

The Design and Development of an Artificial Hand
Incorporating Function and Cosmesis.

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1974.



**I hereby declare that the composition and content of this
thesis is my own work.**

Gordon Kenworthy.

Summary.

The thesis presents some of the work carried out as part of the research and development programme for the provision of practical artificial upper limbs for a group of congenital amputee patients.

The account commences by reviewing, in Volume 1, the problems presented by this population of amputees in the context of an on-going limb fitting service, and shows how the difficulties of prehension arise in this situation. The provision of upper limb prostheses in general is then reviewed with reference to representative literature on the subject, where various inadequacies of existing systems are considered in the context of the immediate practical problem of the provision of adequate prehension facilities for bilateral amputees.

The experimental and practical work of Volume 2 commences with an appraisal of the requirements for a hand prosthesis in the light of the information derived from Volume 1, and this, together with the results of some simple experiments, leads to a broad specification for a hand mechanism. Various experimental mechanisms are then described, leading to the development of a mechanism suitable for patient trials. The problem of the provision of the cosmetic cover for the mechanism emerges as the major obstacle in the way of further progress, and a new process for cosmetic glove production is devised. This is followed by consideration of the various problems of control associated with the hand prosthesis, some working hardware is developed and guidelines for future work on control are outlined.

The thesis concludes with an appraisal of the work following trial fittings on patients, which shows the principles to be successful in operation and indications for future trends are given

in the context of a wider amputee population who may benefit from some aspects of the work.

Acknowledgements.

I would like to express my gratitude to Professor David Simpson for his continuous guidance and support during this work; to Mr. K. Anderson and Mr. A. D. Small for their work in the production of hardware and their advice on practical matters; to Mr. A. M. Devlin for his excellent photographic work, and to my wife for the typing of the manuscript and her assistance in many aspects of the whole project.

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Section 1.

The immediate commitment and its influence on the formulation of
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1.

Section 1.

The immediate commitment and its influence on the formulation of a prosthesis development programme.

1.1 The origin of the general problem.

The problem of the provision of artificial limbs is a familiar one with a history which extends as far back as pre-Christian times. The results from this work show that a marked lack of progress has been made in comparison with other fields of human achievement during the same period, and even under the influence of 'modern technology' progress has been distinctly limited, as a review of the literature shows. The reasons behind such a state of inertia are not hard to discover since development suffers from the one major factor which appears to influence the degree of success of a large proportion of man's activities - finance. Despite the large numbers of amputees produced as a result of two world wars, there has never been any great social pressure for the development of sophisticated prostheses for the relatively small proportion of the population which is affected.

Paradoxically, this situation was reversed by the advent, in the early sixties, of the 'thalidomide tragedy'. The population affected by limb defects due to the use of the drug thalidomide was minute in comparison with disabilities arising from other causes, but the sensational effects of the social guilt which arose from an inadvertent maiming of a section of the population, heralded a revolution in the public attitude to disabilities in general.

In particular, the thalidomide problem led to the introduction of special programmes for the development of externally powered

artificial limbs in an attempt to provide the severely disabled children with a means of leading a life which could to some extent be regarded as normal, and this situation provided the environment for the work which is described below.

1.2 The environment for the work.

Although the arrival of the funding for development programmes led to the commencement of research work directed towards the provision of arm/hand prostheses in various establishments, the degree of success has, in many cases, been distinctly limited. However, the unique conditions under which the work described in this thesis was carried out, serve to illustrate one of the fundamentally important factors lying behind the production of successful prostheses, since a direct commitment to a group of patients has led to the development of prostheses which are capable of providing sufficient prehension for bilateral amputee children to attend normal schools on a routine basis.

Therefore it is necessary to describe in some detail the themes and the environment underlying the whole project. The effects of the environment will be seen to be particularly important, since all new work has necessarily required to be compatible with the complete powered prostheses and limb fitting programme already in existence at the time of commencing the development of a hand prosthesis.

The programme for the development of a cosmetic hand prosthesis was therefore an integral part of the research programme functioning behind a limb fitting service based upon young upper limb amputees of varying degrees of disability, the majority of the patients being

the victims of the effects of the drug thalidomide, the extensive nature of disabilities occurring in these patients having led to the establishment of a specialised unit concerned with the development and provision of externally powered arm prostheses. This unit is under the directorship of D. C. Simpson at the Princess Margaret Rose Orthopaedic Hospital.

1.3 The influence of previous work.

At the time of commencing the hand development work, the provision of externally powered arms through this unit had been continuing for a period of more than six years, during which time many items of hardware had been developed, and various important concepts of control had been established in the light of the considerable experience obtained by fitting newly developed limbs directly to the patients.

Thus, in commencing a new project within an existing system directly concerned with successful management of patients, considerable external influences prevailed which affected the hand project, and it is therefore essential to cover these factors in order that the hand development may be seen in its true light as a part of an overall scheme for the rehabilitation of disabled patients.

1.4 Fundamental decisions.

The general problem can be simply defined as "the provision of the means by which an armless child can become self-sufficient" and although the justification for such work can hardly be questioned, the lines of action taken can be radically different, having immense implications for the patient. Fundamentally, two alternatives are

presented; either to modify the amputee's environment to suit his disability, in order that he may operate independently within that environment, or to provide him with the means by which he can manipulate the normal environment as far as possible. The first approach is probably the easier to achieve, the modifications would be well defined, very numerous, but of an essentially simple nature - for example to provide special toilet facilities, special working and feeding arrangements, etc. It is apparent that such modifications could only really apply to the patient's home environment to any great extent, thereby restricting him to a quite abnormal existence. The second alternative, to provide a 'universal' facility which the patient can use to manipulate a normal environment, permits a much more liberal existence, although some special facilities may be necessary for the more difficult tasks in the daily routine. Although it is possible to debate these points ad infinitum (taking either side!) it was considered (Simpson 1966) that fewer constraints, either physical or psychological, would be imposed upon the patient, by providing him with an arm-hand prosthesis which was self-contained, portable, having the basic configuration of a normal arm when worn, and being capable of as many as possible of the normal functions of the human upper limb.

Following the decision to provide the amputee with a hand/arm system, two problems arose, the major one being that of control, whilst the second was concerned with the form of the hardware and mechanism itself.

1.5 Control principles.

The solution of the problem of controlling a powered prosthesis formed the basis for the successful development of the practical

prostheses used in Edinburgh, and therefore requires some explanation in order that the subsequently developed hardware be viewed in the context of the control requirements.

Simpson (1964 and 1970) based the fitting of prostheses upon the fact that since the amputee has to live with the prosthesis, the controls should be specifically designed for compatibility with the patient's own natural control systems.

In practice the choice of control principle was made in favour of a position servo controlled mechanism which was considered to be compatible with the natural systems of limb control, and indeed control on this basis could be considered as an extension of the normal physiological proprioception (Simpson 1971).

The feasibility of this control matching depended largely upon the fact that it was known that the central nervous system receives active feedback of joint angle information (e.g. Rose and Mountcastle 1959), and therefore there is information relayed to the natural control system concerning the attitudes in space of the various mobile body segments. Experience of the effect of the alteration of these angular positions with limb position allows the individual to control the limb and as a learning process this is analogous to the acquisition of knowledge of the length of each interjoint segment, thereby permitting each position of the hand to be defined by joint angle information.

The phenomenon of extended physiological proprioception (e.p.p.) depended upon the fact that the superposition onto the natural system of a linear mechanical system would present no problems other than the learning of the magnification factor of the new system, since

every position of the output of the mechanism would be uniquely related to the control input position, which in turn is known by the central nervous system by virtue of the natural position feedback arrangement. This is analogous to the use of a golf club, where the effects of the 'extension' to the arms are easily learned in order that the ball may be struck; although the subtleties of control beyond that stage often appear insuperable for many golfers!

1.6 The mechanical requirements of a prosthesis.

Once the control principles had been established, the important decisions remaining concerned the form of the mechanism itself, the criteria for which were governed by social and psychological factors, since in order for the amputee to be able to live a normal life in a psychological sense as well as a practical one, two things must happen - he must feel that he is socially acceptable, and other people must readily accept him. These two facts, though not necessarily dependent upon each other, tend to be closely linked. They could be achieved in two ways; a long term re-education of people to accept without question the abnormal activities and appearance of a minority, or to provide a prosthesis which is anatomically and functionally similar to the normal system. It is neither necessary nor possible for the prosthesis to simulate exactly its natural counterpart, on the contrary, it should be acceptable to the eye at a glance, without creating a macabre 'dead' effect on close inspection. This approach achieves a simple compromise between the shock on seeing a deformity and the shock on seeing a 'dead' appendage. In the same way the cosmesis must be dynamically satisfactory (Simpson 1966) the action being basically

that of a natural system, without being so realistic that the prosthesis appears to be a strange 'real' arm.

Thus, it was decided (Simpson 1966) that the mechanisms for the arm and hand prostheses should be in a form which, as far as possible, represented the appearance and functional behaviour of normal arms and hands.

1.7 The development and use of practical prostheses.

In order to meet these requirements powered prostheses were developed on the basis of a pneumatic power source, with piston actuators (Simpson and Lamb 1965). These prostheses (Figs. 1.1, 1.2 and 1.3) were provided with powered elbow flexion, wrist rotation and grip facilities, with wrist flexion being linked to elbow flexion in order to maintain stability for drinking operations, etc. The shoulder joint was passively mobile with friction clutches allowing passive pre-setting of the attitude of the prosthesis as a whole. Prehension was provided by means of a specially designed powered hook (Fig. 1.2) since the function of available hands was inadequate, or, where a degree of cosmesis was demanded, a pincer grip type powered hand of limited functional capability was provided. (Figs. 1.1, 1.3).

The arm prostheses in this form were fitted to groups of children for a period of over five years, the specific modes of application being governed by the types of disability encountered. In particular, the group of thalidomide children fell into two anatomical groups, amelics with no arms (Fig. 1.4) and phocomelics with shortened arms and fingers of limited power and range of movement. (Fig. 1.5). Clearly the amelics presented the more



Fig. 1.1 The early prosthesis developed in Edinburgh.

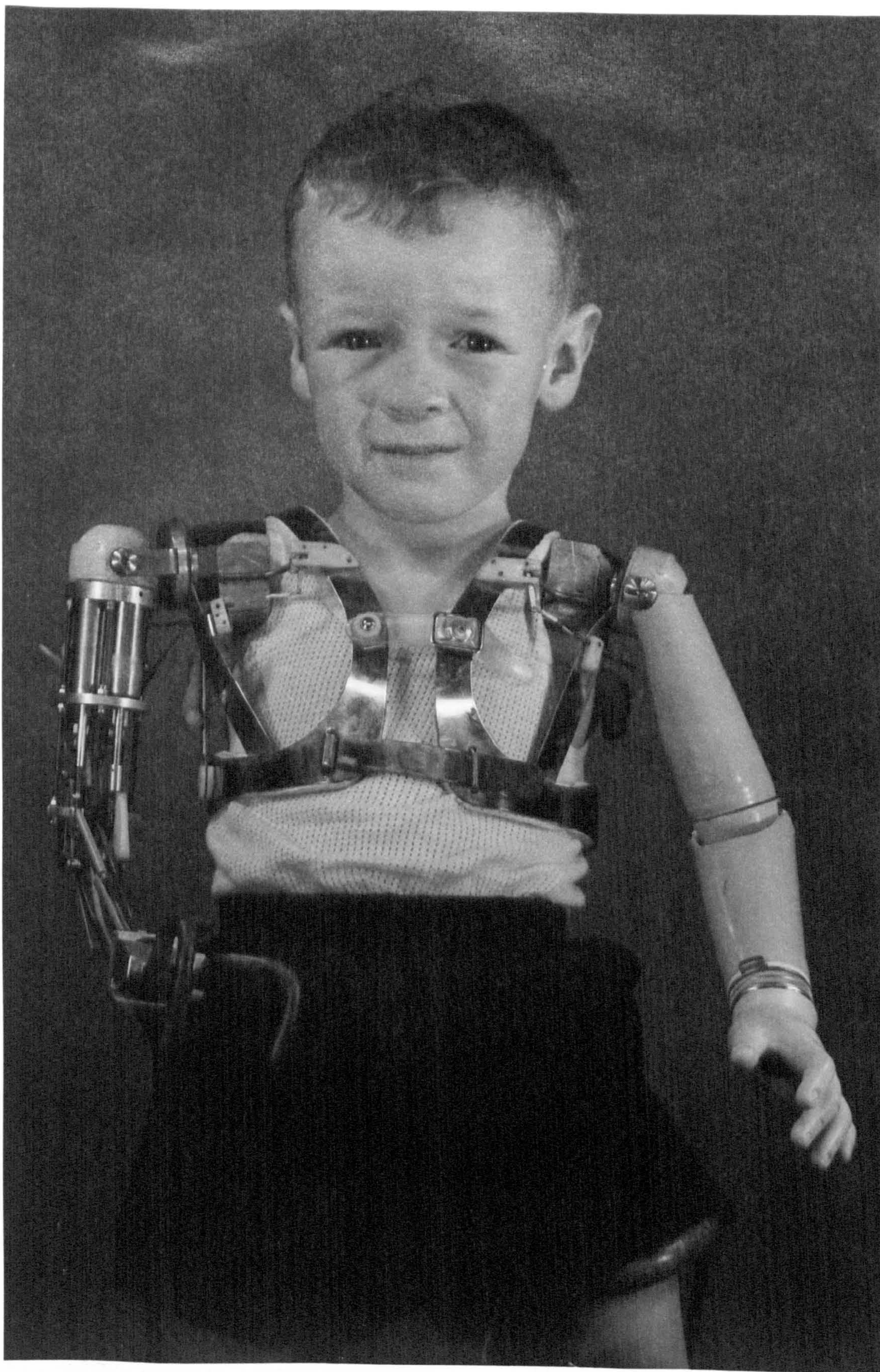


Fig. 1.2 The early prosthesis developed in Edinburgh.

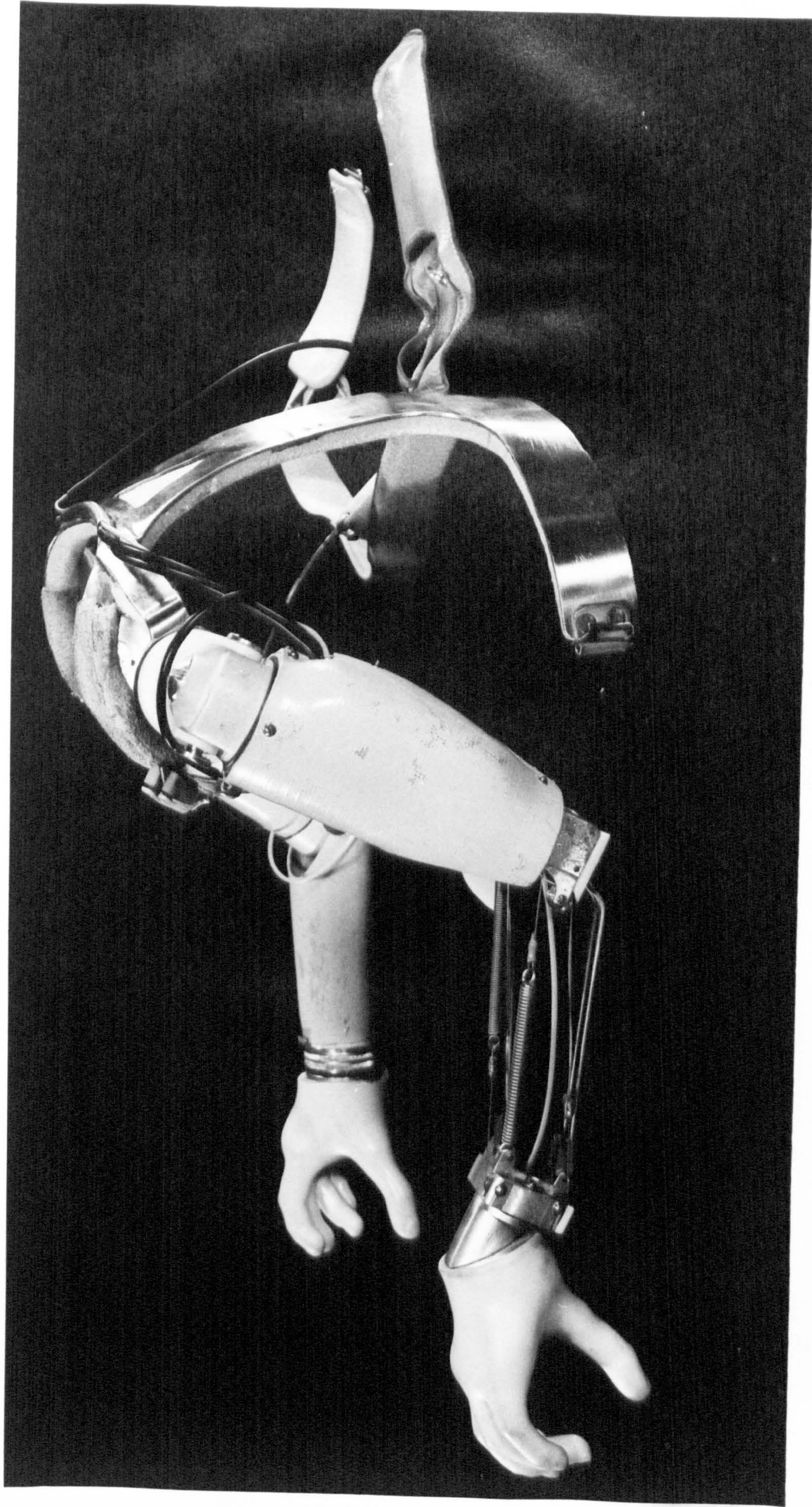


Fig. 1.3 The early prosthesis developed in Edinburgh.

