with the position of the centre of rotation found using the splints.

The form of the human skeletal carpus was investigated in the tranverse plain using profile guides. Differently radiused profile guides were made to determine the approximate radius best fitting the dorsal arch of the carpal bones (4). The proximal form of the metacarpal shafts appeared to be tapered into the carpals (3), therefore, a taper was introduced into the volar side of the form (5).

The previous model hand showed problems routing analogous extensor pollis longus and brevis tendons. Using the described underlay and profile guide methods a the form of a concave facet was determined and included in the computer 'solid model' (6).

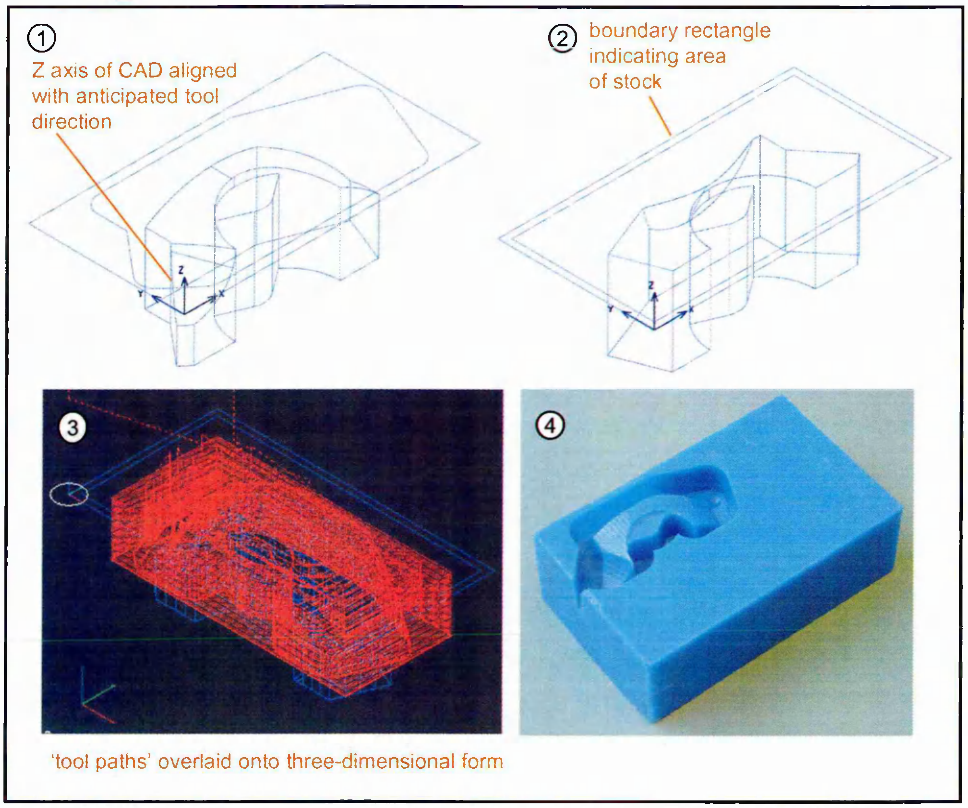


Fig 7.19 Three Dimension Machining of Distal Carpal Form

The details of form from the CAD development work required machining in a 'three-axis' strategy. The machining considerations were included in the development of the CAD solid model, this included orientating the z axis of the solid model with the anticipated tool direction (1). Additionally, a boundary rectangle was included with the global co-ordinates aligned to its bottom left corner (1). This rectangle represented the stock which the form was to be machined from, with the negative z direction indicating removal of stock.

The computer aided machining software (CAM) was able to automatically create tool paths resulting in a form requiring minimal manual finishing (3). Figure 7.19 (4) shows the tool paths tangibly tested in an easily machined block of wax.

The chosen material for the distal carpal row was a lightweight bearing plastic, similar to that used in the first model hand. This was chosen as analogous tendons will run across this component, favouring a low friction material.

The design requires holes outside the plane of the machined surface features. Therefore, once the stock was machined to size the holes were machined using a manual milling machine. The stock was then transferred to a CNC milling machine. Four sides of the stock were used as datum faces. Three corresponding to the initial position of the origin x,y,z. One side of the design was machined then removed from the vice. The resulting machined 'pocket' of the partially machined form was refilled using a soft polyurethane two part casting plastic. This was skimmed then replaced into the vice jaws to the to be at the underside of the stock. The polyurethane served to hold the highly contoured form whilst the second side was machined. This material was subsequently easily parted from the desired component.

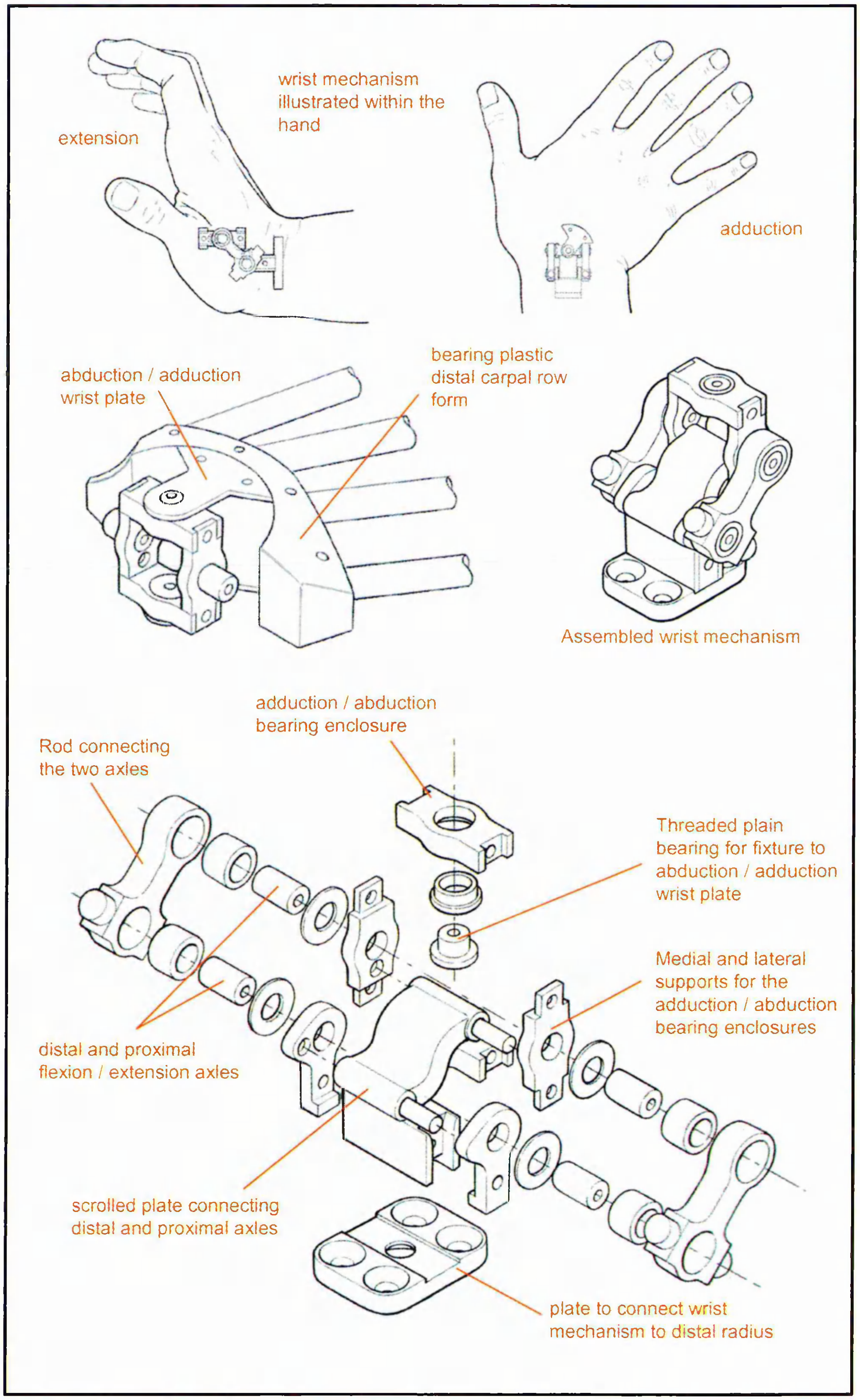


Fig 7.20 Principles Embodied Within the Model Wrist Joint

The diagram above shows the model wrist mechanism along with indications for the principles embodied within its design.

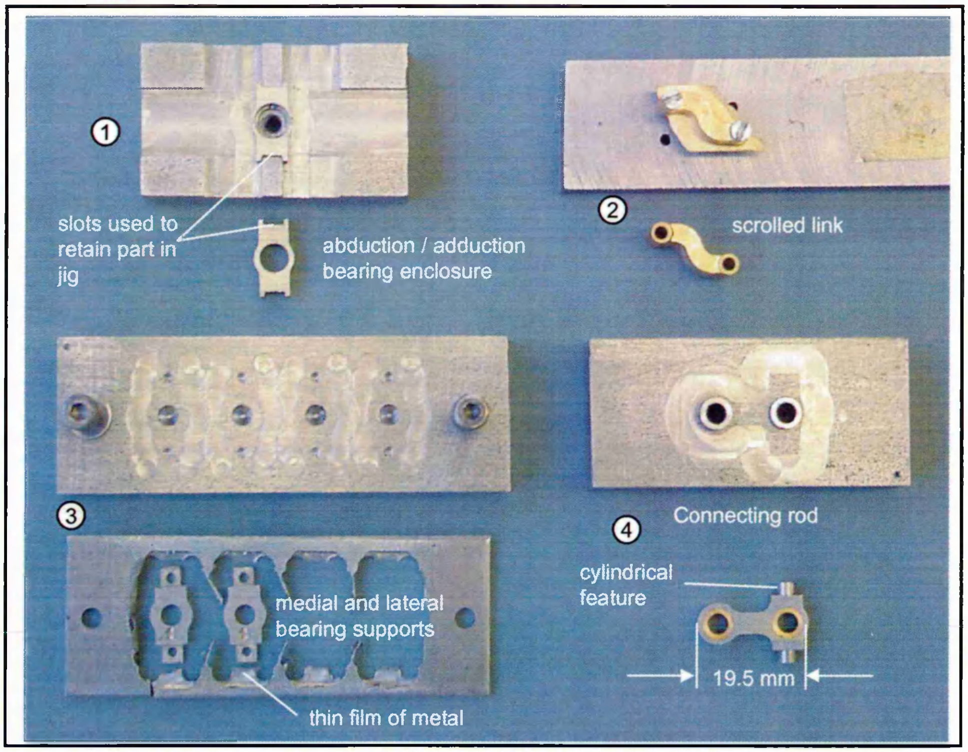


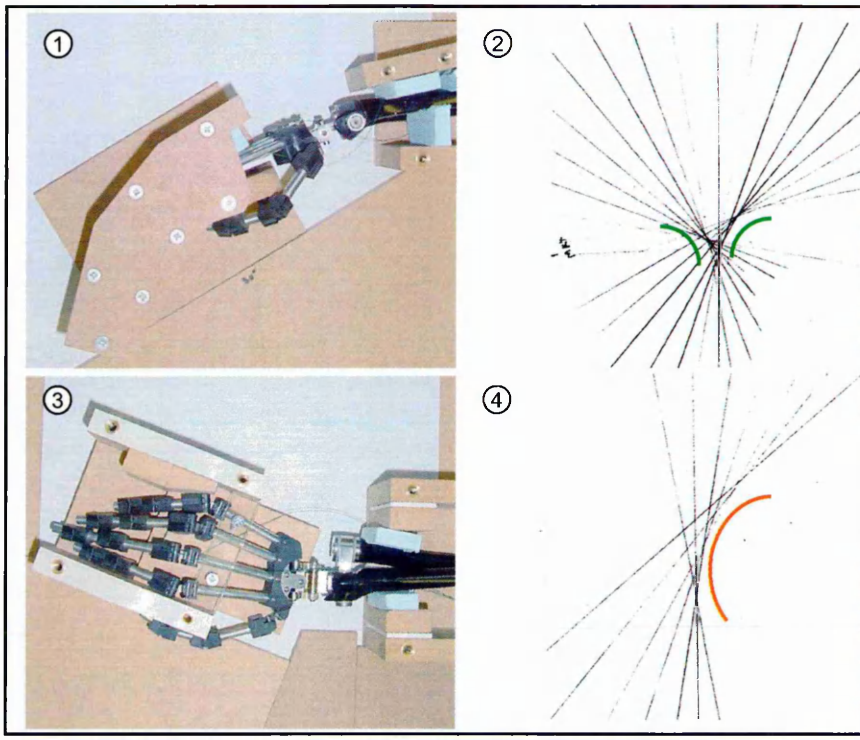
Fig 7.21 Jigs Used during Manufacture of Small Wrist Components

The forms developed for the linkage mechanism needed to be of a miniature scale to fit within the volume occupied by the human carpal bones, consequently, the longest component was only 19.5 mm. However, the coupled pulley experiment indicated that the components would need to be rigid to maintain the correct movement characteristics. Consequently, mild steel was chosen as the prototyping material.