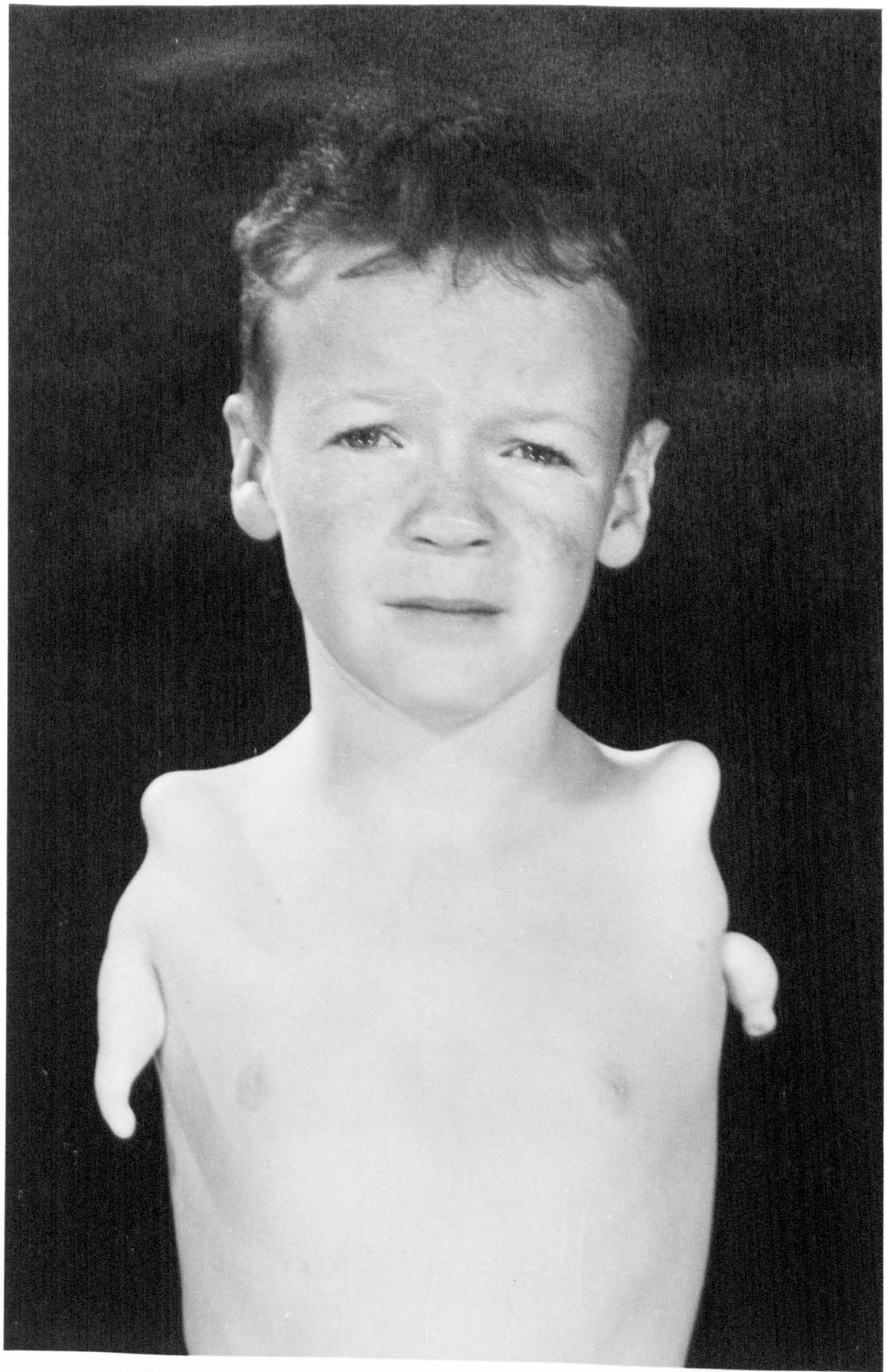


Fig. 1.4 Amelic child.

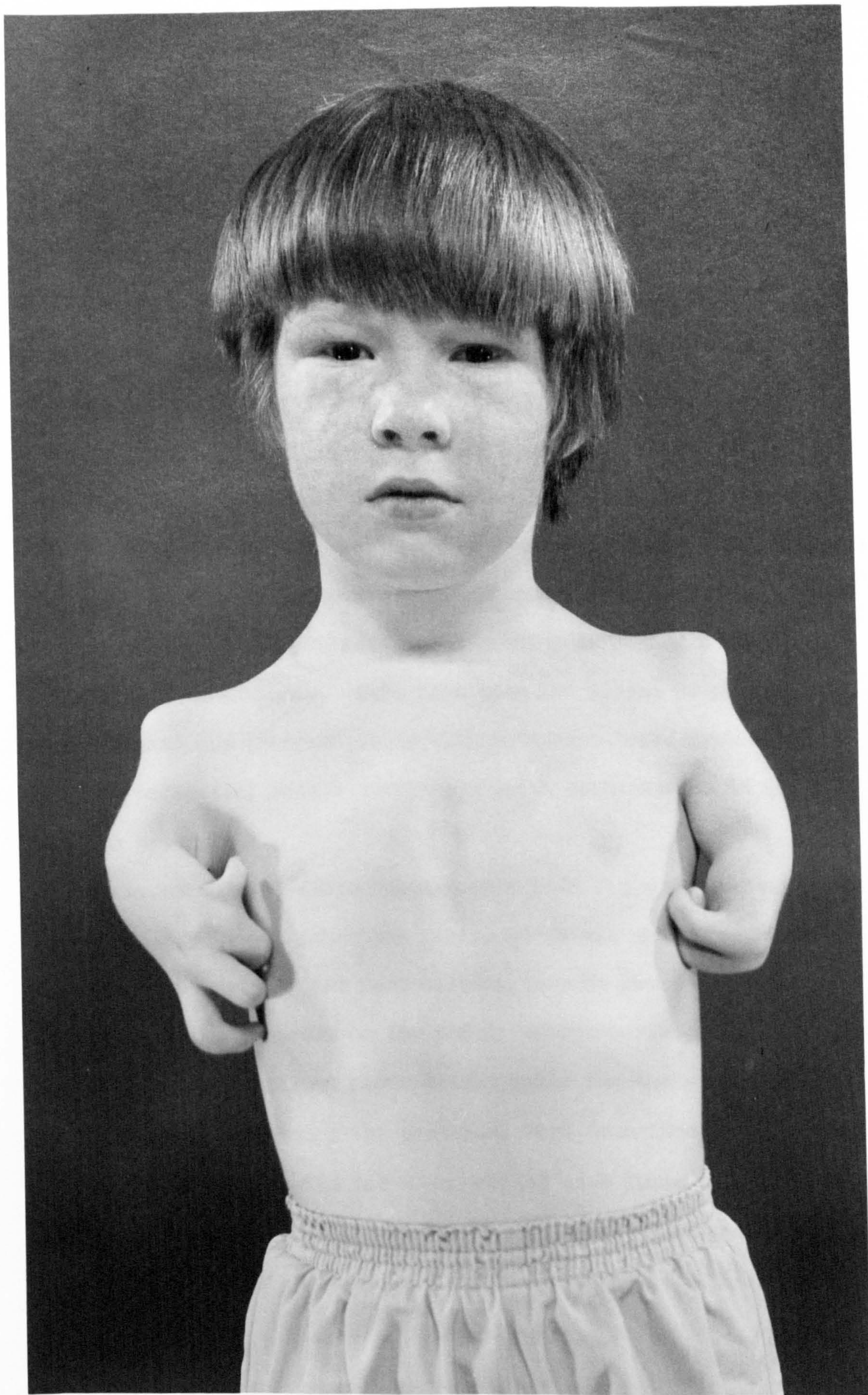


Fig. 1.5 Phocomelic child.

severe control problem in terms of control sites, one site could only be available for each movement if unique position awareness was to be retained. However, it was found that clavicle movement could provide two substantially independent motions, backwards and forwards, and up and down. (Fig. 1.6) Thus the two clavicles could provide four control sites, and these were harnessed as movements relative to the stainless steel harness which carried the prostheses.

1.8 The demand for more versatile prostheses.

Experience with the arm in this form had shown that whilst the control principle of position awareness had proved most satisfactory, with good acceptance of arms by the patients, the increasing age and hence activity of the patients was beginning to demand a more versatile arm prosthesis. This situation led to the proposals for a co-ordinate arm (Simpson 1965) with movements based upon spherical polar co-ordinates, with a stabilised wrist mechanism as in the previous prosthesis.

In order to meet these requirements work had commenced upon the design of a system of pneumatic piston actuators and force demand valves for the driving and control of a complex prosthesis; the choice of pneumatic power as the energy source having been made upon the basis of an excellent power/weight ratio for the piston actuators. At the time of commencing the practical work described in this thesis, a prototype arm mechanism had been devised with logic operating on the control system in order to provide the required co-ordinated movements. This device did not perform adequately due to phase lags in the control systems and a new design therefore became necessary in order to satisfy the increasing need for an arm with a more

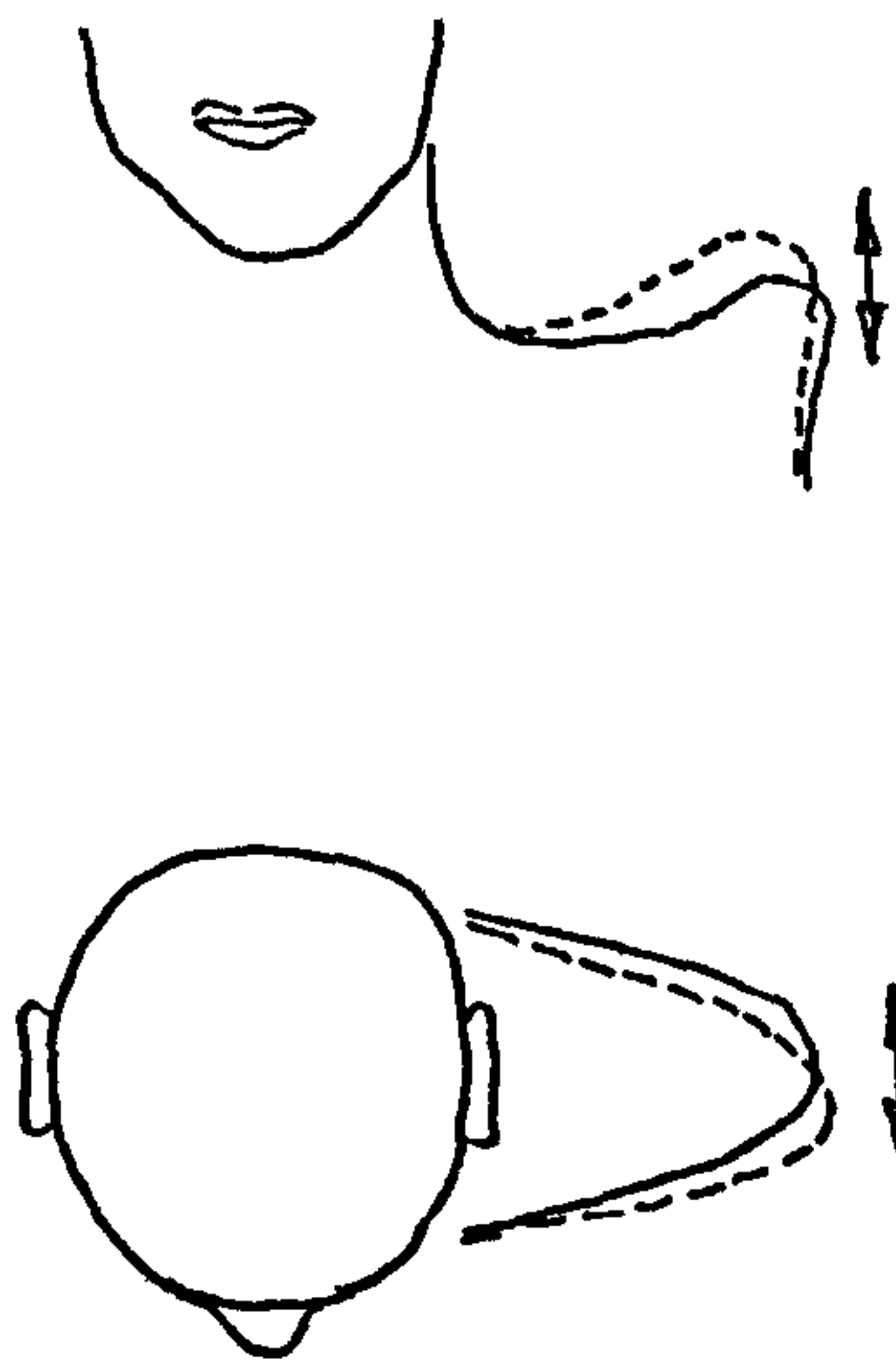


Fig. 1.6 Shoulder movements available for use as control sites. .

comprehensive range of movements than the simple device which had been in service for several years.

These more versatile prostheses were devised specifically in order to position the hand in space on a spherical polar co-ordinate system with an integral wrist rotation facility and a stabilised wrist flexion system, and since these developments have been described elsewhere (Simpson and Kenworthy 1972, Kenworthy and Simpson 1973) they will not be covered in detail. However, the most important factor was that experience in the use of these more advanced prostheses served to highlight the functional inadequacies of the available cosmetic hands, since the increased versatility of the arm prosthesis gave rise to a new realm of functional situations which were not satisfied by the available hands.

1.9 The engineering implications of experiences with arm prostheses.

Although the more complex arm prostheses led to increasing demands for a more adequate hand prosthesis, the engineering experience gained in the development and maintenance of the mechanisms of the arm prostheses provided a great deal of information which directly influenced the development of the hand design. Thus, some indication of these trends will be given in order that the reasoning behind the hand design may be more readily appreciated.

The most important feature which arose from experience with fitting prototype versions of the arm was the fact that it was necessary to accept the incidence of failures and breakages as being inevitable during the evolution process towards an improved device. However, an acceptance of a fact of this nature in a programme of limb fitting made it essential that the process of

repair could be carried out rapidly and simply. Thus, it was crucial to the success of the programme to provide an arm with a type of construction lending itself to the rapid interchange of faulty parts for new sub-assemblies. Details of the way in which this was achieved can be seen in Figs. 1.7, 1.8 and 1.9 where the spaced plate construction provides an open structure into which items such as modular piston actuators, modular valve assemblies, etc. can be inserted and removed relatively easily, this fact significantly reducing the turn round time for the majority of repairs.

A particularly significant attribute of the spaced plate structure is its high strength/weight ratio, making it an economical use of light aluminium alloy materials. However, extensive experience with the arm prosthesis in use on amputees showed that weight savings elsewhere led to an excessively high failure rate, thus, the simple and light shoulder rotation mechanism of Fig. 1.10 had to be replaced by the considerably heavier structure of Fig. 1.11 indicating that in certain high load areas some degree of flexibility in design was essential in order to maintain a service of limb fitting.

The necessity for the continuous changes in design was illustrated by a major alteration in the structure of the arm prosthesis, the change resulting from the use of gear trains (Figs. 1.9, 1.10, 1.11) as the mode of force transmission. Prolonged use of arms based upon the use of precision gears of this type showed two major drawbacks from this source.

(1) Faulty machining in an accurate manufacturing process led to errors in the meshing of gears, requiring extensive attention in

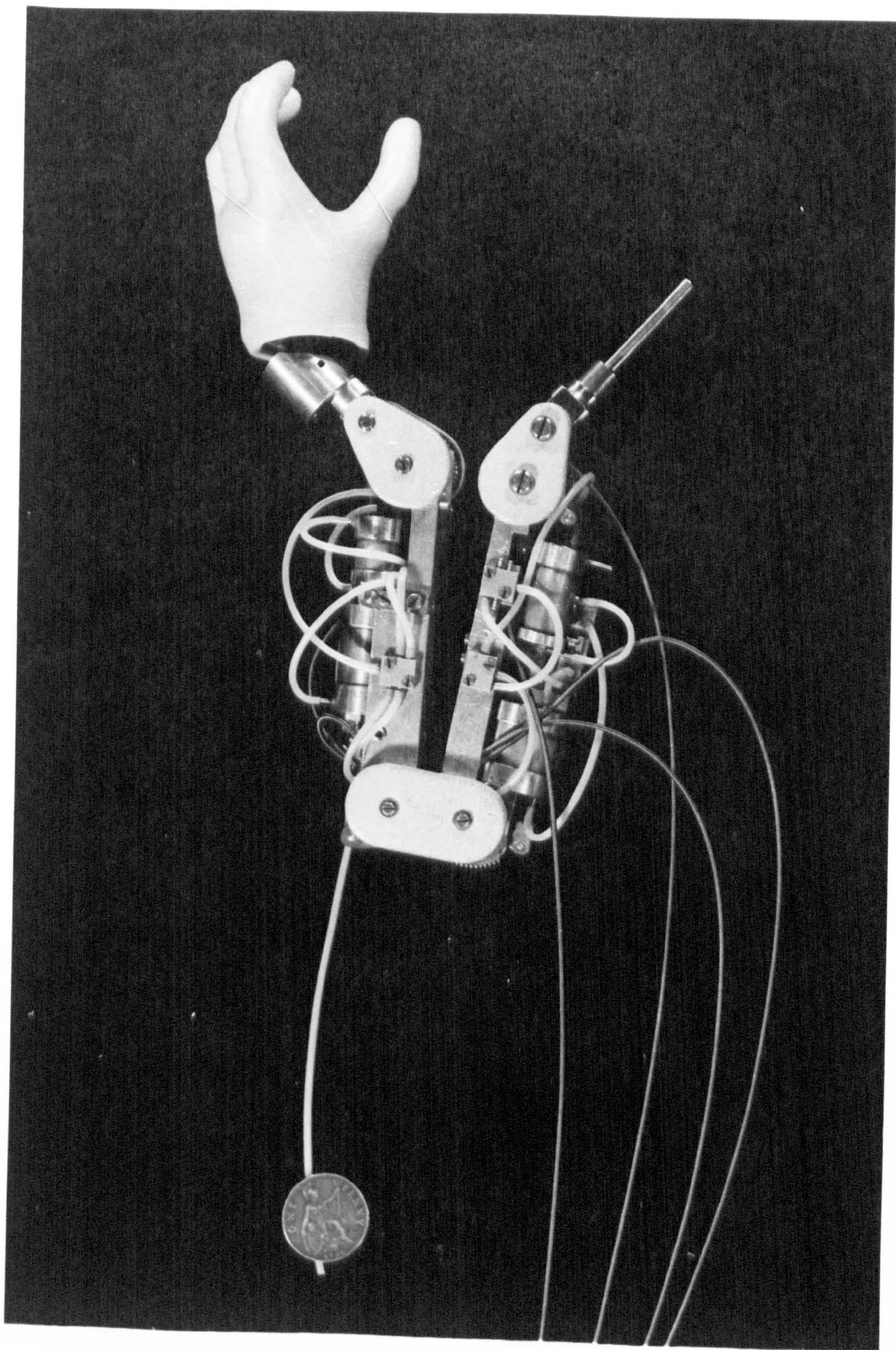


Fig. 1.8 Arm with sideplate construction.

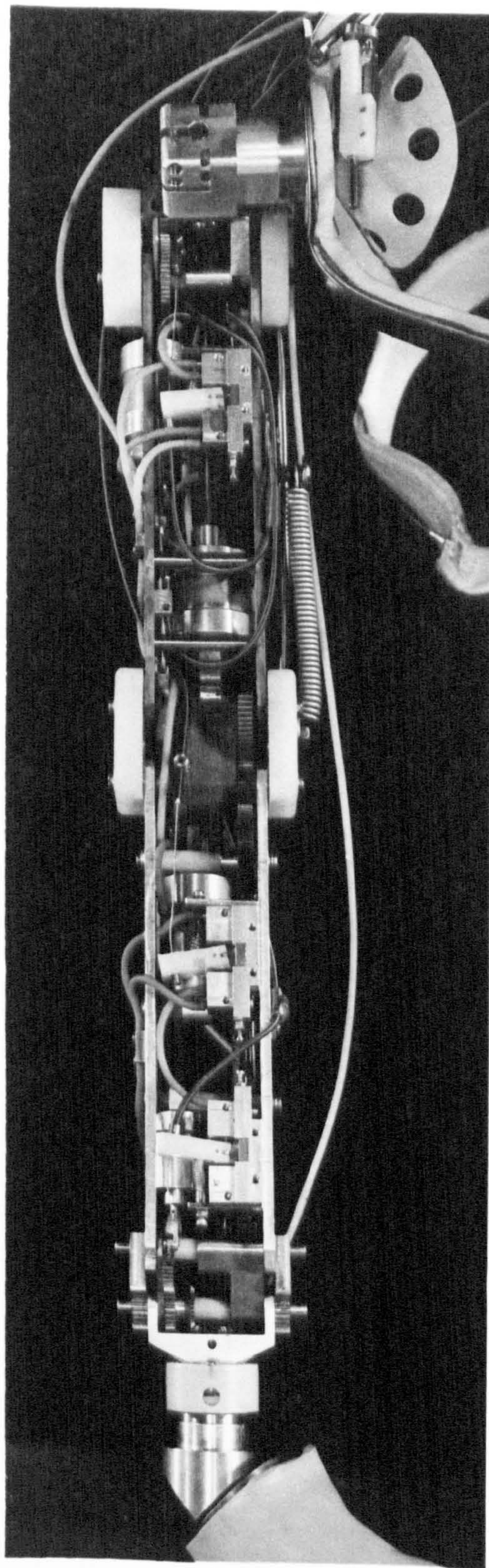
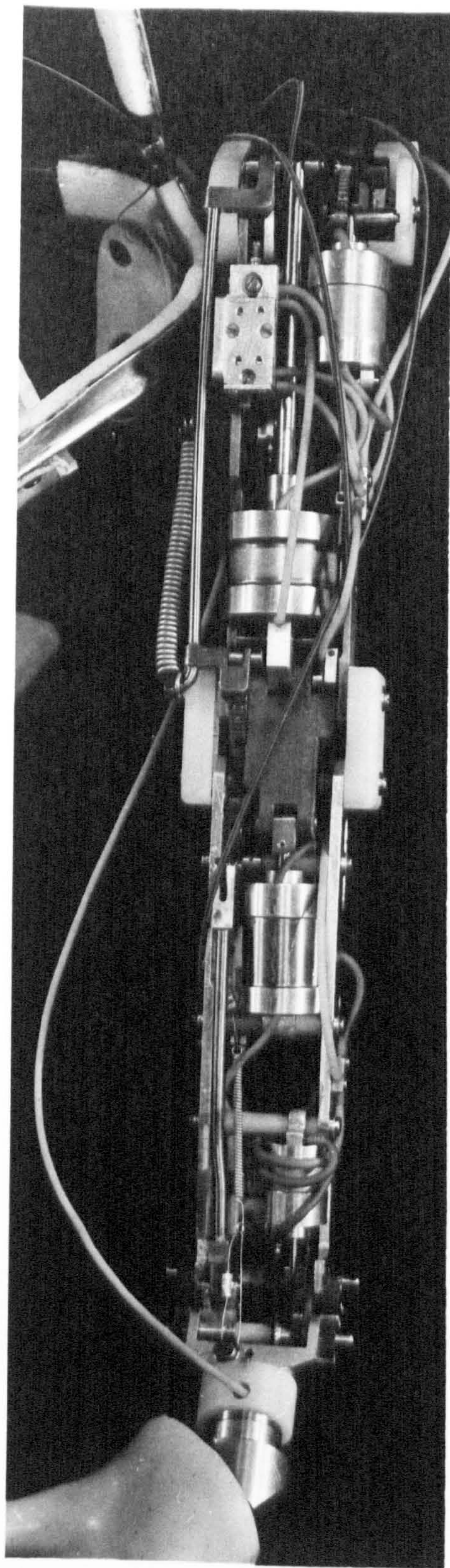


Fig. 1.9 Arm with sideplate construction.

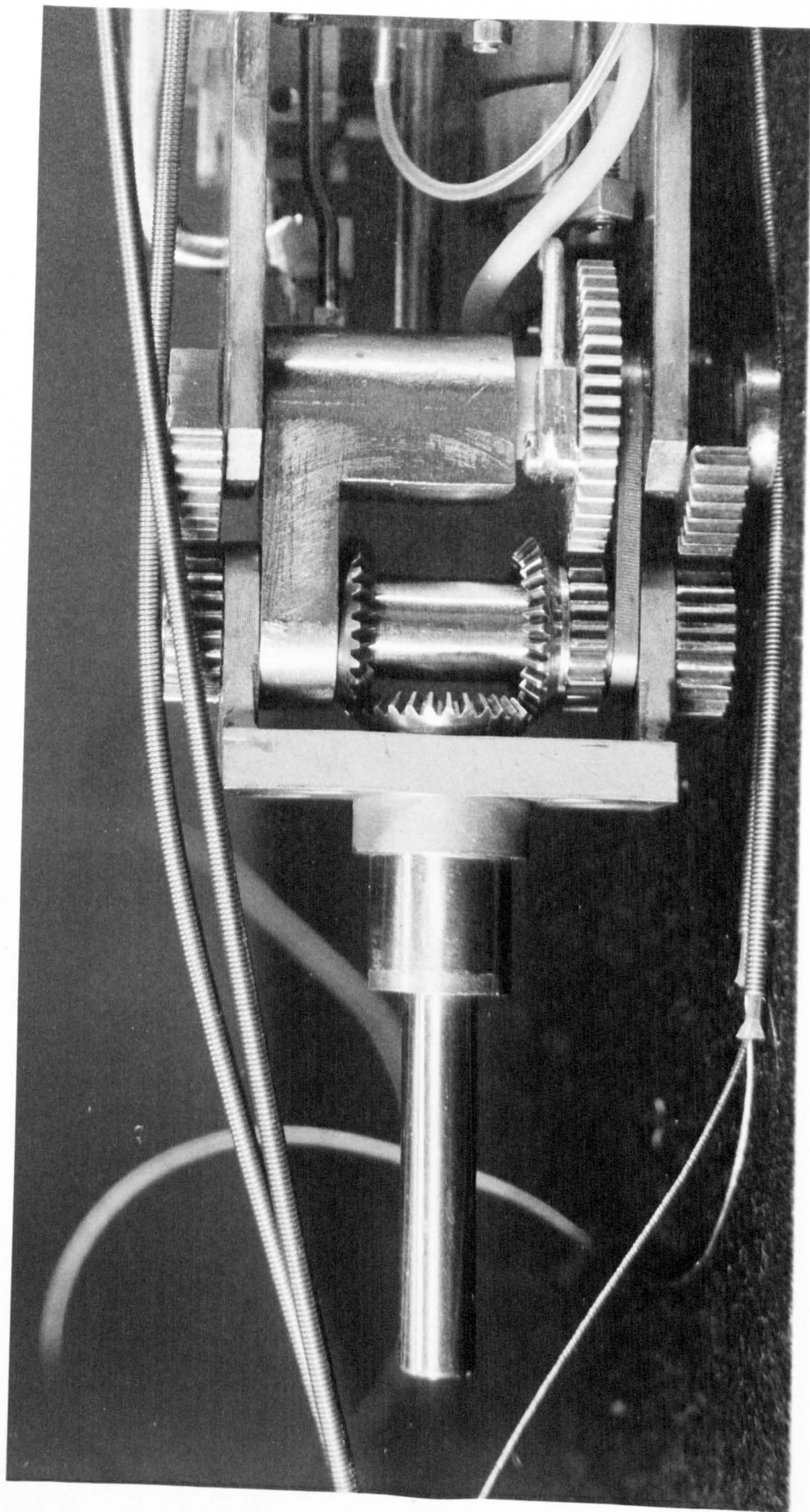


Fig. 1.10 The rotator mechanism at the shoulder.

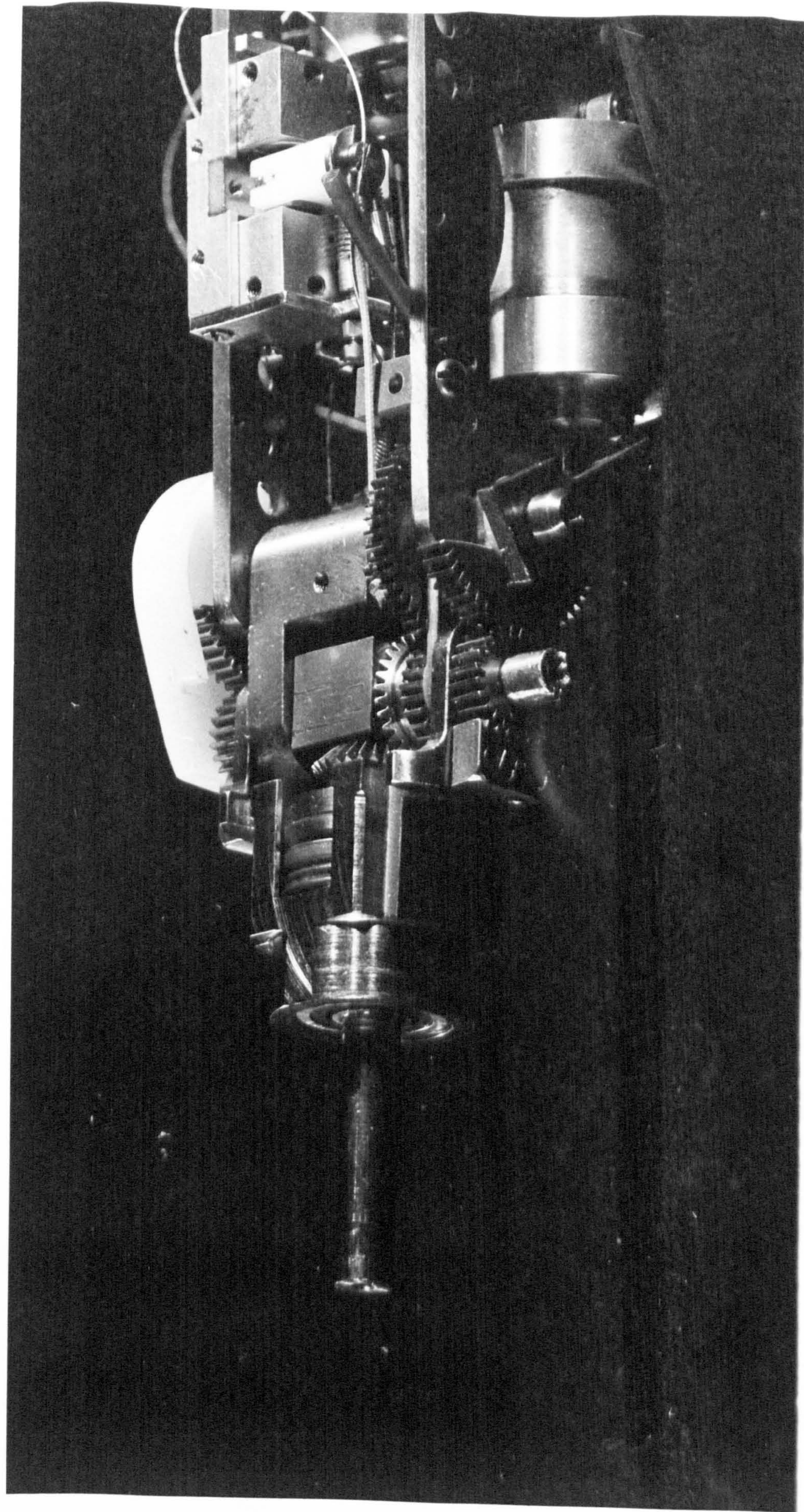


Fig. 1.11 Strengthened and improved shoulder rotation mechanism.

order to remove backlash or stiffness in the mechanisms.