Due to the small scale of the components, conventional vices and fixtures were unsuitable, therefore, several holding jigs were machined. The miniature adduction / abduction bearing enclosure was made by first machining slots in the sides and drilling the various holes. The slots were then used to locate the component on a steel jig, and secured through the central hole using a machine screw. The final profile was then machined onto the sides of the part (1). The scrolled crank was prototyped in hard brass for its bearing properties. The brass stock was first drilled. A steel jig was made with four holes corresponding to the position of the scroll in mirrored positions. The brass stock was roughly cut to length and secured with machine screws to the jig. Half the depth of the profile was machined, then the scroll was placed on its reverse side and a mirrored profile machined (2).

The more simple distal axle supports were machined in multiples (3). This could be done as the program was designed to leave a small thickness of metal between the parts and the remaining stock to maintain the location of the parts throughout the machining sequence. The thin metal film was subsequently easily cut to free the components.

The connecting rod between the distal and proximal axles required a cylindrical features machining in plane out of plane to that of its the profile (4). These 'bosses' were first machined into the sides of a length of correctly ground stock. The stock was then rotated through 90 degrees and the holes machined in this length. Finally the stock was roughly parted to length and the final profile machined in the jig shown (4).



R.O.M (degs)
flex / extension
175.0
175.0
177.0
175.5
human wrist*
170

R.O.M (degs)
add / abduction
63.0
62.5
61.5
62.5
human wrist*
55-60

Fig 7.22 Tests on mechanical Model with using Splints

The model wrist was assembled and connected to the model hand, forearm and elbow sections. It was then possible to place the hand within the splints and assess the quality of the movements (1, 3).

As the model is only an analogy of the human wrist at skeletal level it was necessary to place foam block to the sides of the splint to simulate the bulk of soft tissue around the intact human wrist (3). Once this model was secure within the splints similar procedures to those followed to produce the recordings of incremental movement.

The recordings appear close to those of the intact human wrist. There appears to be a single centre of rotation in the plane adduction / abduction (4). Whilst the four bar link characteristics are evident in the recording for flexion and extension (2). However, difficulty was found in securing the skeletal model into the space previously occupied by the bulk of an intact hand.

Due to the lack of soft tissue surrounding the wrist and forearm it was difficult assess the range of wrist movement using goniometric techniques. Therefore, the splints were used to calculate the range of movement of this joint, shown in comparison to human wrist (*Kapandji 1982) in table 1. However, difficulty was also experienced in securing the skeletal model into the splints designed for the intact human hand.

Whilst these results were promising it was felt that further qualitative evaluation was needed to ascertain whether the subtle differences in wrist mechanism added to the closeness of the anatomical analogy. It was considered that to obtain a valid qualitative evaluation of the wrist joint it was necessary for the limb to be complete with hand and elbow; so that the form of the model would appear somewhat familiar to the person asked to evaluate the joint.

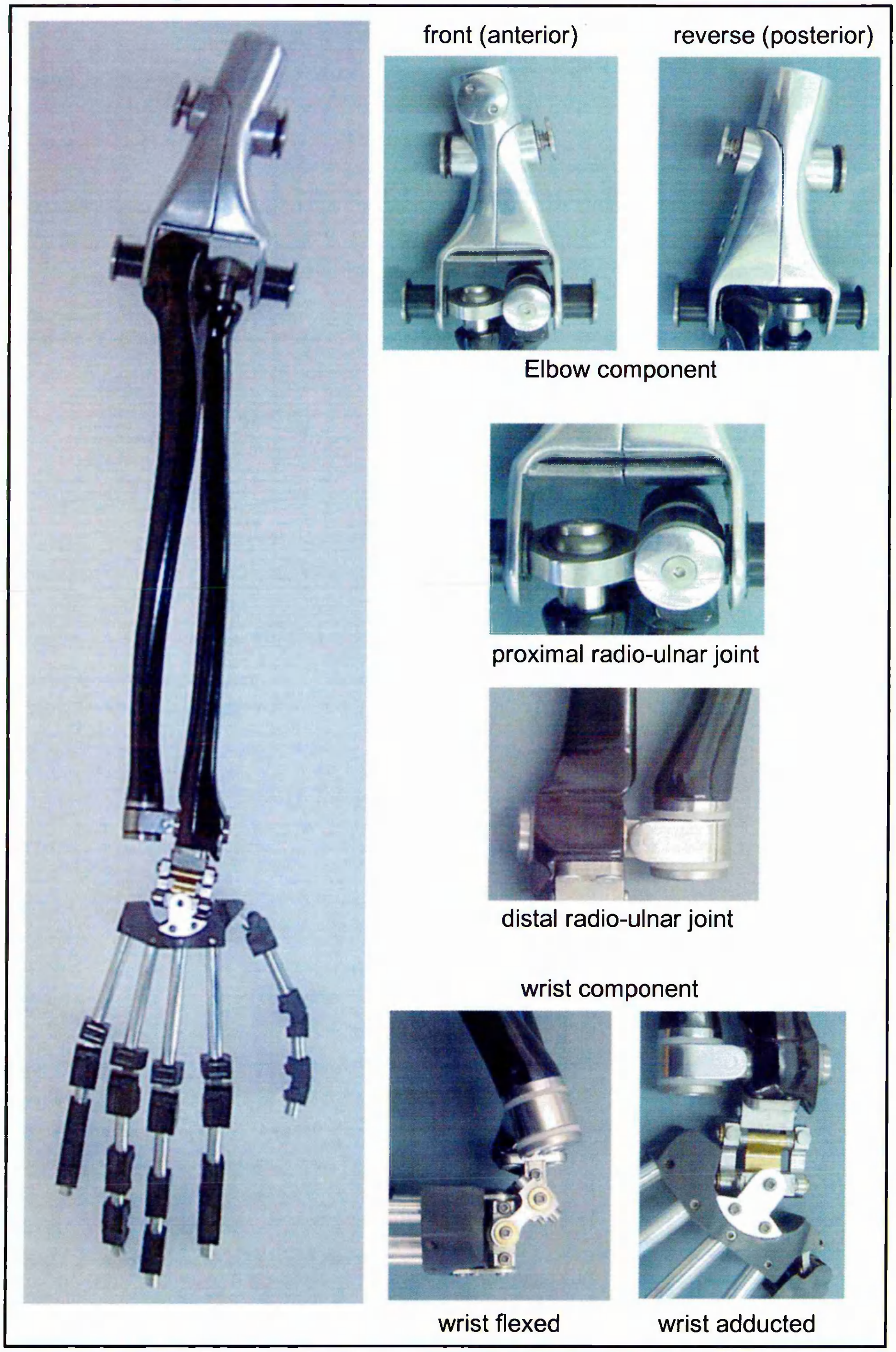
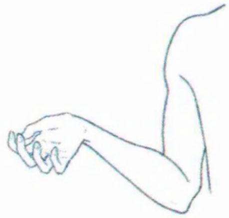


Fig 7.23 Components of the Assembled Skeletal Model Arm

Once the model limb was complete, with new components for wrist, forearm and elbow and the earlier finger joints retained, it was thought appropriate to submit the model limb for qualitative evaluation. This was done for two reasons. To determine whether the joints were achieving a close analogy of the human limb. In addition, a key prosthetics researcher was presented with the limb for evaluation to determine if any of the principles embodied in the model were appropriate to the field of prosthetics.



Qualitative Evaluation by Lisa Halse, Osteopath

Lisa Halse is an osteopath in Sheffield. She was invited to evaluate the model wrist elbow and forearm. She was selected as she routinely uses palpation of intact limbs as part of diagnosis, and therefore was considered to have a keen sense of what the articulations human limb should feel like. The aims of the evaluation were for L. Halse to indicate from palpation where deviations from the original anatomy appeared to arise. During the evaluation L. Halse was encouraged to mark the model arm with adhesive paper markers where she considered the model to diverted from the original anatomy. The interview took place in the research workshops at Sheffield Hallam University. Present were L. Halse, R. Erol, C. Rust and G. Whiteley. The evaluation lasted for approximately 45 minutes.

Her initial views of the model arm were noted down as very positive, commenting that she was very impressed by it and had never seen anything like it before.
The remainder of the interview with L. Halse was tape recorded. Below are the salient points she made, together with quotes from the transcript of the interview.

(1) L. Halse carefully palpated the model forearm in pronation and supination movements commenting:

'It's definitely mechanical…there's no sense of …things receding and coming back….It's <requires> a sort of springiness of a kind.'

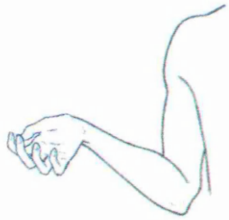
(2) L. Halse contrasted the model to the human forearm indicating the absence of soft tissue within the model was hampering her evaluation

'…you can feel if it's <original anatomy> alive..you can feel there's a sort of slight expansion, or rotation and contraction sort of feel to the tissue.'<considered absent in the model>

(3) Both the original model wrist and the current model wrist were presented to L. Halse for palpation. Her first palpation was of the current wrist joint.

'It's incredibly mobile…it's definitely in need of some attachments (muscular constraints)'

'This <current model wrist> is definitely better than the joint you've got there <original model wrist>. This feels basically a lot lighter. That one <original model wrist> feels much more mechanical. You get a real kind of end stop, as opposed to this one, which feels like..yeah there is a kind of end stop but it doesn't feel quite so clumsy.'



Evaluation by Lisa Halse Continued

(4) L. Halse considered that although current model wrist possessed the range of movement of the anatomical carpus, she felt that more flexibility was required in its form permitting transverse flexibility across its arch.

'…I think you need to do something about getting more flexibility across the arch…there is a degree of flexibility between the carpals and the metacarpals'
'..normally when you put your thumb out there like that <adducted and extended>…you spread the carpals, and it's almost like you want some…elastic tissue in it or something … to compress, but will spring back.'

'I think the springiness is important….in order to make it feel like a real hand it needs something less rigid.'

'..make it more elastic…then you'll get some of the shock absorbence that you don't get in this material <indicates metallic sections>'
'if anyone was to fall on this thing <current model wrist> in extension it's just going to go <demonstrates impact going right up through the arm>'

(5) On picking up the model for palpation L. Halse commented on the difference in weight between proximal and distal sections of the model.

'It's massively heavy <model elbow> … it won't integrate <with the movement of the amputees body> while it's got this massively heavy joint.'

(6) L. Halse was content with the quality and range of movement of the model elbow being close to the original anatomy. However, throughout her palpation of the elbow L. Halse indicated that the sinuous form of the model elbow aided the analogy to the original anatomy.

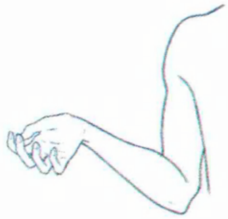
'…the kind of movement through, and feel of it,…it feels like its much more alive.'
'It's the form, because of the curve this way, and the curve that way, and it's rounded.'

(7) L. Halse indentified that there was a need to review the form and dimensions of the epicondyles on the model elbow.

'The lateral one <humeral epicondyle> is a lot smaller than the other one <medial humeral epicondyle>…you look at that elbow <model elbow> and you think well visually…this is much too wide <width between epicondyles>'

(8) L. Halse considered that the model 'origin' Brachioradialis was currently in the wrong position, and may be of an inappropriate form.

'…it's not like when you look at an anatomical text book and it has a little red dot saying that's where it is, it is not as clear as that…it's covering <origin of brachioradialis> quite an area rather than just a little point…It's much more ..of a line, it's not a spot…I'd say it was way to... high <proximal> for brachioradialis '



Evaluation by Lisa Halse Continued

(9) L. Halse palpated the finger joints and was content with the ranges of movement of the IP joints, but, commented that the model MCP joint was;

'..Incredibly mobile.... it's double jointed...'

However, L. Halse was concerned that the form of the joints too mechanistic.

'...This hand is very strange because its not got its arches <indicates absence of longitudinal arch of plalanges>'
'...It's the form <cubic form of model finger joints>....this is sticking into my hand going jab, jab, jab'

(10) L. Halse indicated at several points that the lack of soft tissue within the model was hampering the close analogy of the model to the original anatomy.

'...you've got to build on <to the model> some muscle..'

'..if you start putting on something..elastic,..you know something that can conform into that function <indicated contracted muscle of forearm> ...and it has elasticity to go back again,..you can start building up soft tissue in the model it will feel more real..'

'It's brilliant, but it's nothing like a real hand because it's got no soft tissue'

(11) She additionally felt that the absence of soft tissue was hampering her evaluation of the model

'...I want it to have all the rest of the soft tissue on..., to feel'

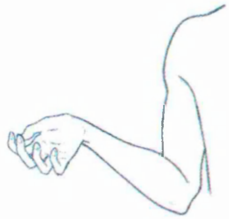
(12) L. Halse was enthusiastic about the methodology used and hoped to be consulted again when more practical progress had been made.

'...your trying to do something...which is great...a huge improvement on what's been done before.'

'..it's brilliant...'

'I'd love to come back and see how it's going.'

The evaluation concluded by L. Halse expressing a desire to review the model again when more progress had been made towards analogies of the soft tissues of the limb.



Evaluation by D. Gow, Biomedical Engineer at Princess Margaret Rose Orthopaedic Hospital

D. Gow is a biomedical engineer and a key figure in the design of new prostheses. He and his colleagues have designed and prototyped the widely publicised multi-articulate upper-limb prosthesis based on the 'pro-digits' concept (containing the actuating electric motor within the volume of the finger).

The evaluation of the model took place in D. Gow's office at the Princess Margaret Rose Orthopaedic Hospital. Present were D. Gow and G. Whiteley. The evaluation lasted approximately 45 minutes and was taped recorded. Before D. Gow was presented with the model an outline of the research aims were given by G. Whiteley. Salient points from this evaluation are presented below using quotes from the transcribed tape recording.

(1) D. Gow's Initial Remarks

'It's <the model> sort of an engineering challenge…taking that from an inert skeleton to a powered and controlled device…It would take us a generation I think.'

(However, D. Gow expressed an interest in the details of the design of the model limb for practical shorter term utilisation. Particularly in the joints of the model hand).

(2) The Model Finger Joints.

'Yeah that's very, very impressive….you are sort of producing the bits that are actually important, because these..you know the joints…<points to finger joints> nobody as far as I'm aware in prosthetics or robotics has really come up with a simple machinable system that gives you the anatomical equivalents.'

(3) Anthropomorphic Joints supporting Functionality

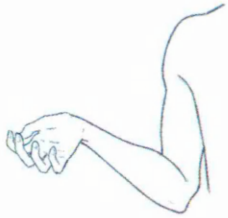
'…the attitude of the hand becomes an issue because a flat hand isn't much use for prehension…hence the compromised grip that most prostheses have. So again a device where you can alter the the attitude of the thumb, even passively, to give opposition and...lateral pinch or...the power grip. Again I think that would be a commercial breakthrough.'

(4) Anthropomorphic Joints supporting Passive Cosmesis

'I think that in certainly in the sense of a passive device while it may be attractive to have that form of movement <adduction / abduction at the MCP joint> it just depends how you protect that from being damaged.'

(5) Using the Model as the Basis for a Body-Powered Device

'…basically I don't see how difficult it would be to produce a voluntary closing hand with this..<model hand>'



David Gow Evaluation continued

(6) Modularity of the Joints Supporting Economic Manufacture

'The attraction to me is if this < the model limb> brings any spin-offs in the sense that our own work has done which is to start looking at all of this thing as a modular system…once you start saying you've got a system…you start ringing bells about cost. Cost coming down in terms of bulk manufacture.'

'…if I can get a hand...made up of virtually the same parts just with or without power sources then probably I've produced something I can make in quantities that are four or five times greater than the moment…..that would mean that some of parts are made in almost economical quantities…'

'on this…system where you had certain joint lengths and segment sizes for different hand sizes and left and right hands you can immediately see a production engineering approach to it.'

'..if I could produce a skeleton like this …you'd start to interest manufacturers in terms of injection moulding ….you'd start to produce economic quantities of these things.'

'In essence this has to cost something like 20 quid to make. And you could just about imagine a system based on joints like that <indicates model finger joints>. Because the joints have got similar form..'

(7) Further Develpemnt from Elements the Model's Design

'This <the model limb> interests me from the perspective that the challenge of this is to see this as more than just a design exercise, mimicking the human body , but taking elements of this and making them practical from a prosthetics point of view.'

'So things the that I can see that are immediately attractive to me are; that a skeletal hand system like this would potentially be able to be used within a cosmetic sense.'

'..this <model hand> I could see us making that fit a silicone glove as it is…'

'…that's really quite an exciting concept to see that hand <the model hand> start there with effectively rigid and strong mechanical phalanges …and to have some sort of articulating system beyond the metacarpophalangeals.'

(8) Chief Constraints on Prosthetic Technology

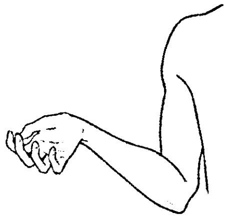
'…from a prosthetic point of view what holds prosthetics back is the need for simplicity and reliability and cheapness…'

'…. the prosthetics industry is so small and so driven by the need to make their next step incremental…'

' You don't get the desire to leap forward <in the prosthetics industry> with this <indicates model limb> because no one can afford the outcomes>'

(9) Articulations Supporting Human Movement (Dynamic Cosmesis)

'….technology that we've currently got is now getting interested in this <points to model arm>, is getting interested in articulation. Because the patient, the human element, dictates that people get the benefit of better dynamic cosmesis'.

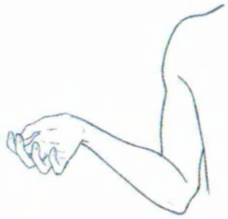


David Gow Evaluation continued

(10) Comments on existing technology

'....my feeling is that the technology that we've got is akin to the stone age...'

This evaluation of the model was followed by discussions with both D. Gow and his colleagues in the research work shops at Princes Margaret Rose Orthopaedic Hospital. D. Gow indicated that he would like to be kept in contact with the progress of the research. He also requested a replica of the joints of the model hand to experiment with.



Qualitative Evaluation by Professor Jon Stanley, Orthopaedic Surgeon University of Manchester

After evaluating the model forearm D. Stanley was informed of the subsequent plans the research had to design an anatomically analogous wrist joint. D. Stanley asked to be contacted when this was complete, as he thought Professor J. Stanley, one of his fellow surgeons, and respected authority on the anatomy of the human wrist would be appropriate to evaluate the model wrist.

The evaluation by Prof. J. Stanley took place at Northern General Hospital, Sheffield. Present were Professor J. Stanley, D. Stanley, G. Whiteley and C. Rust. The evaluation lasted approximately 30 minutes, and was tape recorded.

Before Prof. Stanley was presented with the model arm to palpate the brief aims of the research were given. The aim of the evaluation was stated to inform the researcher where the model appeared close to the anatomy, and where it was viewed to divert from the anatomy. Although Prof. Stanley was specifically contacted to evaluate the wrist, his comments encompassed all the analogous joints.

(1) Initial Remarks

'I mean it's absolutely super, really beautiful.'

(2) Regarding the Degrees of Rotational Freedom of the Human Wrist

'It has three degrees of freedom, not two..<like the model wrist>…Which is longitudinal rotation…it's not very much, it only has to be about 20 degrees.'

'If you could put another <degree of rotation>…I'm just wondering where you could put it …it's not much, but you can actually fix the wrist and rotate the hand.'

(3) Wrist Articulation in the Plane of Adduction / Abduction (Radio-ulnar Deviation)

'As far as the wrist is concerned the radio-ulnar deviation are nicely done, and that's <palpates the model wrist> the right amount of motion.'

(4) Articulation in the Plane of Flexion and Extension

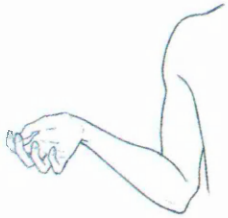
'I can see you've got a beautiful linkage here to shift the axis forward haven't you…It's very nice <comment on movement from palpation>.'

'…no that's beautifully done. I would complement you on that.'

'I'm impressed by the way you've done the linkage for the wrist that is very nice. That really does look normal.'

(5) Overall impression of Wrist Joint

'I would say that the only thing that is missing is just the long axis rotation <at the wrist>. I'm not sure you need very much <movement in this plane>, and I'm sure you could incorporate it into the hand level without disturbing what is basically an extremely nice design. Because it does exactly what a wrist does, it just doesn't rotate <around long axis of the forearm.'



Qualitative Evaluation by Professor Jon Stanley continued

(6) Forearm Joints Reproducing Human Like Movement

'As far as pronation and supination are concerned, that's fine <palpates the model> it doesn't actually work that way. But it's pretty close…it's actually reproducing the movement pretty accurately.'

'…in terms of the net effect, overall it's pretty good, in fact it's very good…you'd be hard pressed to tell the difference <between model and human forearm articulation>'

(7) Origins of the Anatomical Mechanism for Forearm Pronation / Supination

'…the axis of rotation is based on an interosseous membrane it doesn't work on two fixed linkages.'

(8) Difficulties assessing the model against a human limb.

'I'm trying <palpates model with eyes shut> to ignore what it looks like and try to see what it does.'

(9) Absence of soft tissues

'..what you need to do is cover it in a rubber glove or something filled with silicone or saw dust, just to give it that damping effect…'

'…once you've <the researcher> got it powered up and some damping on it, it will be absolutely super.'

The evaluation finished with Professor Stanley indicating that he would like to evaluate the model wrist again when further work had been completed on the models actuation.

Discussion

A discussion of the development of the whole arm is included in the next chapter. Therefore this discussion is focussed on the model wrist joint.

The evaluation of the model hand indicated that the translation of IP joint principles to the wrist joint appeared unsuccessful. In the initial stages of the second cycle of wrist development principles from the development of the MCP joint were translated to the wrist, and again appeared inappropriate. Therefore, it was considered that a stage of creative reasoning was needed for the wrist joint including a stage of extensive observational drawing.

Similar to the development stages in the development of the forearm joints it was found that the creative reasoning process required supplementary techniques. An additional stage of measurement taken form splints was including to further inform the design of the wrist joint. Like the forearm joints an extra stage was necessary as the movement of the intact human joint observed was indicating a complex coupled movement.

The prototyping methods used to develop the wrist included the extensive use of CNC machining. This was both used to create complex forms modelled on the form of the distal carpus, and miniature components for the wrist mechanism. CNC appeared successful both in ensuring the accuracy demanded of miniature components and also the creation of accurate complex forms.

The evaluation of the joint showed again the difficulties of assessing the model against the human limb without soft tissue on the model. This was evident in difficulties experienced fitting the model limb into the splints designed for the intact limb. This was also evident in the transcripts, where evaluators indicated a need for an analogue for soft tissue to add properties such as 'damping' to the joints. The evaluations by L. Halse and Prof Stanley highlighted that they the considered the articulation of the model wrist to be close to that of the human wrist. However, L. Halse indicated a need for further inter-carpal articulations and Prof. Stanley indicated a need to include a further limited degree of freedom aligned with the long axis of the forearm.