(ii) The fundamental accuracy of the mechanism deteriorated rapidly with use as the wear introduced slackness in bearings and backlash in gears, resulting in large position errors at the end of the arm, thereby seriously disrupting the concept of position awareness.

These faults were removed by the use of belt and pulley drive systems, which permitted construction techniques of low accuracy and the removal of wear effects by the tensioning of the belts (Figs. 1.12, 1.13, 1.14).

Thus, it became apparent that techniques of automatic error and wear removal could and should be adopted.

Significant contributions to the solution of the strength/weight problem were also made by advances in the arm development, particularly from the use of sheet stainless steel in the fabrication of the harness used for carrying the arm on the patients (Figs. 1.15 and 1.16). Extensive experience in the use of this material led to an appreciation of its possibilities for use in hand prostheses. A similar contribution was also made by the introduction of, and experience with, plastics materials. Thus the pulleys and the elbow block of Figs. 1.12, 1.13 and 1.14, and the bearings used in all the joints of the pulley-based arm were constructed from plastics materials, this approach representing a considerable saving in weight (the specific gravity of most plastics is of the order of 1, whereas that of most metals is of the order of 5 or more). In addition, the use of plastics materials permitted the manufacture of pulleys, for example, by injection moulding processes which are cheap and rapid methods of manufacture.

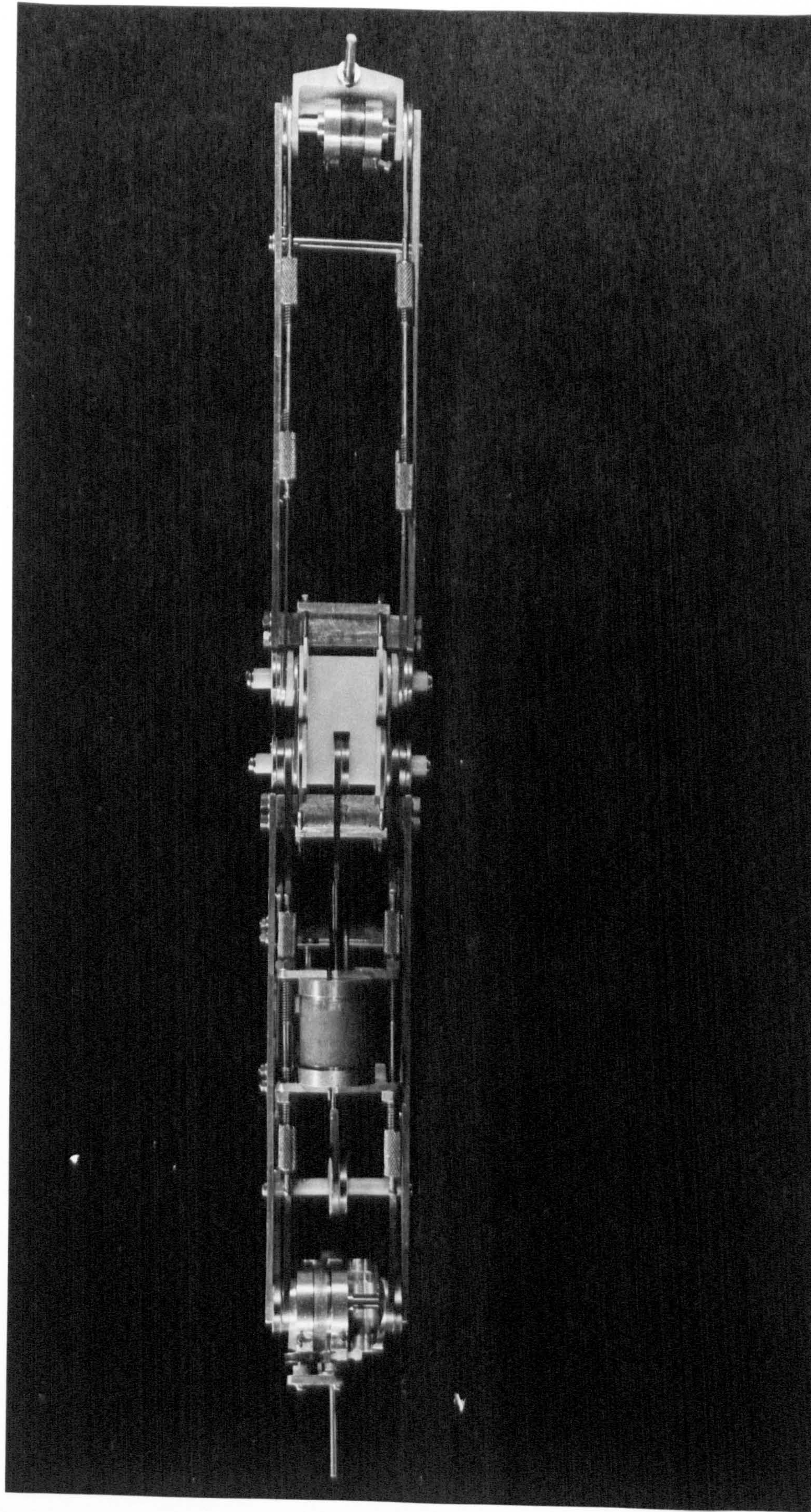


Fig. 1.12 Second generation co-ordinate arm of simplified construction.

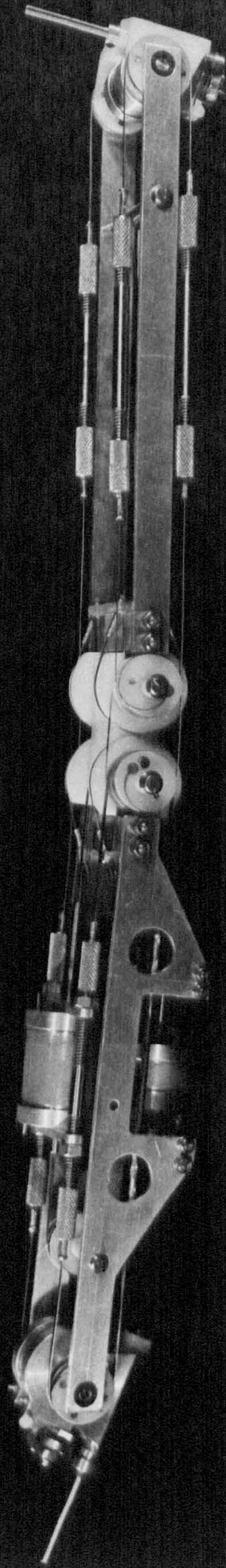


Fig. 1.13 Second generation co-ordinate arm of simplified construction.

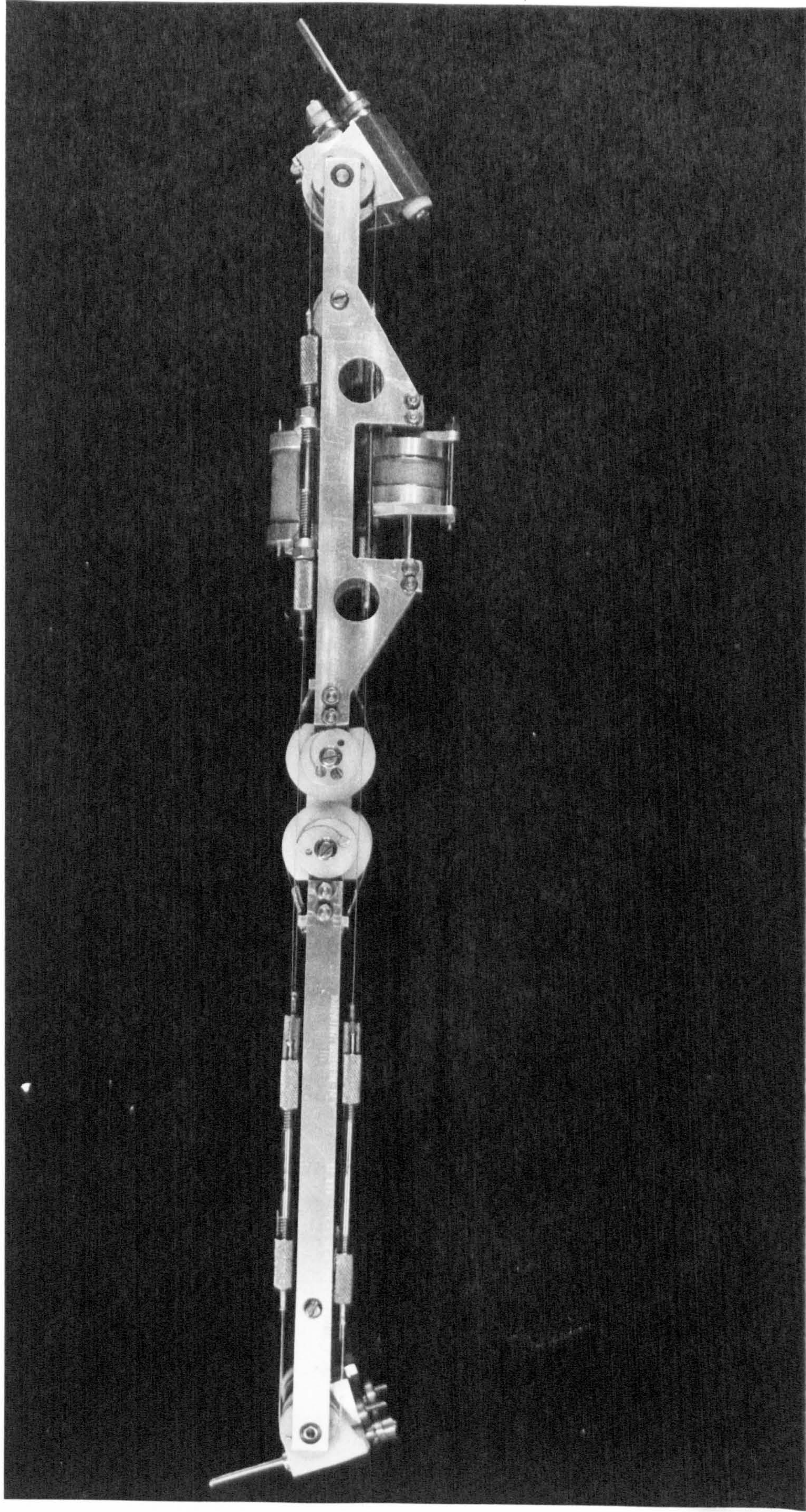


Fig. 1.14 Second generation co-ordinate arm of simplified construction.

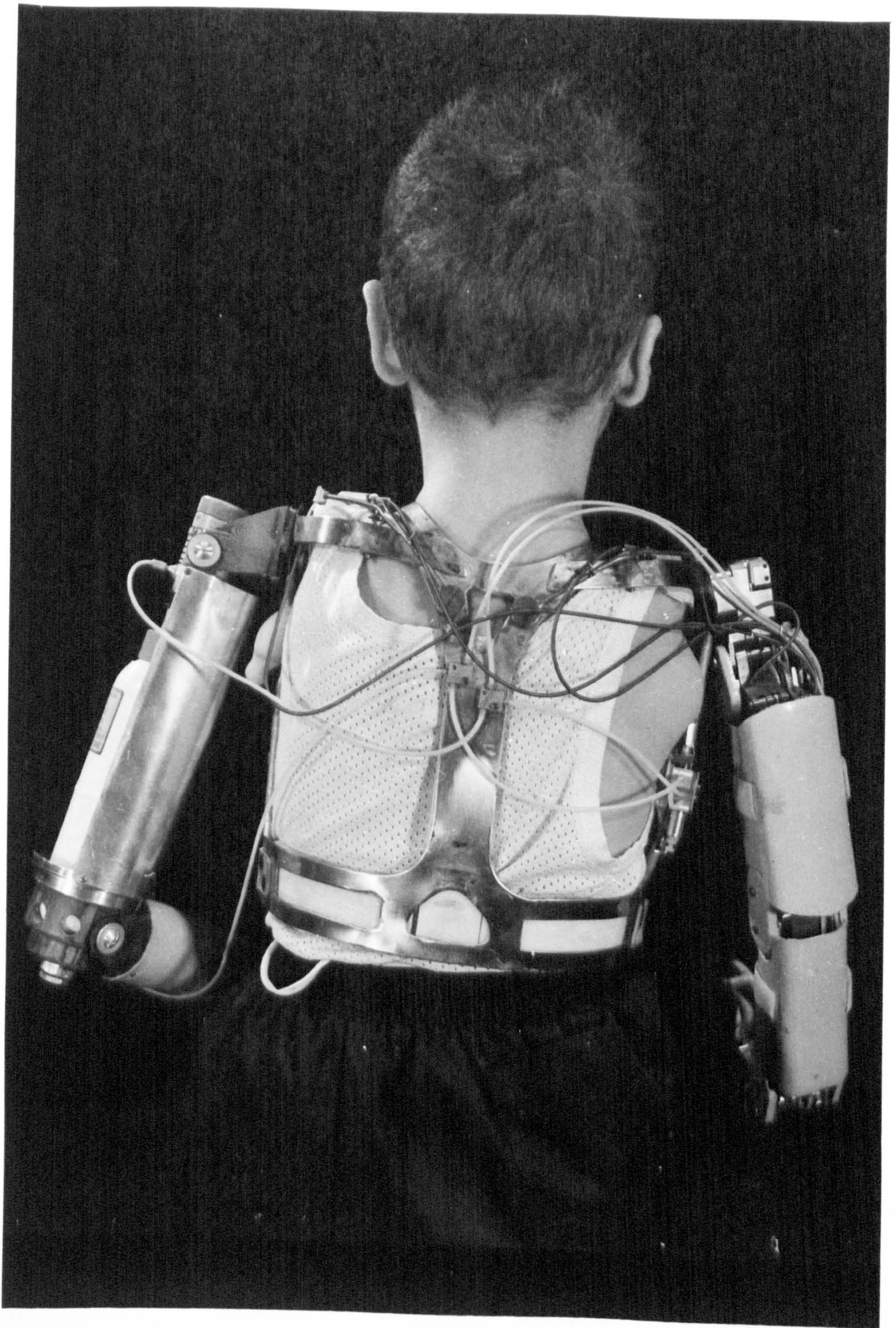


Fig. 1.15 Prototype co-ordinate arm fitted to amelic child.