Conclusions and Suggestions for Future Work

This thesis has described the development of an articulated skeletal analogy of the human upper-limb. The stimulus for this work has come from the needs of amputees who currently must chose between prostheses that either appear outwardly like the original limb and posses limited or no function and devices mechanistic in appearance that provide some useful functionality. The prostheses provided to amputees have not significantly changed since the clinical introduction of the myoelectric prosthesis in the 1970's (Kostuik 1980). Research efforts have largely focussed on refining these historical prosthetic designs (Banerjee 1982, Parker and Scott 1988). Additionally, incremental developments from these archetypes appears to have resulted in further division of function and cosmesis.

Amputees require both functionality and cosmesis from their prostheses (Fraser 1998). It is only the limitations of currently available prosthetic technology that necessitate amputees to proiritise between cosmesis and function (Tura 1998, Herder 1998, Fraser 1998).

The starting point for the work in this thesis was the proposition that design principles appropriate to a future generation of prostheses combining both cosmesis and functionality in a single device would only result from the close analogy to the human upper-limb. A crucial first step in this process is the development of a close analogy of the articulations of the skeletal limb, which not only could form the basis of a prosthesis, but might also be used to test appropriate actuation and control strategies. Therefore, the aim of this research was to elucidate design principles to construct such an analogy.

The method used to develop designs for the articulated model limb have been based on close observation of the original anatomy (Conrad *et al* 1995) and the production of physical models / prototypes (Archer 1995). Models have been used to refine initial joint ideas to more resolved prototypes suitable for quantitative and qualitative evaluation. Tangible objects have been used to enable a broad evaluation of the design principles and thereby add to subsequent stages in the design process (Archer 1995).

The resulting models have been evaluated to assess the closeness of the anatomical analogy achieved. The subtleties of human movement and joint structure indicate that quantitative evaluations may not be sufficient. Additionally, the human skeletal limb is not self supporting, but rather is dependent on soft tissue connections for some of its form and function (Kapandji 1982). Therefore, measurements at the surface may not reflect movements at the skeletal level. For these reasons a process of qualitative evaluations by professionals with extensive anatomical knowledge was undertaken. The models have additionally been reviewed by a wide range of 'end-users'. These are primarily amputees but occupational therapists, prosthetists, prosthetics manufacturers and leading prosthetics researchers have also been consulted to assess any practical outcomes that might result from the model limb. In addition, criticism has been sought from researchers involved in the development of novel muscle like actuators in the hope that production of a tangible model would stimulate interest in the application of these technologies to the development of a future prosthetic device.

Both the qualitative and quantitative evaluations performed on the models indicate that the model joints have achieved a close level of analogy with the articulations of the human limb. Additionally, review of the model by end-users, indicates both short and long term applications for the design principles embodied in the model.

Evaluations

Throughout the research difficulties have been experienced comparing the ranges of movement of the model joint with those reported for intact human joints. This has principally been caused by the absence of an analogy for soft tissue within the model.

Problems caused by soft tissue coverage of the intact joints appeared particularly acute in the evaluation of the forearm. To validate the designs measurements were required on intact joints which are deep within soft tissue and which display a complex coupling (Kapandji 1982, Amis 1990). However, the difficulties experienced in this work in measuring intact human joint movement have been experienced by other researchers investigating the movement of the forearm (Youm et al 1978).

Therefore, it appears appropriate to use the qualitative evaluations to compliment the quantitative methods.

Qualitative evaluations for comparing the model joints with the articulations of the human limb involved visual and tactile examinations of the model. The materials used in the model have quite different colours and textures to those of the human arm and there is no soft tissue covering the model. Significantly, the lack of soft tissue was commented on as a factor impeding evaluation. Suggestions for possible tests with the model covered with a suitable cosmetic cover were made by one participant in the evaluation to enable him to more closely assess the model joints against those of the human limb. However, the visual differences between the model and the human limb appeared advantageous in assessing the potential of the model to form part of an eventual prosthesis. For example, features such as the modularity of the finger joints were easily recognised due to the contrast of between the metallic struts and the black plastic joints.

Qualitative evaluation also indicated that a 'damping quality' was absent from the joints. It was also suggested that this could be achieved within the model by incorporating analogies for the soft tissues. Again, this could not be incorporated into this first model as its detailed design arose from close observation of the skeletal human limb, with no soft tissue attached to it.

The skeletal structure was taken as the basis for the mechanical analogy described in this thesis, as it is the fundamental anatomical structure from which the form and function of the limb arise (Kapandji 1982). However, the limitations of informing design principles mainly from observation of skeletal anatomical models have become evident. Therefore, future design cycles may be further informed on the significance of soft tissue through MRI scanning on live subjects and observational drawing studies of the ligamentous and tendinous structures revealed in cadavers.

Modifications to Research Method

The research method adopted, which is a form of practice led design research (Archer 1995) required both supplementation and revision as the research progressed.

In the original implementation of the research method, the first stage, the analytical stage, combined observational drawing with sketchbook idea development and literature review. During the development of the distal and proximal radio-ulna joints it was found that the observational drawing and sketchbook idea development in the analytical stage was insufficient. It was found too difficult to visualise the potential effects of different mechanical configurations which mimicked the complex coupled movements of the linked distal and proximal joints. Therefore, during the development of the forearm joints it was necessary to add mathematical analysis to the analytical stage to aid the investigation of potential mechanical configurations.

Implementing the iterative nature of the research method, where evaluations feed into subsequent cycles of design work, has not been as straightforward as initially envisaged. It has become evident that the cyclical development of the articulations of the limb was not always appropriate. This was especially evident in the development of the forearm and elbow joints where the functions of the proximal radio-ulnar joint were not separable from the functions of flexion and extension of the elbow.

Additionally, as the research progressed it became evident that small iterative cycles incorporating an evaluation were not always appropriate. Meaningful evaluation of the model appeared only to be possible when significant anatomical sections were complete. For example a whole hand form was necessary for the quantitative assessment of the ranges of movement of the joints of the fingers using goniometric techniques.

Both the limitations of method in developing the forearm and elbow joints, and the difficulties experienced in gaining a meaningful evaluation from isolated components of the model necessitated revising the research method, in particular revising it to permit the development of joint designs concurrently. Where joints were developed separately, such as the second iteration wrist joint, this was because the design appeared to be a significantly less successful analogy than the other joints.

Joint Principles Derived Sensitive to Context

It was found that many principles elucidated using observational drawing from specific joints were not portable to other joints of the limb. This was especially evident in the evaluation of the first model wrist. The mechanical analogies developed from observation of the joints of the fingers did not appear to be readily transferable to the wrist. Instead, it was found that close observational studies were required for each joint.

Limitations of Mechanical Analogy

Initially, the model hand was developed with a view to actuating the wire tendons extrinsically. Therefore, analogous wire tendons were routed through the wrist to facilitate remote actuation. The tendons were 'actuated' through pulley wheels to pretension the wires and provide complimentary movements of flexor and extensor tendons. Using this method it was possible to control flexion and extension movements of the fingers. However, linking flexor and extensor tendons highlighted problems caused by mechanically coupling the movements of the fingers and the wrist. It was found that on flexion of the wrist the fingers would extend, and vice versa. Several mechanical schemes were devised on paper to compensate for wrist movement. However, a simple mechanical arrangement could not be identified. This questioned whether the use of mechanical analogy was appropriate to identify the design principles for the dynamic components of a future prosthesis. From the anatomy and physiology literature it was found that the coupling mechanism is achieved through low level spinal synapsing (neural connections) (Fox 1993). Additionally, robotics research is investigating control algorithms that mimic theories of the biological spinal chord (Hannaford et al 1995). In light of this research it was concluded that a mechanical analogy was not appropriate to mimic these mechanisms.

The identification of research into neural control strategies (Hannaford et al 1995) for the natural arm and hand, combined with evidence of 'artificial muscle' research (De Rossi et al 1992, DellaSanta et al 1997) suggested that the appropriate focus for the work should be the further development of a complete anatomically analogous skeletal model upper-limb. Which could form a platform for the outcomes of work from these other areas. In particular, such a platform could focus such work towards the requirements of a prosthesis which offers both the form and function of the natural arm and hand.

Comparisons with Previous Robotic Devices

The comparison of the kinematics and structure of the model hand to previously developed robotic hands indicates the potential for the model to form the basis for an 'artificial hand' which would aid telemanipulation using data glove control. Data glove control assumes the remote manipulator mimics the real hand, but the current generation of robotic hands have diverted from an anthropomorphic structure; either through scale (Herzinger 1995) or kinematic layout (Jacobsen et al 1984, Mason and Salisbury 1985). It has been found by researchers investigating the control of such dexterous manipulators that effective control of the 'slave' manipulator is aided if it possesses a similar arrangement of joints to those of the 'master' glove (Caldwell et al 1995 and Perlin et al 1989). Therefore, the model hand, with its kinematic arrangement derived from the articulations of the human hand may have a potential use in this field.

Additionally, the derivation of the kinematics and scale of the model hand from that of the human hand mean that the hand can potentially manipulate and grasp objects designed around the anthropometric constraints of the human hand. This has been demonstrated by configuring the model hand around many domestic products and controls (levers and handles). However, to achieve full functionality of the hand including grasp and manipulation will require extensive further research into appropriate actuation and control strategies (Jacobsen et al 1984 and DeRossi et al 1992).

More Complex Prototyping Techniques Aiding Qualitative Evaluation

As the research has progressed the joint forms developed have become more complex, and the prototype manufacturing techniques have become similarly more complex. This has resulted in the techniques used in the development of the wrist which allow not only the realisation of a complex form but also a complex embedded mechanism. Evidence in the transcribed evaluations pertaining to natural joint movement indicates that complex forms adds to the effectiveness of the analogy of the model, therefore, justifying the more complex prototyping methods used.

End-Users Involved in the Design Process

With the introduction of the model hand to the focus group, the groups expections for a future prosthesis changed. Prior to the introduction of the model hand the view voiced by the group was that they regarded prostheses as primarily cosmetic or functional. However, after the introduction of the model hand the indications from the group were that a future prosthesis combining both cosmesis and functionality could be envisaged. In the introduction given to the focus group science fiction images had been shown and this did not change the groups expectations. It appeared only with the introduction of the tangible model hand that these expectations were changed. This indicates a potential benefit for the use of models in user research.

The input of the amputees was valued and a progress report has been regularly given to this group on the state of the research and criticism invited. The literature warns against raising expectations of amputees to an unacceptable level (Curran and Hambrey 1991). Therefore, using the model as means of presentation was considered appropriate as the potentials and limitations of the model could be easily assessed by amputees.

Expectations for a Future Prosthesis

The principle finding from attendance at a regular amputee support group has been the desire from the group to see the model limb actuated. Additionally, a desire has been voiced by the group to work with other researchers from complimentary disciplines such as actuation and control to support more rapid development. Both these aspirations for the research from the support group are being addressed.

Creating Enthusiasm for a New Generation of Prostheses

Previously, the majority of prosthetic research has focussed on developing iterations on established archetypes (Banerjee 1989). However, the development of the skeletal model, embodying features that may support a practical prosthetic implementation appears to have reawakened interest in this research field. In particular, interest has been shown from researchers working on novel actuators. Currently, a model arm has been delivered to a laboratory in Pisa. These researchers are initiating experiments that apply novel actuation methods to actuate pronation / supination movements of the model forearm (Chiarelli 2000).

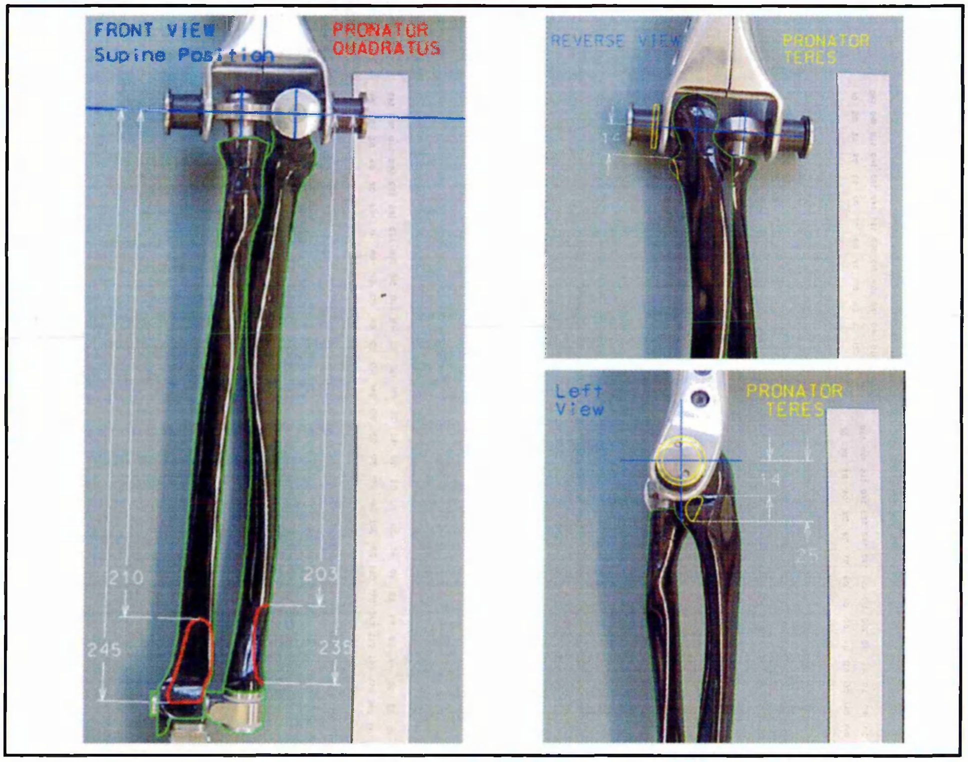


Fig 8.1 Muscle Origins and Insertions 'Mapped' onto the Model Limb

Figure 8.1 shows some initial communication with this group indicating how the muscular attachments of the human limb relate to positions on the model limb. Additionally, a replica model arm has been requested to provide a 'demonstrator' for this new actuation technology being developed in Pasadena (Bar-Cohen 2000).

Potential Short Term Implementation of Design Principles

The review of the model by both a key figure in prosthetics research and a prosthetics manufacturer have highlighted the significance of the modularity of the joints of the hand to aid the short term implementation of design ideas into prostheses. Delivery of replicas of the finger joints have been promised to one key prosthetics researcher to support his work on combining both static and dynamic cosmesis in prosthetic terminal devices (Gow 2000).

Summary

Evaluations indicate that the model limb represents a close analogy of the articulations of the human upper-limb and it embodies design principles that appear to have both short term and long term significance to the field of prosthetics.

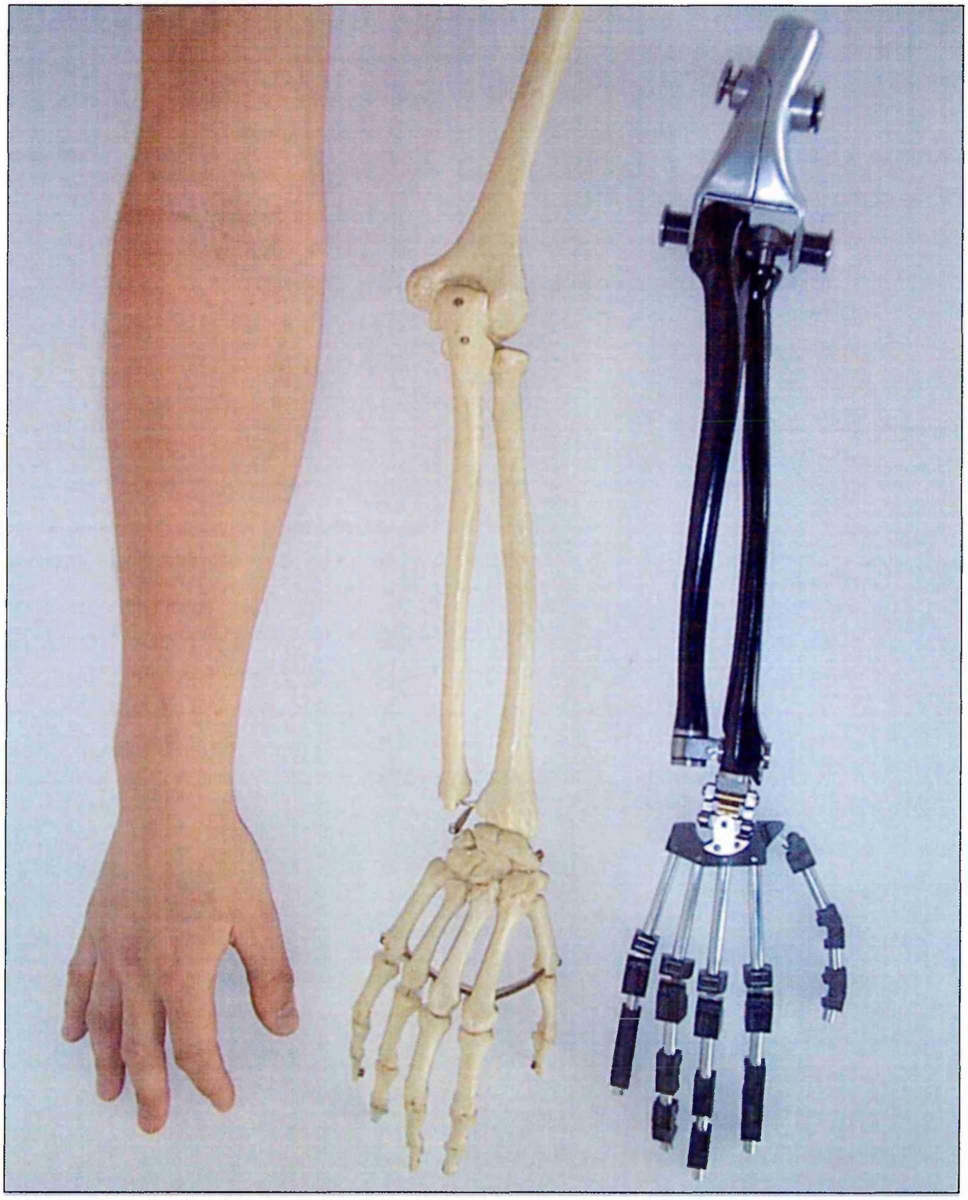


Fig 8.2 The Current Model Limb

The production of tangible models has aided the evaluation of the model and is also supporting further research into other aspects of the limb in other laboratories.

Dissemination of the model to robotics laboratories may indicate wider uses of a close skeletal analogy of the human upper-limb.

Suggestions for future work

Suspension

The need for new ideas for prosthetic suspension methods was highlighted in the focus group. Developing new design principles for this aspect of prosthetics appeared inappropriate at the time of the focus group. However, as the research has tackled more proximal joints of the limb, potential new strategies for suspension using the principles of close analogy have become apparent. These now need to be pursued.

Implantable Joint Designs

Qualitative evaluation of the model elbow and wrist joint by orthopaedic surgeons revealed that the closely anatomically analogous joints might be developed towards a 'linked' implantable prosthesis. Of principle interest was the potential the elbow joint showed for a method of linking the radius to the humerus whilst still permitting natural pronation / supination and flexion / extension movement. The current surgical procedure involves the excision of the head of the radius when implanting a hinge-like elbow prosthesis (Sulzermedica 1991). If this direction is pursued it appears appropriate that quantitative methods may be more prominent to ensure the structural properties of the proposed designs are appropriate. Additionally, investigations will also be needed to determine appropriate 'biocompatable' materials for an implantable device.

Structures for Actuation and Tendon Guidance

The evaluations of the model hand indicated that tendon guidance and joint constraints required further work. Additionally, evaluations of the quality of movement of the forearm and wrist suggested an analogy of soft tissue within model would be advantageous. One of the main aims of future work would be to develop the skeletal analogy, adding tendon guidance and actuation structures.

Structural Analogy

Whilst the original goals were to ascertain whether joints could be made that would provide close analogies of the articulations of the upper-limb evaluations of the model have indicated that form is also important in achieving a close analogy.

For example, the 'bones' of the model hand are simple cylinders, whilst the forms that connect the joints of the model forearm are modeled to the form of the radius and ulna bones of the human skeleton. It appears that with the use of strong lightweight materials, such as carbon fibre, these forms can be made to withstand the predicted forces on a prosthesis (Snaith 2000).

Further work is necessary to determine the level of 'form analogy' that will both, provide the structural requirements of a future prosthetic device, but will also support small scale modularity and effective manufacture that has been indicated as desirable.

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Using practice led design research to develop an articulated mechanical analogy of the human hand

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Contemporary prostheses have developed from small iterations on moderately successful archetypes. This has resulted in modern designs that can either be termed cosmetic or functional, with neither attribute being fully satisfied. A new strategy is needed to develop a generation of upper-limb prostheses that will integrate both cosmetic and functional requirements in a single device. It is hypothesized that design principles applicable to a new generation of prostheses will result from exploring close analogies to the human upper limb. A method of practice led design research has been adopted to explore appropriate analogies, using the production of physical models to elucidate the design problem to the design team and other interested parties. This method uses a consciously iterative approach whereby criticisms and lessons learnt in the development of early models are embodied in subsequent models. This paper describes the first iterative cycle. It includes a critical review of the devices currently available and a study of mechanical analogies to original anatomy which form two of the inputs to the development of a skeletal model hand. It details the lessons learnt from this study and concludes on the wider application of practice led design research in medical engineering.

Introduction

Contemporary prostheses can be separated into three categories: passive, body powered and externally powered (figure 1). Each offer the amputee different attributes.

Passive prostheses

A passive prosthesis provides a static appearance of a human arm and hand and consequently is also termed a cosmetic applicance. The passive prosthesis has the longest history; the first one recorded being an iron hand worn by Marcus Sergius, a Roman General who lost his right hand in the Punic War (218 to 208 BC) [1]. The most effective passive prostheses are tailor made using craft techniques. However, the illusion of a natural arm and hand is only partially achieved as movement is an essential part of cosmesis [2,3].

Body-powered prostheses

Body-powered prostheses use the relative movement from an intact joint to control the movements of the prosthesis. The body-powered device was invented in 1812 by Peter Baliff, a Berlin Dentist [4]. It comprised a mechanical hand with fingers that could be flexed by movement generated through a cord attached to a harness secured on the amputee's opposite shoulder [1]. Such devices have remained largely unchanged, using movement of the amputee's shoulders to control both movement of the arm and gripping action (prehension) of the terminal device.

Body-powered prostheses are relatively lightweight due to the absence of a power source, yet can produce fast movements and large prehensile (gripping) forces [5]. The mechanical connection between the prosthesis and the user has the key property of an unbeatable link between the movement of the prosthesis and movement of an intact joint, which provides the user with both force and positional feedback [6]. Body-powered prostheses are relatively simple devices which are both durable and reliable.

Externally powered prostheses

The current generation of powered prostheses normally use electromyographic signals from the vestigial musculature of the upper limb or shoulder to control movement of the arm and/or prehensile action of a terminal device (prosthetic hand or other end effector). Externally powered prostheses were developed in response to the needs of the Thalidomide victims and veterans of the Korean and Vietnam wars which coincided with the advances in micro-electronics and control system components which occurred during the early 1960s. One of the advantages of myoelectric prostheses over body powered prostheses is that they leave the remainder of the user's body unconstrained. However, using electromyographic signals for control provides no position or force feedback to the user. In addition, when compared to body-powered prostheses, they have been shown to be relatively heavy and consequentially uncomfortable in use [7].