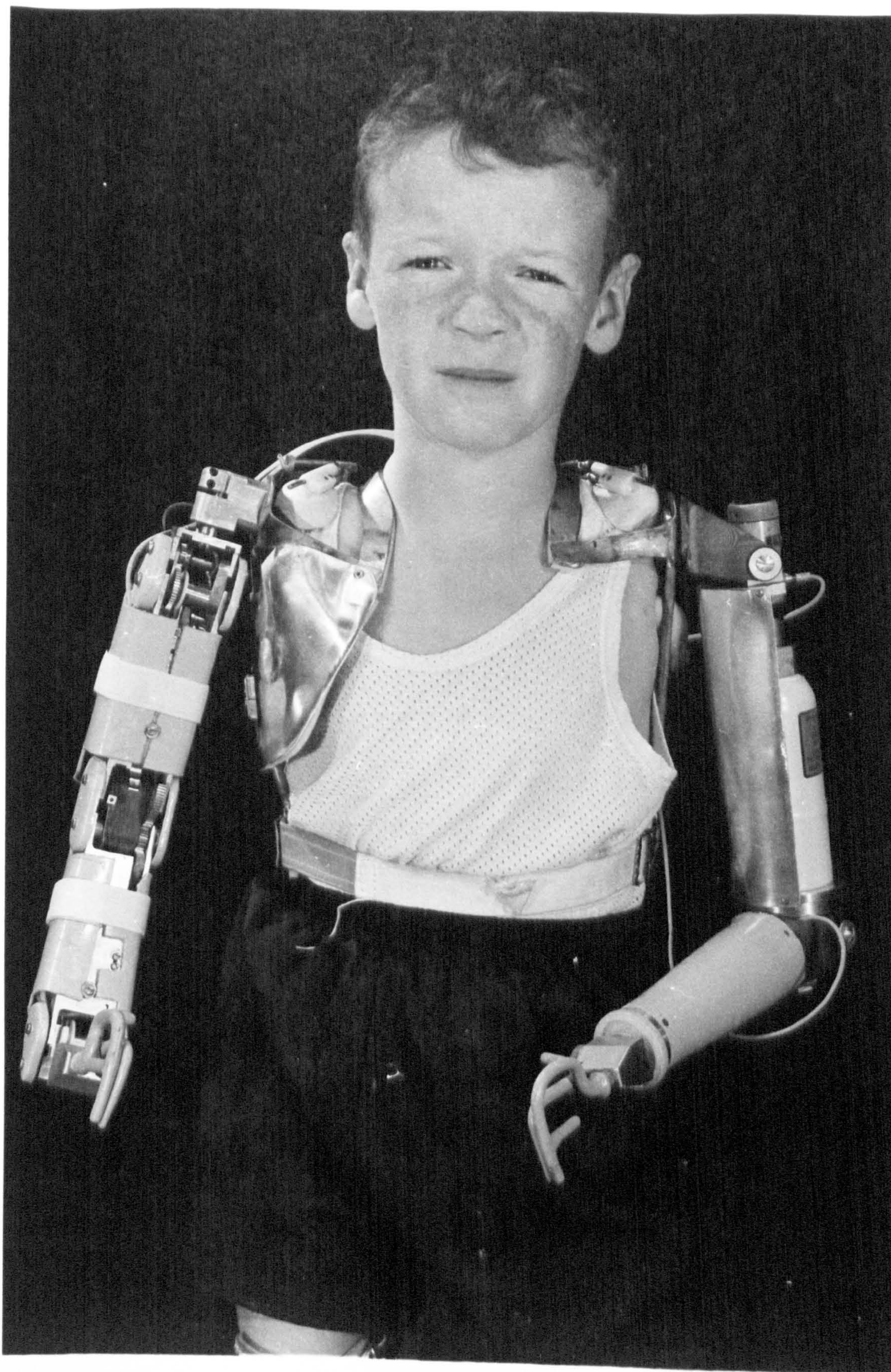


Fig. 1.16 Prototype co-ordinate arm fitted to amelic child.

1.10 Guidelines for prosthesis design.

Thus, a design philosophy developed to satisfy the demanding engineering conditions of arm prostheses which were used extensively by the patients, the most important features of this philosophy being:

- (1) Designs which modified themselves to suit the prevailing conditions were less prone to failure.
- (2) The use of a diverse range of materials could usefully and significantly reduce the weight of the device.
- (3) A certain failure rate must be accepted as inevitable, and modular interchange of faulty parts was essential in order to expedite repairs.

1.11 The results of the arm prosthesis programme.

The arm development programme therefore produced four major results which influenced hand design in various ways:

- (i) The concept of e.p.p. in the controlling of prosthesis movements was seen to be a workable solution to the control of multi-movement prostheses.
- (ii) An engineering design philosophy was developed which could satisfy the mechanical requirements of the prosthesis specification.
- (iii) A group of severely disabled children was leading a more normal existence than would have been possible otherwise.
- (iv) Considerable restrictions were imposed upon the activity of the arm prosthesis by the various inadequacies of the terminal device.

Items (i), (ii) and (iii) have been considered in some detail, and it remains to illustrate in more detail the various aspects of

experience with the terminal device in the context of the use of the arm prostheses.

1.12 Experience with terminal devices in the fitting programme.

The historical background of terminal device development is covered in the literature review, where it is deduced that the functional success of hook devices considerably outweighed that of available cosmetic artificial hands, and this fact was exaggerated considerably in the practical experience gained in the provision of the externally powered arm prostheses for bilateral amputees, as outlined above.

Thus, a situation developed where an arm prosthesis had been designed with 'realism' as a basic theme, and yet functional requirements demanded that a functional hook be used in the only part of the upper limb not concealed by clothing! This arrangement of hook device, wrist rotation, stabilised wrist flexion and spherical polar coordinate positioning in space proved quite acceptable functionally, but many of the patients were prepared to forego the function of the hook in favour of the limited cosmesis and function offered by the commercially available hand prosthesis. This phenomenon is well recognised in the wider aspects of upper limb prosthetics work, as the literature review shows.

However, the implications of this situation for bilateral amputees, are very different from those for unilateral disabilities where inadequacies may be made up by the good limb. In the case of the bilateral amputee, the whole history of successful function with the externally powered arm and hook becomes useless when cosmesis becomes a significant factor, unless a functionally adequate cosmetic hand can be provided.

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intended specifically for application to the problems of thalidomide amputees, the implications for all other groups of amputees requiring hand prostheses were borne in mind, since the functional aspects of an improved cosmetic hand would clearly benefit any patient who requires terminal devices of any sort. Therefore developments were carried out with a view to the subsequent diversification of the work, allowing for modifications which would be necessary to suit the conditions of various groups of amputees, and in order that the work could be carried out in a manner which would lead to a hand prosthesis suitable for general application a review of relevant literature was made. This is summarised in section 2, where the various aspects of upper extremity prosthetic systems are reviewed in order that the problem of hand design could be appreciated in the wider context of upper extremity prosthesis development in general.

Section 2.

The wider aspects of upper extremity rehabilitation - a review of relevant literature.

Chapter 1 The provision of prosthetic hardware.

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- " 3 Cosmetic gloves and associated materials for hands.
- " 4 Control - theoretical considerations.
- " 5 Practical control systems.
- " 6 The use of muscle electric potentials for control.
- " 7 The effects of the drug thalidomide.
- " 8 Touch and sensory feedback.
- " 9 Theoretical analysis of position servo control systems.
- " 10 The normal upper limb - a brief assessment.

Bibliography.

Chapter 1.

The provision of prosthetic hardware.

- 1.1 Introduction and historical background.
- 1.2 Work with terminal devices and the selection or rejection of cosmesis.
- 1.3 Hook prostheses.
- 1.4 Hand prostheses.
- 1.5 The simple prostheses.
- 1.6 The multiple movement prostheses.
- 1.7 Evaluation.
- 1.8 A different approach to hand prosthesis construction.
- 1.9 Conclusions.
- 1.10 Indicated lines of further development for hand prostheses.
- 1.11 Work on the development of externally powered artificial arms.
- 1.12 Complete arm prostheses - pneumatic power medium.
- 1.13 Conclusions drawn from the review of pneumatic systems.
- 1.14 Complete arm prostheses - hydraulic power medium.
- 1.15 Complete arm prostheses - electric power medium.
- 1.16 Development of items of powered prosthetic hardware.

Chapter 1.The provision of prosthetic hardware.1.1 Introduction and historical background.

The history of prosthetics is similar to the history of many of the so-called 'modern' innovations which we tend to think have an exclusively twentieth century origin. In fact, the development of prostheses had progressed hardly at all from the medieval armourers art until the introduction of externally powered prostheses following World War II. Furthermore, the majority of upper extremity prostheses which are fitted consistently to patients within the National Health Service are still no more sophisticated than the prostheses of Goetz von Berlichingen of the year 1504 or thereabouts. Even this prosthesis had been preceded, some 1700 years before, by the device worn by a Roman general following the loss of his right hand in battle, an event which was recorded by Pliny the Younger. These, and other hand prostheses of antiquity, are particularly well detailed by Putti (1929) in a review of historic artificial limbs. The same ground is covered in a later review by McCord (1963) who ventures further towards the present with the flexible rubber hand of Marks and the introduction by Mr. Dorrance, an injured sawmill worker, of the original Dorrance hook in 1912.

The process which caused vast alterations in the development of active prostheses had been initiated in 1812 by Baliff, a Berlin dentist who made use of elbow flexion movements to operate an artificial hand. This was followed in 1844 by van Pietersen's use of trunk movements to activate an elbow flexion motion. Work of this nature, combined with an increasing survival rate of war-injured

from wars such as the American Civil War (1861-65), laid the foundations for early work on active prostheses. Firms such as the Marks Co. (1853), Hangers (1861) appeared in the United States, making mainly wooden prostheses. In Britain Blatchfords (1890) was the only prosthetics firm in existence in 1914, but many appeared soon afterwards, such as McKay's with arms and Steepers (1917) with the Calet arm from France. In order to deal with the increased numbers of amputees, the Ministry of Pensions set up a contracting department at Roehampton to provide a more organised service for the amputee.

At this stage, the trend towards active limbs was entirely governed by the utilisation of body power for driving elbows, etc. The principle behind this system is similar to that of the early work, in that a powerful body movement available to the patient is harnessed to drive the prosthesis.

Such motions may be harnessed by making use of the variations in body dimensions such as the acromion-acromion distance measured across the back during a shoulder shrug movement. This type of control and power is commonly utilised in the conventional upper limb prostheses in current use. A procedure which achieved popularity in the early half of this century, made direct use of muscle movement by means of direct attachment of the prosthesis cable to the muscle. This was achieved by means of the technique of cineplasty introduced by Vanghetti (1906), using a surgical technique for effectively making a hole through a muscle, attachment being made to a pin passing through the hole. This technique was improved by Sauerbuch (1916) who made a neater job of the operation by lining the hole with living skin, thereby

achieving a longer lasting attachment. This type of procedure has been largely replaced by external attachments permitted by improved harnessing techniques and is uncommon today.

McKenzie (1965) gives a useful appraisal of the conventional body powered artificial limbs, in which the main reasons are given for the success of these prostheses. The chief factors are the relative simplicity and reliability of the prostheses combined with a robust structure and a control system which provides the patient, via the power cable, with position and force information at all times. However, against this must be set the considerable effort required by the patient in order to achieve high forces from systems of limited mechanical advantage, and the discomfort of the harnessing and the awkward movements which are often required to activate the devices.

In general, the literature concerning the development of upper extremity prostheses is extremely sparse until the years following the Second World War. Work during the period up to 1945 seems to have consisted of an extremely slow foundation-laying process, during which the social structure of the world altered in such a way that it was no longer acceptable to discount people from normal life on the grounds of physical disabilities. Attempts which were made are typified by the hands of Pecorella (1919) (also Editorial 1958) and Dale (1946) and the electromagnetic hand mentioned by Borchardt (1919), isolated works rather than the results of an organised prosthetics research programme.

The effects of the changed social structures since are shown by the present world-wide tendency for public funding of prosthetics research, and it is this fact, combined with the vast technological

advances of the post-war years, which has produced the vast amount of new work in the field of artificial limbs in general.

Development work concerning the production of externally powered patient hardware for upper extremity use has shown a tendency to develop in several distinct ways, according to the type of institution concerned with the work. In particular, little specific attention has been directed towards research into the design of hooks as terminal devices, whereas the might of various large units has been directed to the production of cosmetic, functional hands. The interesting contrast here is that the piecemeal, in the field, development of hooks has proved far more successful than the heavy-weight research work with hands.

The development of hand prostheses has followed two distinct lines of approach which may be described as 'the fully anatomical' type, and 'the simplified anatomical' type. The fully anatomical type has fully jointed fingers which flex around a gripped object, and usually possesses a degree of thumb function. The simplified anatomical type envisages hand action as a pincer-like opposition of finger and thumb, finger flexion occurring at the metacarpophalangeal joint only. The latter type of mechanism has usually been developed at establishments directly concerned with the fitting of patients whereas the fully articulated type of hand with its multiple function potential has often been the object of a more academic exercise in control or engineering design.

The production of items of externally powered hardware for use by substitution into the readily available conventional prostheses has been a common activity at establishments with a direct patient commitment. An example of this type of procedure is typified by an

electric elbow developed at the Ontario Crippled Children's Centre in Toronto (1965) and McLaurin (1965). Such powered units are designed to replace conventional elbow mechanisms with a minimal degree of modification. However, since this approach is not directly relevant to the unified development of a full working prosthesis, more attention will be directed towards the work of those establishments concerned with the development of fully comprehensive arm prostheses. In addition, it should be noted that no specifically simultaneous development of arm and hand prosthesis has been carried out in any work previous to that pursued at Edinburgh, emphasis has always been placed firmly on one aspect or the other, which has usually resulted in an inadequate mating of hand and arm systems.

1.2 Work with terminal devices and the selection or rejection of cosmesis.

The provision of a prehension device for an artificial arm has been the subject of a variety of research programmes, the basic trends of which have been indicated above. However, before entering on a review of the various aspects of the work, it is informative to give some indications of the difficulties present in trying to formulate a research policy for terminal device development. The most awkward of these problems is presented immediately - cosmesis or no cosmesis? In this matter the opinions of some medically based workers in rehabilitation serve as a useful introduction to the situation presented to the developer of prostheses.

The hard practicalities of the problem were succinctly summarised by McKeever (1944) in a review of upper extremity amputees and prosthetics: "the more nearly the prosthesis approaches the lost hand in shape and appearance, the less useful it is to the

Army Prosthetics Research Laboratory (APRL) hands they found that "the fitting of children with upper extremity amputation with a hand terminal device did not improve their adjustment to the prosthesis". However, this appeared to be due to the poor functional capabilities of the hand as they conclude that in this matter the anticipation was greater than the realisation.

Similarly Fishman and Berger (1955) estimated that, if the function of the APRL hand were improved, 90 per cent of amputees might be expected to accept hand prostheses.

More substantial evidence in favour of the necessity for cosmesis was provided by Fishman and Kay (1964) who surveyed the results of fitting the APRL-Sierra hand instead of a Dorrance hook. In a group of 77 patients, 21 wanted the hand exclusively, 49 took intermediate standpoints and only 7 rejected the hand. In this situation the overall impression was that the cosmesis played the definitive role despite the fact that the hand was more difficult to operate, heavier, worse functionally and provided less prehension force.

In a questionnaire survey of the 7000 British Limbless Ex-Servicemen's Association patients Simpson found that a majority of patients prefer the cosmetic device, a fact which has been further substantiated by requests from the thalidomide patients fitted with full arm prostheses at the Princess Margaret Rose Orthopaedic Hospital, Edinburgh, even for existing hand prostheses which are functionally poor, and whose cosmesis also leaves much to be desired.