A key feature of any active prostheses is the functionality of the terminal device which must replace the function of the lost hand. In 1909 the 'split hook' was invented by Dorrance [4]. This design dispenses with the cosmetic appearance of the hand in preference for two curved pincing jaws (figure 1). As well as being

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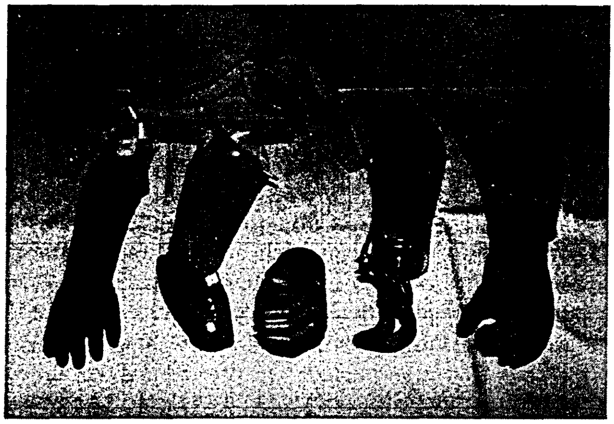

Figure 1. Contemporary upper limb prostheses. From left: (1) a 'cosmetic' passive prosthesis usually chosen for its surface appearance; (2) CAPP myoelectric prosthesis; (3) end effector for a body powered prosthesis: an attempt to mimic natural appearance; (4) body-powered prosthesis with split hook terminal device; and (5) typical externally powered (myo-electric) prosthesis.

durable, the split hook allows the amputee to see what is being manipulated.

The split hook contrasts in both form and function with more cosmetic approaches in the provision of a terminal device. However, in these cases, it is less easy to see the object being manipulated and the mechanism is covered with a glove which is easily damaged and rapidly becomes discoloured. The split hook was originally designed to be used with body-powered prostheses. Mechanistic solutions have also been developed for myoelectric prostheses.

A new approach

Contemporary prostheses have developed through conservative iterations of established historical and engineering principles [8,9], an approach which was perceived to be necessary in order to satisfy the requirements of simplicity and reliability [10]. This approach makes it difficult to combine both functionality and cosmetic appearance into a single device which in turn has limited the acceptability of upper limb prostheses to amputees [11].

It is clear that there is a need for a new generation of upper-limb prostheses that address both functionality and cosmetic appearance in a single device. We hypothesize that small scale iterations on the established designs are unlikely to integrate these requirements, in fact recent developments such as the CAPP device [12] appear to have further divided cosmesis and function. We further hypothesize that appropriate new design principles will only emerge from a reassessment of the anatomy of the human upper limb. If the natural limb is regarded as the 'gold standard' against which a prosthesis is assessed, then it is necessary to consider the extent which recent advances in materials, control and actuation technology [13–15] permit the production of an anatomical analogy. The process of finding solutions to technical problems through analogies of biological systems has a long and successful history [16,17].

As a first stage in the development of a prostheses based on an anatomical analogy, a model hand has been developed and evaluated. The hand was chosen as a starting point as it is the most complex structure of the upper limb. This approach was adopted in the belief that any design principles arrived at in the production of the hand should be applicable to the rest of the limb.

Method

The research methodology employed is a form of Practice Led Design Research [18,19]. The research follows an iterative process with repeated cycles of creative reasoning, physical prototype or model construction and evaluation of the prototypes and models by end-users of the product. The results of the evaluation are then used as an input to the next iterative cycle. The production of prototypes and physical models as an integral part of the research process not only elucidates the problem to the design team but also provides the researchers with a tool to stimulate criticism from the end-users at an early stage in the design process [18]. The end-users within the context of this study inlcude: amputees, prosthetists, occupational therapists and prosthesis manufacturers. A key element of the research method is the involvement of end-users in the design process. Informal contacts with the amputee group provided the designers with the opportunity to discuss the results from existing evaluation studies with users and for those discussions to form the user input to the creative reasoning step of the first iterative cycle. The designers made several informal visits to an amputee support group and found that the majority of members of the group expressed high levels of dissatisfaction with contemporary upper-limb prostheses, which supported the findings of existing evaluation studies [7].

The first cycle in the development of the model hand started with a study of the anatomy of the human hand and arm from commercially available three-dimensional anatomical models. These were scrutinized by the production of detailed drawings, a process we have termed 'observational drawing [20,21]. It was only in trying to replicate the subtleties of bone and muscular structure on paper that the intricacies were fully understood.

Following the production of the observational drawings, drawings of mechanical 'skeletal' hands were produced which whilst they contained joints and structures which could be manufactured, still adhered closely to the anatomical structure of the human hand (figure 2).

By adhering closely to the biological structure of the human hand it was found that many of the biomechanical mechanisms could be replicated in a physical model. For example, fine steel wire could approximate the flexor and extensor tendons to the digits. Interphalangeal (IP) joints could be treated as similar 'joint modules' with one degree of freedom. Similarly, Metacarpo-phalangeal (MP) joints could be treated as 'joint modules' with two degrees of freedom. A simple compliant joint module at the carpo-metacarpal (CM) joints on digits three and four, contributes to the cupping action of the palm when the thumb opposes these digits. In addition, insights gained from the observational drawing process suggested principles that could be applied to manage the complexity of guiding the tendons to the fingers. The routing and anchoring of the tendons in the model hand was done through features incorporated in the joint modules. The problems of routing the analogous finger tendons through an articulated wrist of the mechanical 'skeletal' hand were resolved by the production of an approximation of the extensor and flexor retinaculi.

In designing the 'joint modules' several approaches were considered, including commercially available miniature engineering components. None of the available components were suitable as they lacked routing and anchoring features for 'tendons' and therefore original designs were produced (figure 3). The joints and most of the structure of the hand model was made from a lightweight bearing plastic. This was chosen for its low friction, light weight, ease of machining, and availability. The joints were produced by CNC (Computer Numerical Control) machining which allowed rapid production of several intricate joint modules. The joints were made of several component parts which had to be drilled and assembled (figure 4). Jigs to enable the drilling and assembly process were also machined by CNC to maintain accuracy when conventional machine tools needed to be used. The CNC process was driven by 3D CAD modelling software which allowed rapid changes to the design in response to evaluation and several iterations of the joint designs were generated before the model was submitted for formal evaluation.

A number of expert review groups were formed to evaluate the design principles and questions elucidated through the production of the model hand. All those involved in the evaluation not only viewed the model hand but were encouraged to explore its functionality for themselves. These included groups of amputees; a number of designers from different disciplines; researchers with a specialized knowledge of the anatomy and physiology of the human hand and specialists in the rehabilitation of amputees. This represents the first cycle of an iterative research process and we wished to elicit the widest possible range of comments from users. Therefore the initial evaluation of the work by amputees was carried out using a focus group. To stimulate discussion in the focus group, a video was produced. This included documentary material about current prostheses [22], discussions by designers of automata [23] and film clips from popular films which

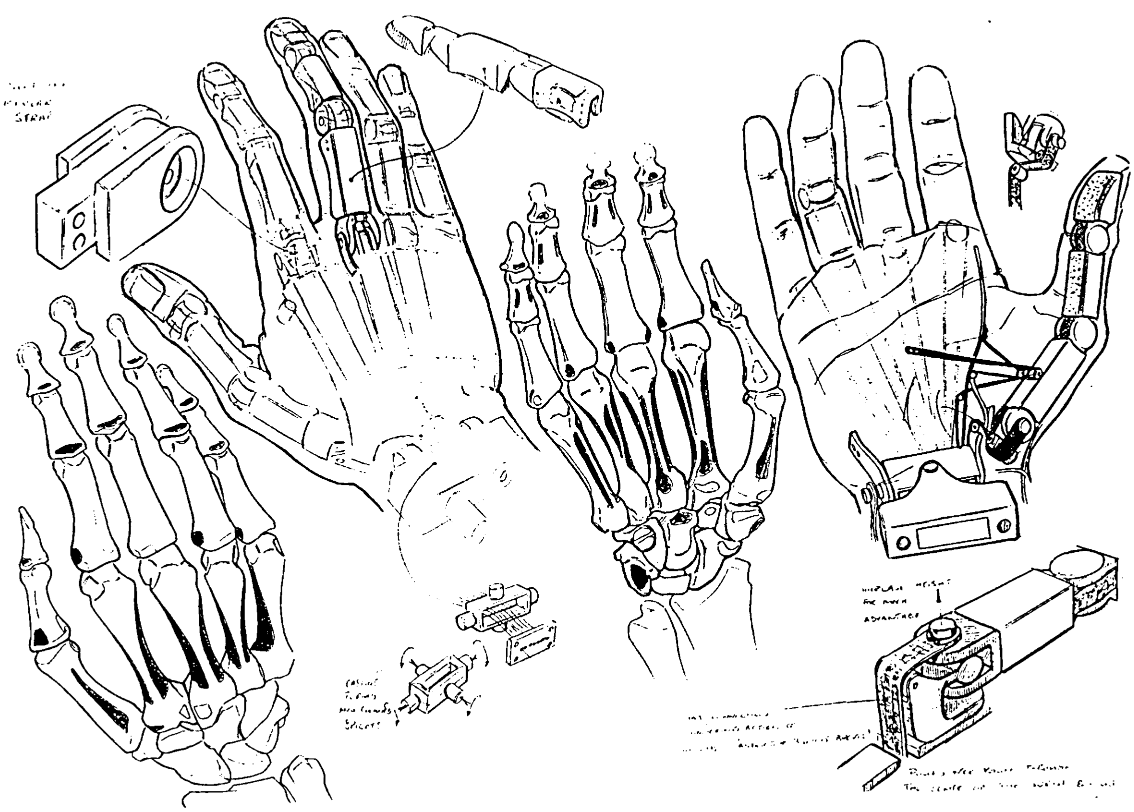

Figure 2. Examples of development drawings produced during the observational and initial creative stages of the design process.

deal with ideas such as life-like robots [24,25], the use of technology to enhance or replace human body functions [26] and the problems of creating life-like movement in animation [27].

The consequent discussion was recorded on video and analysed by the design research group.

Results

The analysis of the observations and views from the various evaluation groups have been collated under three headings: Technical, Human Factors and Manufacturing.

Technical evaluation

The results of the technical evaluation arose primarily from discussions within the design group itself, together with other researchers having a specialist knowledge of anatomy and physiology.

(1) The model which resulted from the implementation of the concepts developed through the anatomical analysis and observational drawing bore a resemblance to a skeletal hand (figure 5).
(2) The overall dimensions of the model, and of the individual joints, are closely comparable with the original anatomy.

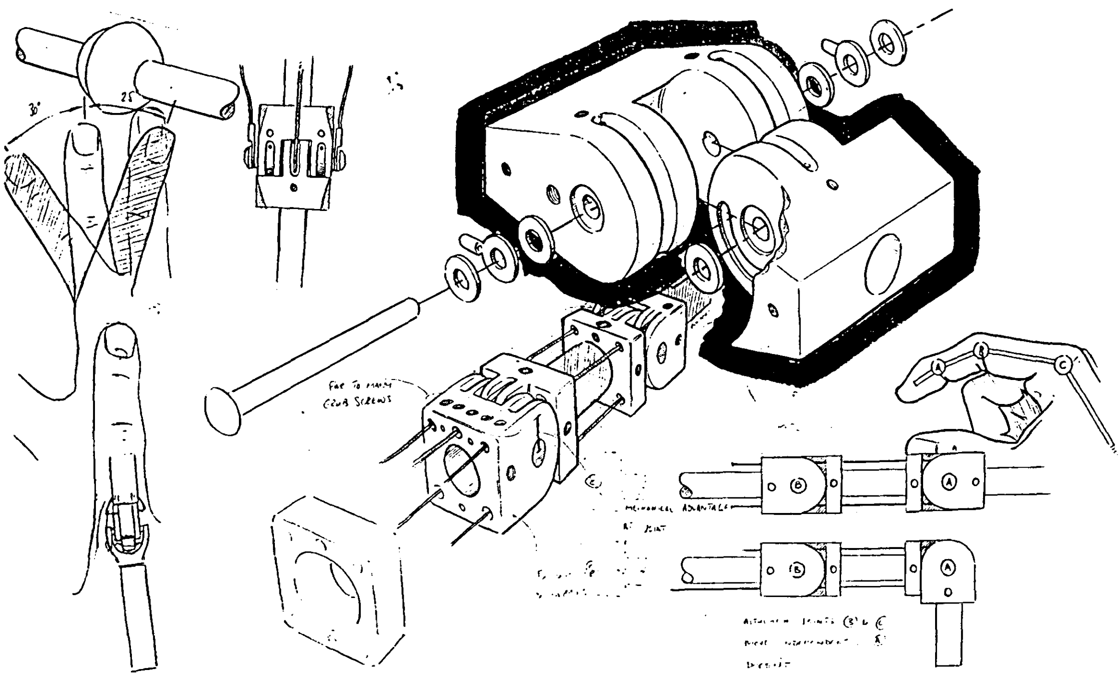

Figure 3. Examples of development drawings used to analyse the problems of articulation in the analogous design.

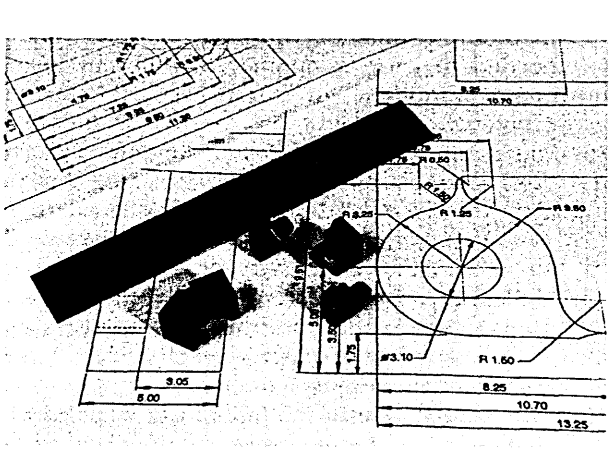

Figure 4. Components from the model that comprise an interphalangeal joint.

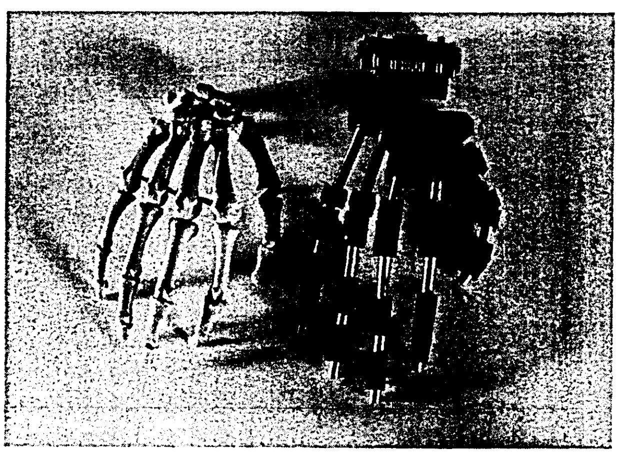

Figure 5. Comparison of skeletal model with original skeletal anatomy.

(3) The model was implemented using only two types of joint module. An IP joint which is a tendon joint, and an MP joint which is a universal joint.
(4) In the natural hand, movement is achieved through tendons connecting the muscle to the bone. Within the model, the tendons were fine steel wires. It was possible when different 'wire tendons' were pulled to flex, extend, adduct and abduct each finger. Similar movements were also possible with the thumb and at the wrist.
(5) The high degree of articulation has resulted in a skeletal model that can be positioned into a variety of grip configurations (figure 6) and initial measurements indicate that the articulation is closely comparable with that of the original anatomy. The gross grip dimension achieved (170 mm) is considerably wider than that obtained by a typical commercial myoelectric hand (Otto Bock Company—88 mm) or a dorrance type hook (Hugh Steeper Ltd—113 mm).
(6) The articulations that provide adduction and abduction at the MP joint enable a wide span to be adopted when grasping a sphere (door knob) or a narrow span where this is needed for a precision grip (coin).
(7) The wire tendons are used antagonistically to provide movement as they are in the original anatomy. With reference to analogies of the tendons to the flexor digitorum profundus and extensor digitorum it was found that their co-operative action could not be mimicked mechanically by linking them around a pulley.
(8) Flexion and extension of the wrist was found to interfere with the relative positions of the digits. In a natural hand, the muscles that control the different tendons do not function completely independently, but rather there is coupling between the different muscle activations. In order to better mimic the movements in the natural hand, a study of the biological processes which provide neutral 'muscle tone' is required to elicit the nature of these couplings.

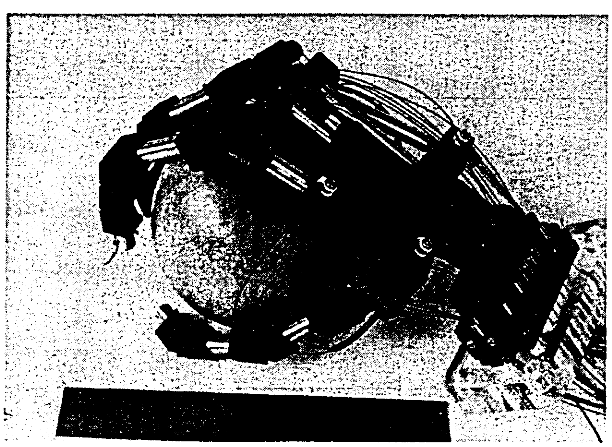

Figure 6. The first cycle of the project has resulted in a lightweight highly articulated analogy of the skeletal human hand produced by CNC manufacturing processes.

(9) Some of the analogies to the original anatomy are only partially successful, for example the use of a universal joint with two axes of rotation for the MP joint, which is more closely analogous to a ball joint. The universal joint does not possess the range of movement that results from the articulating surfaces and constraining ligaments of the anatomical MP joint, nor does it provide some of the constraints which are needed.
(10) The model flexor/extensor retinaculi exhibits unwanted 'latching' effects caused by relative movement of the tendons over the pivot centre responsible for abduction and adduction of the wrist.
(11) In the model hand, each wire 'tendon' is independently controlled and attached to one articulated segment. In the original anatomy many muscles and consequently tendons act together and this is especially true in the full extension of the finger. Closer scrutiny of the original anatomy is required to produce more successful analogies in a subsequent model.
(12) As the model was developed to examine articulation it was not appropriate to measure grip strength or speed of closure.

Human factors evaluation

The design reviewers' analysis of the focus group discussion produced the following observations:

(1) That the users viewed their existing prostheses as inadequate. They also believed that there was nothing better available and had low expectations for future devices. These views were strongly expressed and reflected a generally negative view of upper-limb prostheses.
(2) Amputees perceived prostheses as being either cosmetic and functional and did not expect both needs to be met by a single device either now or in the forseeable future.
(3) Many amputees made limited use or no use of their prosthesis because of suspension problems and/or an uncomfortable fit.
(4) The hard surfaces of most existing prostheses caused problems especially when dealing with children.
(5) In order to function 'normally' some amputees needed to carry a number of different attachments for their prosthesis and this caused problems.
(6) Some amputees had made attachments or adaptations for their prostheses and indicated that the ability to adapt the design was important to them.
(7) The amputees recognized that natural movement was essential for cosmesis.
(8) Unilateral amputees were worried that lack of functionality in their prostheses led to overuse of their contralateral hand which could cause repetitive strain injury.
(9) The presentation of the model was followed by a change of perception towards the idea that a single device could embody both cosmesis and functionality.

(10) Some users indicated that their main need was for a cosmetic device and that this was extremely important to their self-confidence. However one of this group stated that her views had changed since becoming a parent because of the wide range of physical tasks required by child care.

(11) One user, who also had a lower-limb prosthesis, stated that her leg was very satisfactory and met her needs and expectations but that the arm was very unsatisfactory. The group shared her perception that upper-limb prostheses were much less successful than lower-limb prostheses.

Manufacturer's view

On presentation of the design concepts and model hand to a prosthesis manufacturer the model continued to facilitate a discernible change in perceptions.

(1) Initially the views expressed were that it appeared complex, however, after closer inspection of the modular design these views changed, and the model was viewed as a positive step towards an improved prosthesis.

(2) The manufacturer recognized the value of the modular design in simplifying production and lowering cost as well as having the potential to improve function and cosmesis.

Conclusions

The model demonstrated the ability to create a mechanical analogy of the human hand which is dimensionally and functionally close to the original anatomy and has the potential to form the basis of a new generation of prosthetic devices. This has been verified by amputees at a focus group, a prosthesis manufacturer and physiological researchers.

Completion of the articulated hand model has demonstrated that the method of design by close analogy to human anatomy can yield useful results. The resultant principles gained from the production and evaluation of the model hand has shown that research led by design practice is an appropriate methodology for this development.

The approach taken has the potential to provide natural movement in a way which is difficult to envisage with existing prosthetic designs since these do not match the articulations of the original anatomy. The approach taken has also brought about a change in the expectations of the user focus group, in particular their pre-conception that cosmesis and function were not compatible in a single device.

The modular approach to the design of internal mechanical components such as the finger joints demonstrates the potential for such an approach to form the basis of a new generation of prostheses. Modular design can reduce production costs, facilitate ease of maintenance and enable the device to be tailored to the individual [28]. Existing designs are modular by virtue of the system of interchangeable major components but not within each major component.

For an eventual design to function as a prosthesis, subsequent investigations into actuation, control and suspension strategies need to be pursued. Separate research is already underway at other centres into muscle like actuators [14,15,29]. Clearly if such actuators can be made to have characteristics similar to the muscles which control the human hand, they would be appropriate 'prime movers' for the model hand, carrying the analogy of the model with the human hand one stage further.

Discussion

The division between cosmesis and function in contemporary prostheses is not satisfactory. It is arguable that it has resulted from a process of development based on small iterations on moderately successful archetypes [9].

In using human anatomy as the basis for the development of the model, a 'top down' approach to the development of a new prosthesis has been adopted. This has resulted in anatomically analogous solutions being sought from outside conventional prosthetic technology.

Using an approach led by creative design practice, new design principles have been deduced for the next cycle of creative reasoning and model making. The tangible nature of the research model has changed the views of both end-users and a manufacturer leading them to decide that a new generation of prosthetic appliances was possible.

A number of problems identified in the research suggest that a closer examination of human anatomy is necessary to improve the mechanical analogy. In the evaluation it was found that flexion and extension of the wrist produced unwanted finger movements. In the natural hand the muscles that control different tendons do not act independently, but rather patterns of activation are necessary to produce the apparent independent movements of different joints. In order to better mimic the movements of the natural hand, further study of these patterns of activation in the normal hand is required.

Similarly, the resolution of the problem with the 'latching' behaviour of the model when the hand was closed requires further study of the anatomy of the tendon guidance system in order to resolve it. The model hand was the 'construction' phase for the first iterative cycle of the research. In this cycle we have concentrated on producing a mechanical analogy of the hand and examining its articulation. In future cycles it will be necessary to quantify performance parameters for the models including grip strength and angles of movement.

The research has not, so far, considered static appearance and there is a need to introduce to the project an understanding of the problems of appearance and tactile qualities at close range and importance of these attributes in relation to natural movement.

The initial success in developing a model hand based on a close study of the human anatomy using a practice led design research method suggests that this approach may be applicable to the design of other devices as the combination of physical model making and reference to end-users at an early stage in the development provides several perspectives on the design problem.

Further cycles in the research will include production of physical models which address a wider range of factors such as structural performance, appearance and manufacturability; verification of user research findings by quantitative questionnaires and structured interviews; evaluation of appropriate technologies for control and actuation.

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G81-OS3.02

The Development of Upper-Body Prostheses Directly Analogous to Real Limbs

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Introduction The hand and arm are visible in everyday life and consequently upper-body prostheses require a high level of dynamic and static cosmesis. Current appliances either optimise static appearance or optimise function; the long-established materials and methods used in the construction of prostheses make it difficult to integrate both. This clearly requires designers to revert to first principles in an effort to reconcile the requirements of cosmesis and function. Using a method of "practice based design research", research which consists of iterative cycles of creative development, physical modelling and evaluation to inform subsequent cycles; we aim to demonstrate a completely new approach to the design of upper-body prostheses based on close mechanical analogy to the human hand and arm.