It is apparent from the works outlined above that the objective opinion of clinics concerning what a patient's attitude towards prostheses should be, carries little weight with the patient except

perhaps when attending the clinics. There is therefore little point in providing a patient with a functional prosthesis which he will not use habitually, and the main difficulty lies in ascertaining whether or not he really does make use of the device in his normal environment. In view of the understandable desire of patients for a cosmetic functional hand, it is clear that the most universal solution to the problem would be to provide a hand which is, functionally, at least as good as the available hook devices.

The large numbers of hooks and other special devices which have been constructed are symptomatic of the failures in the provision of cosmetic hand devices. This phenomenon of a proliferation of hooks is also an indication of the relative ease of the design problem when the designer is untrammelled by the restrictions of external appearance and shape, and he is able to make specific devices for specific tasks.

1.3 Hook prostheses.

There are so many varieties and variations of varieties in the world of the hook prosthesis that a detailed appraisal of them all is impossible in the time available. However, some indication of current trends can be given by considerations of various specific devices.

Apart from the original "Captain Hook" type of hook prosthesis, which was just that - a hook and no more, hook prostheses have taken the familiar form of the split hook such as that introduced by Dorrance. These devices take the form of a hook, split along its length, the two parts being hinged at the proximal end, the joint being activated in various ways by the wearer. The possible

variations on this theme are endless, different hook shapes, protruberances from the blades, lengths of blades, etc., quite apart from the different modes of attachment and use. Examples of specialised attachments are given by Kuhn (1970) who arranged that the hook be allowed to turn aside to expose the amputation stump for active tactile feedback purposes, and Clarke et al (1970) who found that a built-in wrist adduction for the hook attachment facilitated gripping because of the improved visibility of the hook ends.

Although the realm of specialised devices is not of direct concern to the hand project it may be worthwhile to refer to some of these in order to indicate the type of hardware which has been made available. McKeever (1944) refers to the Bowler hook, which had a ratchet closure mechanism, thus enabling the user to grip around an object and maintain the grip for some time. In this situation it is more significant to regard the hook as a tool holder rather than a prehension device. A similar type of device has been described by Older and Hall (1963) who used a sort of multi-angle vice which clipped onto the wrist, and permitted some gripping during the healing phase by patients with hand injuries.

The more standard hook prostheses usually take the form of a simple split hook, with closure being maintained by a spring or strong rubber cord. Opening is usually achieved by means of, for example, a cable operated by shoulder shrug motion operating on a lever arm attached to one hook blade. Thus the patient always works against the load of the spring, which is necessarily high since it provides the gripping force. Useful examples of individual improvements on this system are given by Mazet and Taylor (1952) when they describe the Northrop hook and the APRL hook. The Northrop

hook retains the conventional voluntary opening characteristics, but combines this with a two-level spring force, one of which may be selected at will by the patient. (This arrangement is available on various standard hooks supplied at present - for example several members of the Otto Bock hook range use this technique). The APRL hook uses a voluntary closing mechanism which automatically maintains the grip on first release, the re-application of force allows opening.

The choice between voluntary opening and voluntary closing of a prehension device is really a matter of the personal preference of the patient. Although Ritter and Sammons (1965) found that the ability and user incentive of children fitted with hooks showed a radical improvement following the adoption of a voluntary closing principle, many patients prefer the voluntary opening type because no effort is required to maintain grip once it has been achieved, without the confusion of the sequential type of control used in the APRL device. In view of the ease with which the change from voluntary opening to voluntary closing (or vice versa) can be effected, there is no reason to pursue an argument in favour of either, the alternatives can simply be indicated to the patient, who can then make his own choice in the matter.

Work at the Ontario Crippled Children's Centre (1968-70) has been concerned with the development and fitting of a self-contained electrically powered split hook. Operation is by a worm gear and belt drive from an electric motor, activation being achieved as a result of switch action by the patient. The device opens and then closes automatically, applying a fixed force of 3 lb. The conclusions of a seminar (Peizer 1969) found that this hook had

considerably better handling and user characteristics than any of the then available externally powered hands. The electrical driving of hook devices has also been pursued in other centres, a useful example being that of Fisher and Childress (1973) who introduced a simple electrical attachment for powering a standard split hook. In addition to the work with the hook described above, the Ontario Crippled Children's Centre have also experimented with a three jaw chuck-like operation hook, and with a conventional split hook to be electrically driven from within the forearm.

Before considering the more complex developments of the split hook principle, it is worth mentioning the only real departure from the usual hook-hand principle. Sumida et al (1968) have arrived at a completely different solution to the problem as the result of experience with very young children as hook users. It was noticed that the children tended to make use of a conventional hook before they had developed adequate positional accuracy. This fact, which is confirmed by later work in the same unit (Wendt and Shaperman 1970) led to the development of a device which resembles a crab's claw, with large gripping areas which are padded with rubber tubing in order to achieve a sort of comprehensive grip under the circumstances of inaccurate positioning. Although not suitable for the degree of precision which can be achieved by many more dextrous patients, this type of device may be of advantage in situations where patients are in an early learning phase, or where normal motor control is in some way inadequate (e.g. Parkinson's disease).

Probably the most comprehensively designed hook to be developed has never made any real impression upon the world of prosthetics.

The hook devised by Bottomley (1967) achieves a most comprehensive range of prehensile activities by virtue of its design, without resorting to the use of special grooves, notches and pins for gripping specific objects. The hook, which is pneumatically powered, retains a curved hook blade which is opposed by a mobile 'thumb' which has an articulated distal phalanx constrained to remain parallel to the static blade at all times during the opening and closing of the device. The 'thumb' is arranged relative to the hook-shaped blade in such a way that the distal phalanx makes contact with the hook at a point not at the hook tip. In this way it is possible for an object such as a pencil to be placed across the hook (as a chord of a circle), contacting the hook blade at two points; closure of the 'thumb' then contacts the pencil at a point between the two points of hook blade contact - thereby achieving a stable three-point grip. This built-in stability is also useful for grasping larger objects, such as a beer glass, when the flexed distal phalanx of the thumb tends to overcome the usual tendency of hooks to expel larger objects from the grasp. The one major failing of the Bottomley hook is also due to its type of construction, since the hook blade must protrude below the opposing thumb in order to achieve three-point grips, this makes picking up from a flat surface impossible unless the object is of a certain minimum size.

A somewhat exotic variation of the theme of this type of hook is reported by Ring and Welbourn (1968) who, as a result of a study of force-time variations during prehension, found that the static gripping force could be as little as half that used during the active picking up phase. This led to the design of a pneumatically powered hook of the Bottomley type with incorporated strain gauge

measurement of shear force at the thumb tip. This information was then used to automatically regulate the gripping force to the minimum necessary for the maintenance of grip. Overall control was effected by switch controls operated by the patient. Although this device achieved the desired engineering result, the necessity and desirability of such sophistication is debatable. Practical experience with the fitting of prostheses to patients in the Edinburgh unit has repeatedly shown that automation within the prosthesis is not desirable, it is more beneficial to feed all possible information to the operator and then allow the infinitely more sophisticated human 'computer' to achieve the balanced control necessary for useful everyday operations.

This point illustrates a basic axiom which transpires from experience with prosthesis fitting to children who use the devices as part of the daily routine. There is really no necessity for the introduction of computers or automation in the control of prostheses, for, provided that adequate information is presented in a suitable way to the human system, that system is far more efficient and sophisticated in dealing with the problem than any artificial intelligence is likely to be for many decades.

Probably the most complex hook of all in terms of available movements was devised to provide the terminal device for a functional powered arm developed by the Medical Research Council Unit at Hendon (1970). The hook was devised because there was no adequate functional cosmetic hand available, and insufficient time was available for the development of a device constrained by limitations on external dimensions and shape. The device consists of a fixed hook-like blade which is opposed by two mobile blades which pivot about

mutually perpendicular axes. A laterally mounted hooked blade, in conventional hook fashion, opposes the fixed blade from the side, whilst the second mobile blade opposes the fixed blade itself. The mobile blades are linked by a pneumatic piston actuator, thus allowing both blades to float independently of the fixed blade. When prehension is desired between one mobile blade and the fixed member, the piston actuator must first drive the second mobile blade against the fixed blade before a positive grip can be achieved by effecting definite closure of the first mobile blade onto the stationary member. The blades are notched in order to permit gripping of pencils and similar objects.

Although no expression is made of operator opinions of using this device it is to be expected that the large amount of 'backlash' introduced into the system by the floating blades mechanism is likely to detract from the operating characteristics of the device. A considerable looseness in a system of this nature tends not to inspire confidence in its function, particularly so for a gripping action which needs to have a definite, positive action in order to make the movement easy and simple to achieve at all times.

The authors of the progress report on the device give a list of tasks which the hook could not successfully perform. Unfortunately this list includes many activities of vital importance to daily living such as a stable grip of a knife, jug handles, telephone receivers, and picking up from a flat surface. Considerable difficulty was also experienced with inadequate gripping force and lack of strength in the blades. A lack of robustness is really not tolerable in devices designed for use by children who will instantly abuse a device beyond the limits of any reasonable assessment and

one of the prime reasons for the success of conventional hooks has been their relative indestructibility.

Consideration of the experience of the Hendon workers with this terminal device leads to the conclusion that probably the same degree of function could have been achieved by using a proprietary brand of cosmetic hand, with the added advantage of cosmesis. This is an unfortunate conclusion following such a different line of approach, but better results may have been achieved by the use of the available Bottomley hook, or even a standard pneumatic hook device.

By way of a conclusion to a review of certain hook devices it must be stated that the majority of hooks are extremely satisfactory from every logical point of view; they are strong, simple, reliable, good at picking up, adequate in holding many everyday objects, easy to use by virtue of the good visibility through the skeletal structure, and easy to position because of the use of one stationary blade. Furthermore, the application to hook design of the design features incorporated in the Edinburgh hand could improve hook versatility still more. However, it is an unfortunate fact that the engineering benefits conferred by these points are completely overridden by an understandable but illogical desire by patients for cosmesis. In the short term there is no advantage in resisting this fact, and the realisation of the necessity for cosmesis has led many workers to attempt to arrive at a satisfactory solution of the function and cosmesis problem.

1.4 Hand prostheses.

The work which has been carried out on the development of functional artificial hands has fallen into two readily

distinguishable groups which are characterized by the extent of immediate patient commitment involved. Those workers with a direct responsibility for patient care have tended to produce functionally simple devices with emphasis on cosmesis rather than good functional properties. In contrast with this situation is the more sophisticated work carried out by groups with a more academic background who have in several cases regarded the problems of the control of a multiple jointed device as the objective. These workers have produced complex hands which are quite satisfactory in their movements and appearance, but in fact leave much to be desired as practical prostheses.

In each group classified in the manner outlined above there are, of course, exceptions in the backgrounds for the works, but the structures fall into two groups so naturally that they will be reviewed as such.

1.5 The simple prostheses.

The group of cosmetic functional hands characterized by a relatively simple mechanism was pioneered in modern times by the development of the Vaduz hand. Development work on this prosthesis began in Berlin during World War II under Dr. E. Wilms. The research was continued after the war in Vaduz, Liechtenstein and later in France under Kegel. (Wilms 1950, took out French patents on the device and its control system). The device was relatively sophisticated and ahead of its time in many respects, particularly in the use of the controls. The functional structure appears to have set the trend for many of the prostheses which were subsequently developed elsewhere, since a pincer/3 jaw chuck type

of grip was achieved by approximation of the thumb and the first two fingers, driven via a gear-train reduction mechanism from an electric motor. The hand weighs approximately 400g and incorporates various interesting design features, which include an automatic gearing down for extra gripping power when the fingers are opposed and full motor speed has been achieved. Switching of the electric motor is remotely controlled by means of a pneumatic link consisting of two sacs connected by a tube, whereby the compression of one sac by the stump caused the slave sac to activate the switch controlling the motor. The patient can vary the sensitivity of this system by alteration of the pressure in the pneumatic system. By means of arrangements concerning the slave sac and the switch mounting it was possible to achieve some force feedback which prevented excessive battery current drain during stall conditions. Furthermore a sort of position control is evident under conditions of more moderate force applications to the control, since the device moves to a position which neutralises the input signal, subsequent re-application of a control force initiates a repetition of the cycle.

Concerning the behaviour of this device in use, the extreme sensitivity referred to by Gilpin (1963) appears to have led to complications for regular users, since Lucaccini (1966) finds that frequent readjustments are necessary to maintain adequate function. Lucaccini also feels that, although the device is easy to use, it is really limited to light work, and the poor technical and mechanical work in the device tends to make it unreliable.

Although no direct information is available about the cosmetic results with this hand, it is reasonable to assume that it was

adequate, since no particular problems of glove production are presented by this type of mechanism. However, the functional capabilities are limited by the type of grip action used and the most significant contributions remain in the control field. The automatic variation of gearing in the device provides a useful analogy with the human hand, which also possesses automatic variations in mechanical advantage during flexion by virtue of mobile tendon expansions round the joints.

A body powered hand with an action similar to that of the Vaduz hand was developed in the U.S.A. on the basis of design criteria resulting from the work of Keller et al (1947) who concluded from filmed records of everyday activities of normal hands that 88 per cent of holding actions were in the pincer mode, which was used in the hand mechanism. The relative merit of this data will be considered elsewhere, it is sufficient at this stage to state that the design of the APRL hand as it is known, was based on such information. The device operated in a voluntary closure mode, with a lock to permit retention of gripped objects without continuous effort. The overall structure of the hand was in an exoskeletal form, cast in magnesium with a passively set two position thumb.

Evaluation reports from Fletcher (1954) and Peizer (1969) are moderately favourable, particularly in terms of reliability, although there are the usual limitations imposed by the configuration of the mechanism, for example the difficulty with working on flat surfaces improved by the necessity for extreme wrist rotation or extension in order to allow the fingers and thumb to oppose in a horizontal plane.

The introduction of the APRL hand has in fact imposed extremely severe restrictions upon research with cosmetic hands in the United States. It is a surprising fact that no new developments have been pursued in the realm of hand mechanisms, the only changes which have been made concern operating techniques, power unit changes and techniques of control, all with the same mechanism! This situation is, to a certain extent, typical of U.S. powered prosthetics research, where workers have tended to become bogged down in the mire of existing prostheses, having limited their scope by designing on the basis of replacing existing parts of prostheses, rather than developing totally radical ideas.

Some examples of the variations on the APRL hand theme will be given, in order to illustrate some of the attempts to provide external power. The U.S. Army Medical and Biological Research Laboratory (USAMBRL) hand achieved electrical powering of the APRL mechanism by means of an electric motor mounted in the forearm, connection being almost external to the complete APRL device. Salisbury and Colman (1967) introduced a degree of automation into the device by making use of slip detectors in a manner similar to that of Ring and Welburn (1968) described previously. The USAMBRL system has subsequently been used in a voice operated control system, but this is a control problem rather than a prosthetic one.

An electrically powered version of the APRL hand was produced by Seamone and Hoshall (1970) who modified the existing APRL mechanism to receive an electric motor. Control of this device was effected by myo-electric signals which were used in a pseudo-position-servo mechanism. The servo mechanism was position

dependent only to the extent that the error signal used to drive the device was derived from the difference between myo-electric signal and a position feedback signal, there was no actual relationship between control input position and the output position of the hand.

The American Institute for Prosthetic Research (AIPR) hand is a pneumatically powered version of the same mechanism, and of course differs little from the other devices in its prehension capabilities. The prolonged use of the APRL mechanism is probably due to its reliability, because of the inherent simplicity of the finger movements, a factor which is desirable in all items of prosthetic hardware. In the absence of any readily available alternative, this fact alone explains the lack of internal pressure for the development of new devices, since it has become an acceptable practice, from a non-patient standpoint, to make use of hooks for real functional activities. These facts are substantiated by the surveys of Lambert and Sciora (1959) and Fishman and Kay (1964) who found that the APRL hands used were functionally far less satisfactory than the hook devices, but that cosmetic requirements tended to override this problem.

A hydraulically powered hand of pincer type operation was produced by Heather and Smith (1960). This system used simple plastics parts for the pistons, but never achieved any particular distinctions since the only real difference about the prosthesis lay in its power supply.

The limited competition for the APRL hands on the American market is typified by the Robin-Aids hand which is of virtually the same construction, with the addition of passively mobile inter-phalangeal joints.

A hand device was produced for the Alderson-IBM electric arm (after 1948), but this whole system succumbed to the complications of the control philosophies used in the device. However, the manufacturing techniques used were unusual in that a bronze casting of a hand was dismembered and machined to provide master copies of hand segments which could then be reproduced moulded in reinforced nylon. The mechanics of the device were carefully coloured so that no cosmetic glove would be necessary.

The early appearance of the electrically powered hand in the form of the Alderson-IBM system was not unique, since an electromagnetic hand was mentioned by Borchardt et al in 1919 and Reiter (1948) also had produced an electromagnetic powered hand.

The European version of the APRL formula is typified by the group of hands comprising Otto Bock, Viennatone, INAIL, and the hands devised by Sell and Merten (1969). These hands have very similar structures and mechanisms, with flexion of index and middle fingers occurring at the metacarpophalangeal joint which, combined with the action of the mobile thumb, gives a palmar, pincer like, three jaw chuck grip similar to that of the APRL hands. The reliability of the strong, simple Otto Bock/Viennatone formula has led to applications of this type of device, usually in electrically powered form, by various workers in Europe, for example Germans et al (1970) who used this mode of action as a first step towards the production of a two controlled function hand. Similarly Soerjanto (1971) used the Viennatone mechanism as the basis for experiments with myo-electric control, as have Passerini and Scalas (1970) in Italy.

The grouping of the hand of Sell and Merten (1969) in this category is somewhat surprising in view of their specification for a hand prosthesis, which emphasised the need for a natural looking movement for the device. A few minutes spent exercising one's hand in the fashion of these mechanisms soon proves the point - real thumbs do not comfortably perform the pincer grip action. However, it is important to note that Sell and Merten do appreciate the need for a pronation-supination action to supplement the hand, the inclusion of such a mechanism can do a great deal by way of improving versatility of any terminal device.

The Otto Bock and Viennatone hands, together with the Italian INAIL hand are commonly available for use with myo-electric control units. Interestingly enough, evaluation reports of the use of such emg controlled hands puts little emphasis on any aspect of emg control, rather on the overall lack of functional ability, [Feeney and Hagaeus (1970), Verstappen et al (1972)] whereas Carlson (1970) indicates that the patient preference for emg controlled Otto Bock and Viennatone hands over body powered hooks may be due to the absence of harness straps, etc. rather than because of aspects of control or mechanism. One particularly significant fact which is noted by Feeney and Hagaeus (1970), and has been touched on previously, is that picking up from a flat surface with this type of device is exceedingly difficult without a large degree of wrist flexion. Indeed, experience with fitting child size Otto Bock hands at the Princess Margaret Rose Orthopaedic Hospital, Edinburgh, has resulted in mounting the hands on a permanently flexed wrist connector.

The most publicised and well known hand prosthesis is undoubtedly the electrically powered Russian hand (Kobriniski (1960) and Popov (1965)). This device has become commercially available and widely tried in Europe and Canada, the most significant fact about the device being the control system which was the first widely available system based on the use of myoelectric signals picked up from muscle activity. The mechanism is relatively conventional in configuration, rigid fingers and thumb except at the metacarpo-phalangeal joints, closing in a pincer-type palmar grip, the only major difference being that all four fingers are actively flexed, in contrast with the mechanisms previously described which incorporated active flexion of index and middle fingers only. The original myo-electric control system for this hand was really only an eng operated switch system and various workers who adopted the Russian hand have modified the control side quite considerably. The Rehabilitation Institute of Montreal have adopted the hand for some time, and have made considerable modifications in control systems (Sherman 1964, Sherman et al 1967). The Montreal workers have also introduced training display units for the optimisation of control sites for the device. A British version of the control system for this type of hand has been produced by the Atomic Weapons Research Establishment (AWRE) Aldermaston (Fyson et al 1969).

An assessment of the type of hand which has been illustrated by the above mechanisms can only be made in the context of the conditions under which they were fitted. Unfortunately, due to the extreme similarity of all the mechanisms, the only valid functional comparison which can be made is with hook devices, under which circumstances the hands do not appear in a very good light at all,

except from a cosmetic point of view. Even Peizer (1969) who, as a result of detailed assessments of most of the above devices found the functional qualities inadequate, fails to note the overall similarity of the tested prostheses which has made comparisons between the hands meaningless.

In conclusion then, it can be stated that the pincer-type hands described above are satisfying the requirements of cosmesis and function by providing some degree of active grip (not prehension, which implies active picking up and grasping) in what is essentially a passive cosmetic hand. The success of these hands has been largely due to the reliability of the robust simple mechanisms used and the determination of patients to have cosmetic hands at any cost, a situation which has been most fortunate for the developers of different control systems in the vain hope that function might be improved by changes in the control of the device.

1.6 The multiple movement prostheses.

Modern work with more comprehensive hand mechanisms has reverted to the fully articulated style of the mediaeval armourers or to that of Pecorella (1919), which incorporated 'tendons' into a fully articulated 'bone' structure. The first post-war venture into the realm of articulated hands was made at Roehampton Limb Fitting Centre (Gillis 1948). This prosthesis had fingers which flexed at metacarpophalangeal and PIP joints as the result of a body powered cable pull action. The fingers conformed to a gripped object to a certain extent in that if one were restrained, the others could continue to move. The thumb was passively mobile, having two basic positions, one in which it was opposed by the finger in pincer fashion, and the second in which the fingers closed on the palm unrestricted. The

fingers remained flexed in any position until released by the action of a second cable pull action. This device was of an exoskeletal structure, and exceedingly heavy, but the greatest failing of all was the immense cable pull force required to achieve any gripping force at the fingertips. This lack of mechanical advantage through articulated finger mechanisms is a problem common to all prostheses based on this construction and presents severe limitations in all designs of this type. Experimental attempts to use a 'museum' piece version of this hand at the Princess Margaret Rose Orthopaedic Hospital, Edinburgh, have left the distinct impression that this hand can only be described as having the limited qualities of some dynamic cosmesis.

The most comprehensive attempt to produce an externally powered adaptive hand was carried out in Yugoslavia under Tomovic and Rakic, the hand prostheses being almost universally known as the 'Belgrade' hand (Rakic 1964, 1968 and Tomovic 1970). The hand is an amazing example of engineering ingenuity, movement being accomplished by a series of cams and levers driven from an electric motor which protrudes into the forearm. The movements are programmed into two basic types which are most easily recognised by comparison with the devices previously encountered. The first mode is similar to that of the APRIL mechanisms in that the fingers flex towards the palm (flexion active at all joints), and the index and middle fingers oppose the tip of the thumb in pincer fashion. In the second mode of action the thumb moves away from the line of action of the fingers, thereby permitting the fingers to fully flex into their 'fist' positions, the thumb then closes round the fingers to complete

the fist. The surfaces of the fingers are adaptive to a certain extent by virtue of a soft covering which permits added conformability to the gripped objects.

The whole hand is to a large extent automatic, the only control signals required are 'start' and 'stop' and an adjustment of gripping force. Selection of gripping mode is automatically achieved by a series of sensors in the hand itself, the first sensor touched by the gripped object determines the subsequent behaviour of the hand. This type of control philosophy is one which is not conducive to a good patient/prosthesis relationship, but is essential for the operation of the device by a limited number of control sites. The degree of automation which must necessarily be introduced into fully articulated adaptive hands in order that operation by the patient may be achieved simply is a major factor which militates against such complex mechanisms as practical prostheses, since the patient wishes to be using a hand, not driving a machine. Experience at the Princess Margaret Rose Orthopaedic Hospital, Edinburgh, has shown that a considerable degree of function may be achieved if a simple prehension device is used in conjunction with a pronation/supination facility - a fact which is not given prominence by the Belgrade workers.

The Belgrade hand has been the subject of clinical evaluations, which, although based on somewhat artificial tasks, have provided a useful feedback of information. The first evaluation was carried out in Los Angeles at the University of California by Arezina and Groth (1964). This evaluation gave the designers a considerable amount of information to work with, since it covered almost every

aspect of the design. Arezina and Groth found that the siting of the pressure sensitive detectors in the hand did not cover a sufficient range to permit easy control. The times of operation in tasks which the hand could achieve were comparable with those of hooks, but gripping forces were too low, and the multiple hinged fingers tended to be unstable. The mobile fourth and fifth digits tended to obstruct the manipulation of small objects, a fact which is typical of most hand prostheses when compared with hooks. Similar effects which were found in this evaluation and in most other comparisons of hand v. hooks are the almost unavoidable side effects of reduced visibility and manipulative ability in small spaces due to the bulk of the hand.

Yet another indictment of the pincer grip action is given by Arezina and Groth when they note that gripping on flat surfaces was difficult in the absence of wrist flexion. However, the most serious problem of all was due to the extreme weight of the prosthesis, not surprisingly, in view of the complexity of the hand, in excess of 1kg.

Rakic (1968) records some of the modifications made in the light of the experiences outlined above, the chief action being an improvement in the stability of the fingers and their actuating mechanisms. He also notes the projected introduction of a pronation/supination facility. By 1970 the weight had been reduced to 570g, which, although high, was a considerable improvement on the early models, and this relieved one of the major drawbacks of the device.

Tomovic (1970) seeks to reduce further the degree of patient involvement in the operation of the hand by the removal of the need for selection of prehension force. In order to achieve this he

proposes a slip detector, consisting of a rotating wheel which breaks a circuit and hence increases prehension force until slipping ceases.

An evaluation report by Kay et al (1970) carried out on laboratory-type tasks of gripping various objects in different circumstances is generally favourable in tone. However, two important remarks made in vital parts of the report inspire little confidence in any judgments made as a result:

"... the somewhat worse results with the electronic hand were probably related to the fact that the tested patients were users of the mechanical terminal devices for a long time."

No evaluation of a device is fair under the conditions admitted by such a statement, if insufficient time is available to fit patients in a realistic way in their normal home environment for a considerable time, then there can be no comparison with a device which the patient may have used for years. A situation of this sort would be similar to presenting a brand new car to a veteran motorcyclist and assessing the car by his performance with the new machine after a few days use.

The second remark inspires still less confidence:

"If we discount the troubles the patients had due to weight and aesthetic appearance . . .".

It is sufficient to answer this comment quite briefly - in a functional hand you cannot ignore these facts for one moment.

An overall look at the achievements of the Yugoslav team with the Belgrade hand can only give an impression of amazement, the hand is a truly impressive achievement of control and engineering. However,

as a practical prosthesis, it is limited functionally by the same constraints of finger action that restricted the APRL type of hands, with the extra problems of increased complexity and a reliance on automatic control which is not compatible with the practical requirements of prosthesis fitting.

A hand which has been developed in Italy (Passerini and Scalas 1970) has a fundamentally similar pattern of movement, clearly as a result of close co-operation with the Yugoslav group at the Pupin Institute. A significant functional difference in view of the evaluation report of Arezina and Groth (1964) is that the fourth and fifth digits do not flex fully when the hand is in the pincer grip mode. The major difference, however, lies in the overall control system, which is programmed by a special cam mechanism within the hand itself. The operator is thus able to pre-select the mode of action required.

In Sweden, a considerable amount of effort has been directed towards the development of an adaptive hand, with the mechanisms being driven by artificial tendons powered by electric motors. Lymark and Mohl (1967) give a comprehensive specification for the hand functional capabilities:

1. Four active fingers, adaptive and force controlled.
2. Thumb flexion and circumduction.
3. Dorsal-palmar flexion and extension.
4. Pronation and supination.

Each of these movements is controlled independently by one of four electric motors situated in the forearm. The fingers are driven by pre-stretched terylene cords which are activated by motor action on a pulley arrangement which allows an adaptive grip

movement of one pair of fingers relative to the other pair which may have been obstructed by gripped objects. However, in order to retain stability after the achievement of grip, joint locks come into play on the loading of the fingers, at which stage the flexion mechanism gearing increases to provide extra gripping force. The hand is even endowed with a sprung carpal arch, which introduces a rounded arching to the back of the hand when the thumb exerts opposition pressure in the centre of the palm.

In a partial report on the progress of the hand, Lymark (1968) notes that the hand and the fingers may be passively abducted. Wager (1968) indicates some of the electronic refinements introduced into the control system, such as force feedback from the fingers, and velocity feedback from motor speed. These are incorporated internally within the hand, and are not fed directly to the operator.

The hand was intended to be controlled myo-electrically, which is virtually essential in view of the complexity of the hand since no large scale attempt at automation has been made in the Belgrade fashion. Herberts and Petersen (1970) found difficulties with inconsistent signal strengths using surface electrodes for the control of the prosthesis, and indicates that implanted electrodes would be used in order to overcome the problem.

This hand is a more serious attempt at the provision of a cosmetic hand than is the Belgrade device since thin rubber or pvc gloves are available as coverings for the prosthesis. In order to permit unrestricted prehension it is necessary that the gloves be very light, thin and flexible, but this has made them susceptible to damage. This problem has been overcome by the acceptance of the gloves as 'throwaways' after about a week of use.

The Swedish hand is apparently the only powered hand which is really capable of a lateral action by the thumb, and this is a direct result of the almost complete flexibility of the controls provided by independently powered fingers and thumb, together with the use of some passive abduction features. In an overall assessment of this hand, it must be said that it probably has more potential than any of the other complex hands, and may prove very useful when applied to those below-elbow amputees who are not heavy users of a terminal device and who have several control sites available. In applications to more severe amputations the problems of choosing useful control sites become more severe, which leads to difficulties in most situations which make use of myoelectric control. Concerning the problem of heavy users of terminal devices, it must be said that any articulated finger mechanisms are likely to suffer extremely high loads, whether internal due to the necessity for the high 'tendon' forces which are required to provide an adequate fingertip prehension force, or the externally applied impacts and side loads on fingers suffered continually by normal hands. Under these circumstances it is to be expected that the life of a multiple jointed system of this type may be subject to frequent damage by anyone other than the most careful user.

The approach to adaptive hands has been made in Britain by a group working at Southampton University (Todd et al 1969), and has been pursued mainly as an exercise in control techniques, rather than the provision of a real prosthesis. However, various aspects of the system are of interest, particularly in view of other attempts to fit similar prostheses. The mechanism is based on a 'tendon' type of operation similar to that of the Swedish hand, but the

actuation procedure is quite different since it makes use of a capstan principle by which a slight tightening of a 'tendon' around the capstan causes a magnified force to be applied to the fingers. By making use of two capstans it was possible to arrive at a satisfactory range of speeds of actuation in changing from one to the other. Slip detectors, position and velocity feedbacks and a built in safeguard against excessive gripping forces are all incorporated within the device. The emg control system is level-discriminated for different functions but there is no attempt at any active feedback (other than visual) to the operator. This is because, for prehension, detailed conscious control or feed-in is not required. This is a convenient trap into which many of the 'automated prosthesis' fraternity fall. Although it is frequently necessary in practice to adopt a compromise solution in which the prosthetist is knowingly forced to omit certain functions or facilities, it would be for reasons of expediency rather than because of a conviction that such functions were not necessary.

In a speculative assessment of the requirements for a hand prosthesis, Godden (1968) has made some useful contributions to considerations of artificial hands. He emphasises the predominance of the effect of the phase relationship between fingers and thumb, regarding this as the prime consideration for the achievement of full function in a prosthesis. In this appreciation of the importance of thumb activity during prehension, Godden is one of the very few workers in this field to note fully the medically and anatomically widely understood fact that the thumb is the key to the prehensile and manipulative function of the hand. As a useful

example in illustration of this point he points out that many arthritic patients who are only able to move the thumb in a plane at 45° to the palm are still able to fulfill most functions because of the phase control which enables the position action of the thumb to be changed relative to the clenching fingers.