Materials and Methods An initial cycle of practice based design research has been carried out. In this a model hand has been created by considering both human anatomy and available production techniques. In order to evaluate the model, a focus group consisting of amputees was formed. Discussion within the group was stimulated by film clips showing both real and fictional 'bionic' devices. A Moderator identified the key ideas from the discussion and presented them to the group to establish a consensus opinion. Continuing from this summary the experimental model was shown to the group for criticism. Both the discussion and the group's criticisms of the model were recorded on video tape and analysed using qualitative techniques. The results of the focus group provide the basis for a questionnaire to ascertain the opinions of a greater number of amputees.

Results The model hand produced clearly demonstrated that it was possible using modern precision engineering techniques to produce a device which was an analogy of the human hand and which, after further research and development, could form the basis of a new prosthesis. The results from the focus group (11 amputees) highlighted the division between those who amputees who desired cosmesis(3) and those who required function(8). It was noted that those amputees requiring cosmesis perceived their prosthesis as part of themselves, whereas, those concerned with function were more prepared to regard their prosthesis as a tool. However, a consensus opinion was that both cosmesis and functionality should be embodied in a single design. The most important factor identified by the group was the need to improve the comfort of the prosthesis. Both male and female participants identified that a "soft" surface texture was desirable - the example given was that of handling children. The majority identified a preference to own their prosthesis so that they could be free to customise it. In reviewing the model hand, the potential for it to form the basis for a prosthesis which could integrate both cosmesis and function was identified by the amputees.

Conclusion The preliminary results of the first iterative cycle demonstrate that the approach of developing a prosthesis by reference to human anatomy is both appropriate and practical. The focus groups' priority for a comfortable prosthetic was an unexpected outcome for the researchers'. This is clearly an area which needs to be addressed by the research within the near future. The success achieved by using human analogy for the hand suggests that this approach is an appropriate starting point for the cycle of creative development addressing the issue of comfort and the suspension of the prosthesis from the body.

G81-OS3.03

MINIATURIZED ULTRASONIC BLADDER VOLUME MONITOR DEDICATED TO ENURETIC PATIENTS

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Introduction Enuresis affects 20% of children over 4 years old, and this figure typically decreases by 15% each year. Use of pharmaceutical products or employing a conditioning alarm are not adequate for the treatment of those enuretic patients. The medication would not cure the enuresis and presents side effects and the electronic alarm does not actuate at the moment of micturition, but few seconds later. The need for an efficient means of preventing nocturnal enuresis motivated us to propose a new device. The implantable techniques are not adequate because most patients are young.

Materials and Methods We propose a highly miniaturized device that is based on a non invasive ultrasonic technique which can waken the child before the critical fullness threshold has been reached. Moreover, the power consumption should be very low since the power will be derived from a battery of minimum size that has to be integrated in the same portable device. The proposed bladder volume monitor is composed of five main blocks (Fig. 1): 1) A power manager to reduce energy consumption, 2) An ultrasound crystal driven by an RF transmitter-receiver, 3) A low-power integrated operational preamplifier for echo pulse conditioning, 4) A DC/DC converter dedicated to generating the high voltage needed to excite the crystal, 5) A user-friendly interface to calibrate, command and provide feedback through an alarm.

Results A three-phase clinical validation program was developed, in order to locate the best position for the transducer and to determine the electronic setup of the measured depth. These phases are: 1) Experiments on a bladder model, 2) Clinical tests using a first prototype with a hand-held transducer, and 3) Validation of the device on ambulatory patients. The preliminary results which consisted of testing the device on a group of 41 patients at Ste-Justine Hospital, show good performance of the proposed detector. In fact, the global performance of the device corresponds to a 50% success rate, with a 14% measured error on three patients. The device is based on an ultrasound crystal of 3.5 MHz. The power consumption of the first version of the volume monitor is 24.3 mW (2.7 mA with a 9 Volt battery).

Conclusion The proposed device is able to detect a wide range of volumes, is designed to be flexible and can be installed on various contours of the body. The preliminary results obtained on several evaluation phases show an accuracy of more than 70%. A second version is in preparation which will use an array of ultrasound cells to detect the volume threshold. This device will offer more stability during sleep and will give more accurate results. It is important to note that the device can be used in many other applications, particularly in the case of elderly individuals who are incontinent.

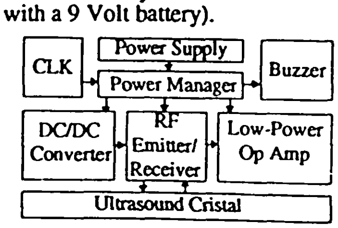

Figure 1.

DEVELOPMENT OF ELBOW AND FOREARM JOINTS FOR AN ANATOMICALLY ANALOGOUS UPPER-LIMB PROSTHESIS

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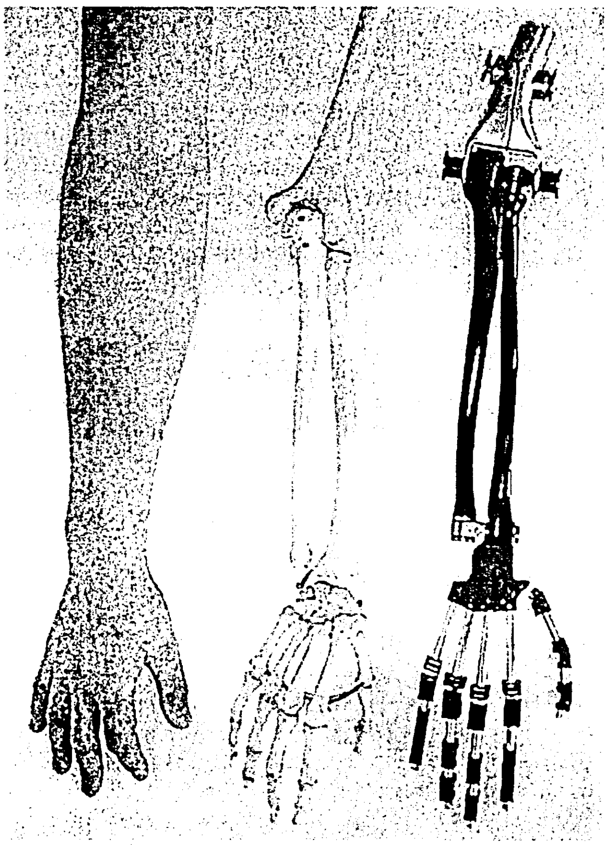

Figure 1: Comparison of Anatomically Analogous model against the skeletal and human arm.

Abstract: Using Practice Led Design Research anatomical analogies for the joints at the forearm and elbow have been produced. These new designs have been positively evaluated both qualitatively by a diverse group of interested parties and quantitatively against existing biomechanical data.

Introduction

Contemporary prostheses have developed incrementally from long established designs[1]. These prostheses do not fulfil sufficiently amputee's needs for both cosmesis and functionality in a single device[2].

In our previous work we used a form of PLDR (Practice Led Design Research)[3], which consists of repeated cycles of creative development, physical modelling and evaluation to develop a skeletal hand model. Using this method we were able to elucidate new design principles which, following further developments, may reconcile the requirement for cosmesis and functionality in a single device.

Whereas the complexity of the model hand derives from the combination of multiple simple joints of similar design, the subtlety of movement of the human forearm and elbow results from the linkage of fewer but more complex joints. Existing prosthetic components that mimic the movements of pronation-supination of the forearm and flexion-extension of the elbow bear little resemblance to the original anatomy. For example conventional prosthetic components for pronation-supination use a single axle at wrist level, whereas this movement is accomplished in the original anatomy through movement of both the radius and ulna bones.

The researchers were interested to find whether the form of PLDR used in the development of the hand model could be used to develop anatomically analogous joints for the elbow and forearm that would facilitate more natural pronation-supination and flexion-extension movements.

Materials and Methods

In our previous work, the development of a skeletal model hand, observational drawings of three-dimensional skeletons were produced as a means of studying the anatomy in detail and also to stimulate new design ideas[4]. This technique was used again in the development of the analogous elbow and forearm joints. However, it was found that supplementary numerical data was needed to gain a comprehensive understanding of the movements due to the complexity of the combined action of the proximal and distal radio-ulnar joints. Measurements were made using splints to isolate movements to readily measurable planes. This, combined with information from anatomical references, was used in the generation of sketchbook ideas for a model forearm. Attention was paid not only to the function of the proposed components but also to their form, which is particularly evident in the more 'organic' form of the elbow fixture.

The designs were prototyped using a combination of craft and conventional precision manufacturing techniques. The sculpted form of the elbow fixture was produced using a lost wax aluminum casting process (fig.1).

Once the analogous distal and proximal radio-ulnar joints had been produced they were fitted into casts of the human radius and ulna bones. It was then possible for these bones to be palpated. This model was presented to groups including amputees, a surgeon with a specialist interest in elbow pathology, an experienced osteopath and representatives from a major prosthetics manufacturer for qualitative evaluation. In addition, a quantitative evaluation was performed by fixing the model ulna to a board and a stylus to the proximal radio-ulnar joint to record its angular movement in response to incremental angular positioning of the distal radius about the ulna. To compare this to the movement that of a human forearm a splint was constructed to fit one of the design team.

Results

Using goniometric techniques the range of movement for both movements of pronation-supination and flexion-extension at the elbow of the model has been measured. These are 180° for pronation-supination and 145° for flexion-extension at the elbow which are within the range of normal human movement[5]. Figure 2 shows the lateral movement of the model ulna against that of a human ulna during pronation-supination, where 0 degrees radius angle represents maximum supination.

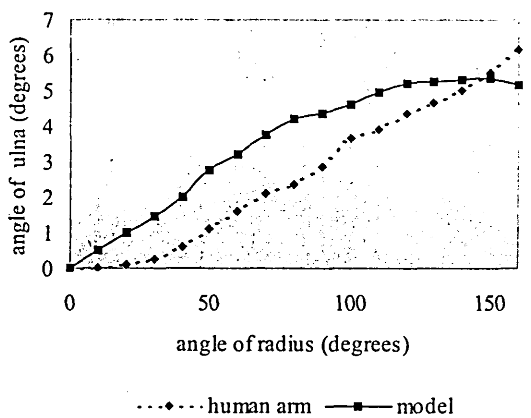

Figure 2: Comparison of Angular Movement of Human Ulna against Model Ulna during Pronation-Supination

Since the inception of the project an amputee support group has been regularly attended and this group has reviewed the elbow and forearm models. The amputees have favourably commented on the naturalness of the movement of pronation and supination and also its endoskeletal design, which has the possibility of being covered with a soft surface, something, which has been highlighted as advantageous in our previous work[4].

The models were presented to a clinical elbow specialist for palpation. On careful inspection of both the ranges of movement of pronation-supination of the forearm and flexion-extension of the elbow, he was content that these were a close analogy of the articulations of the natural limb.

The models were also offered for palpation to an experienced osteopath. It was considered that such a professional would have a keen kinaesthetic sense and therefore would be able to detect movements that appeared 'unnatural'. Her overall impression was that both the movements of pronation-supination and flexion-extension appeared correct and within the natural range of movement. She commented positively on the form of the elbow fixture describing that the 'organic' form added to the anatomical analogy .
Representatives from a major prosthetics manufacturer have also positively reviewed the models. Of particular interest to them was how the system could be adapted to be fitted to a below elbow amputee.

Conclusions

From our work on the development of anatomically analogous joints for the articulations of the forearm and elbow we have found that once again the PLDR method can be used to produce useful models. However, it has been have found that in addition to the observational drawing used in the development of the hand, supplementary quantitative methods are required to understand some of the complexity of the linked articulations that combine to produce the movement of pronation-supination.

Qualitative review by both an elbow specialist and an experienced osteopath has validated the joints both in terms of range and naturalness of movement. These reviews have also validated the use of prototyping methods that allow the production forms closer to the anatomy as such forms have been shown to add to the anatomical analogy.

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