The proposed adaptive hand, on the basis of these considerations, would therefore have a thumb operating in a plane at 45° to the palm, fully articulated fingers, and a variable phase lag between thumb and finger action. This model is a highly desirable target for anyone considering the design of a hand prosthesis, but the hard facts of practicality once again rule out some of the possibilities, such as the jointed fingers for the reasons of stability which have already been given. However, the important fact to note here is the vital nature of thumb action in the prehensile process, and the possibilities which remain even as a result of restricting the thumb action to a fixed plane of motion.

A device has been produced upon these lines by Collins (1971), making use of perspex parts for the structure, and nylon tendons for effecting the movements. The resulting hand has no cosmetic cover and is capable of only small gripping forces, but exhibits an attractive degree of dynamic cosmesis.

Canadian development work with artificial hands has taken a more independent line which is made clear by the development of hand mechanisms of other than the pincer configuration. Nicholls et al (1967) put forward a hand in which the four fingers flexed at the MCP joints, whilst PIP joint flexion linked to this motion also occurred until the fingers closed on the thumb. In order to permit

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full palmar closure, the thumb could move away to the side to allow unopposed finger motion. The control system was strictly of an on/off nature, but as always it was found that function was quite inadequate in comparison with hooks. An interesting feature associated with this hand was the incorporation of a continuous wrist rotation movement.

The type of hand mechanism outlined by Nicholls was realised in the form of the hydraulically powered hand associated with the Northern Electric hydraulic arm system (Stevenson and Lippay 1968) which incorporates MCP and PIP joint flexion in all four fingers, normally operating in pincer-like opposition of index and middle fingers to the thumb. The thumb position is adjustable to permit closure of the fingers in full palmar flexion. Unfortunately no real cosmesis may be attributed to this device, despite its skeletal structure, since no cosmetic cover is used. Functionally the problems are similar to most of the other hands, typified by the inability to pick up the 1/4" high 1 1/2" diameter disc specified by Peizer (1969).

Work in Japan has followed from the initial influence of the Belgrade hand in the form of the Waseda hand (Kato et al 1970) which is myo-electrically controlled, and has both fully jointed fingers and thumb. Prehension patterns are typical of the fully articulated prostheses, being fingertip/thumb pinching in pincer fashion, and palmar grasping when the thumb is moved away from the line of action of the fingers. This hand has the thumb flexion operating in the 45° plane proposed by Godden, a fact which prevents satisfactory flat surface operation. No cosmetic cover is apparent but the fingers are covered in flexible polyurethane to give a soft gripping



surface. Some degree of active feedback is transmitted to the user by means of electrical stimulation of the skin according to gripping pressure.

1.6 Evaluation.

The problem of laboratory type assessments of the functional capabilities of artificial hands is one which has not been the subject of many investigations. This is probably, and quite correctly, due to the view that the only testing ground for a prosthesis is in real use, on a patient. However, Bonvin and Mongeau (1969) in Montreal and Engelhardt and Heipertz (1971) in Germany have made attempts to assess the gripping power of various prostheses. The work of Engelhardt and Heipertz in comparing adaptive and pincer grips led them to revoke Nietert's (Director of Otto Bock) practical remark that the advantages of the adaptive hand are outweighed by complication and weight problems, and thus adopted the adaptive approach. In practice they achieved a lower weight than the equivalent Otto Bock hand, and needed a lower gripping force to achieve the same degree of function. This is quite plausible and correct, but takes no account of active prehension, which is the essential feature of a useful hand - if it can pick up, it must be able to hold.

1.8 A different approach to hand prosthesis construction.

The most revolutionary hand prosthesis of all is typical of the work of its originators in the ingenious simplicity of approach to the problem. The hand devised by Cool and van Hooreweder (1971) must be the simplest and yet most complex hand yet devised and although there are as yet various question marks attached to it, it may prove to be a hand of great potential. The device is pneumatically

powered and is fully articulated at the anatomical joints. Each digit consists of hinged members covered by a woven flexible covering which incorporates a flexible gas-tight membrane. When gas is supplied within the prosthesis, the pressure causes expansion at the joints, and the hinges cause this to create flexion of the joints by virtue of the greater expansion allowed radially away from each hinge. The action is in fact very similar to that of the bellows utilised by Housso (1970) with the bellows action being replaced by the stretching of the membrane cover. The mechanism became feasible as the result of considerable co-operation between the engineers and textile workers who wove the covering in a way which allowed flexion without ballooning under the effects of applied pressure.

The great merit of this system lies in the inherent simplicity of the device, which allows an extremely light weight construction in what is really a hand capable of considerable versatility of movement. However, the very nature of the lightweight construction and the inherent compressibility of the pneumatic power medium may tend to make the prosthesis unstable in situations requiring the use of high forces. For example, the hook-like grip used for many very powerful situations such as suitcase carrying, merely requires a statically stable hook shape, and relies on the structural stability of the prehension device in order to make use of the more powerful arm mechanisms. The main problem here appears to originate once again from the adverse nature of the structure of fingers with regard to mechanical advantage, for, even if an incompressible fluid were used to actuate the prosthesis, any high forces applied at the

fingertips will result in enormous hydrostatic pressures within the prosthesis, thereby creating bursting pressure problems for the designer of the covering materials. Nevertheless, it is felt that this simple/complex prosthesis may prove to be the foundation stone for the future of practically viable adaptive hand prostheses, and it is to be hoped that development will continue along these lines in the direction of a prosthesis which may be regarded as a viable proposition in the real world of prosthesis users.

1.9 Conclusions.

The conclusions to be drawn from this review of terminal devices in general are necessarily the distillations of the various experiences with these devices, as reported by evaluators and users of the devices. It is perhaps surprising that a quite clearly defined picture emerges from such a diverse background, but it is possible to summarise the work quite succinctly under a series of brief headings in a sort of family tree (Fig. 1.1), in which the fact of external power is at all times incidental to the type of mechanism employed.

This family tree makes quite clear the limited lines of approach taken on the development of artificial hands, and the review of the capabilities of these hands has emphasised the functional inadequacies of these systems in comparison with hooks. However, the patient requirements for cosmesis have also been emphasised, thereby firmly placing the onus of development on workers in the field of artificial limbs to provide functional hands of acceptable reliability, function and cosmesis. The pincer-grip type hands are adequate both cosmetically and in terms of

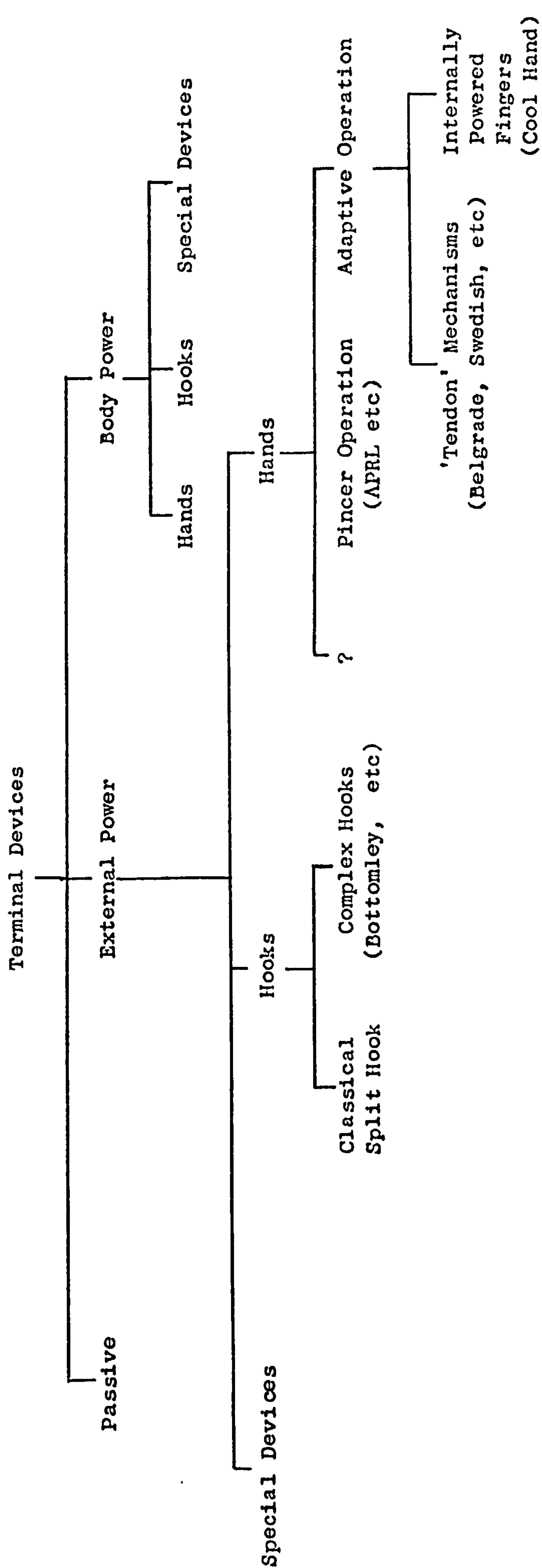


Fig. 1. Terminal Device Development to Date.

reliability, but fail to provide a prehension function which is remotely comparable with that of hooks. Some adaptive hands are acceptable cosmetically, but more may be considered either adequately reliable or sufficiently functional to attract and retain the attention of patients who use their prostheses.

The large void denoted by ? is intentionally placed in the region of complex hooks, since this is the direction in which hand mechanism research must be directed, because certain of the advanced hooks, such as that of Bottomley, are capable of such considerable prehensile versatility even with the use of very simple mechanisms. On reflection it is strange that virtually no work apart from that described later in this thesis, has ventured away from the two existing main streams of hand prosthesis development in the particular direction indicated although this has since been advocated by Moberg (1973) by a balanced assessment of the situation summarised above.

1.10 Indicated lines of further development for hand prostheses.

The net result of these considerations is to place far more emphasis on the action of the thumb, and less on the active participation of the fingers. This approach is confirmed by the clinical appreciation of the peculiar importance of the carpo-metacarpal joint of the thumb, combined with the extreme versatility of the lateral opposition mechanism of hook devices. The cosmetic acceptability of a laterally opposed thumb is illustrated by the only two devices which are hand-like in configuration and possess laterally opposing thumb mechanisms. These prostheses are the Steeper passive hand which is worn with a leather glove and has a

passively operated, laterally opposed spring thumb, and the child's cable controlled hand, which is worn without a cover, developed at the Ontario Crippled Children's Centre (1971). Both of these prostheses have quite acceptable profiles, even without the use of cosmetic covers.

Normally, in any discussions on any subject, it is never safe to generalise, however, the situation prevailing in hand prosthetics work appears to be an exception to this rule, since there is no existing hand prosthesis which is capable of a real degree of prehension - that is, the active grasping or picking up of an object, particularly from tables, shelves, etc. In view of the various facts learned from the prosthesis referred to above, it appears that the most promising approach open to further study is the utilisation of a laterally opposing, active thumb mechanism which should be arranged to be particularly compatible with active picking up from flat surfaces. It is felt that work pursued along these lines may prove Langdale Kelham (1937) wrong in his rather pessimistic outlook for the development of hand prostheses:

"... experiment will continue, despite the fact that it is a matter of conjecture as to whether development along these lines (i.e. mechanical hands) will, in future, be more successful than in the past."

Furthermore, the future hand prosthesis development indicated following an assessment of existing work has a considerably better chance of fulfilling Langdale Kelham's simple but demanding specification for hand prostheses:

1. Natural appearance

2. Light weight.
3. Good, secure grip.
4. Robust.
5. Simple and easy to use.

1.11 Work on the development of externally powered artificial arms.

The development of externally powered arm systems has been a distinctly post-war activity, a fact which is directly related to the advances in the technology of miniaturised power sources and actuation. The problem of miniaturisation still dominates the difficulties encountered in this field of work, and the choice of which power medium to use has directly affected the success of most powered arm projects.

Three distinct types of actuation of the 'muscles' in powered arms have emerged; pneumatic, hydraulic and electric. The relative merits of these systems are reviewed elsewhere, and it will be sufficient at this stage to give only brief reasons for making each of the choices.

Pneumatic power is usually selected for the extremely advantageous power to weight ratio of the actuators or 'muscles', which enables the production of a light weight arm prosthesis. The form of the pneumatic power is usually as compressed CO₂ contained in interchangeable bottles, recharging being a specialised task which is something of a disadvantage. An argument often used by control engineers against pneumatic systems is that the system is soft and compressible, but this will later be shown to be advantageous rather than otherwise in a practical prosthetic system.

Hydraulic power, with similar actuators to those used in pneumatic systems, also has good power to weight ratios for the muscles. This medium is particularly attractive in that the pressures necessary for driving a prosthesis may be produced from small electrically driven pumps, which in turn may be powered from small rechargeable batteries. One particular problem with hydraulic systems is that leaks must be virtually non-existent, since the fluids used are normally messy and can cause dermatitis.

The great attractions of electric power are that the power source is rechargeable in the home, it is clean, control problems are well understood, and components are physically small. However, the unfortunate fact is that electric motors are exceedingly heavy, their power to weight ratio is poor, and this fact alone has militated heavily against the direct use of electric power in practical prostheses.

All these power media have been used in prostheses in various ways, but two distinct lines of approach have been followed and these provide a useful division in the considerations of work in powered prostheses. The distinction lies in the approach which is made at the beginning of the development phase; some workers have gone for the development of a completely new prosthesis, whilst others have concentrated on the development of isolated units such as elbows destined to replace existing parts in conventional prostheses. There are various works which do not fit into either category and these will be considered separately.

1.12 Complete arm prostheses - pneumatic power medium.

The early work of Marquardt (1956) in Heidelberg not only formed the first pneumatic arm prosthesis but was effectively the initiator of all subsequent work in this field. The Heidelberg prosthesis had powered shoulder rotation, elbow flexion and wrist rotation, together with grip supplied by a pincer grip type hand prosthesis. Each movement was powered by the crank action of a piston actuator, control being achieved in a sequential fashion by means of a special six position valve, each position relating to one type of movement. The Heidelberg prosthesis was subsequently taken up by the Montreal group under Mongeau (1966) and used in the rehabilitation programme for thalidomide children. Various modifications were made to the system, and were mainly of a control nature.

The work of Marquardt was followed by that of Simpson (1965) who, after a visit to Heidelberg during the aftermath of the thalidomide disaster, had started work with pneumatically powered piston actuators, but with the important distinction that a great deal of emphasis was placed on the principles of control used with the device. The work on control principles is considered elsewhere, and will not be expanded at this stage, since the emphasis of this section is on the principles of actuation and movement incorporated in the prostheses. Simpson's early prostheses incorporated powered elbow flexion, pronation/supination and prehension, with passive shoulder flexion and abduction.

The success and acceptability of these early prostheses developed by Simpson led to a requirement for greater versatility in the arm functions, and this led Simpson (1965) to put forward the concept of a multi-function arm. Since the general details of the

development of this arm prosthesis are described elsewhere in this thesis, it suffices to say that the work has been successfully accepted by the patients (Simpson and Kenworthy 1973) and that further development is continuing. (Kenworthy and Simpson 1973, Kenworthy and Simpson 1974).

Early development of pneumatic prostheses in the United States was primarily due to Keissling (1965) who developed valves and actuators which were incorporated in prostheses fitted to amelic and phocomelic patients. The actuators devised by Keissling achieved rotation by making use of a helical rotator, by which the linear motion of a piston keyed into a helix caused rotation of the helix, since rotation of the piston was prevented by its special flat-sided shape.

The prostheses which incorporated these actuators provided active elbow flexion, wrist rotation and prehension, with lockable passive flexion at the shoulder. The chief problems encountered with the Keissling (AIPR) prostheses appear to have been ones of control rather than hardware, since an assessment of the components at VAPC (Veterans Administration Prosthetic Centre 1965) under Peizer, found during a piece by piece replacement of conventional prosthesis parts by the AIPR components created problems of inadvertent operation and subsequent confusion. Some of the origins of this work are also covered by Mason (1972).

In Sweden a considerable amount of energy has been directed towards the development of pneumatic components for prostheses (Klasson 1967).³ Initially the work concerned the design of control components, since the arm components used were those commercially

available from the German Otto Bock company. Specialised components were subsequently developed to provide function for phocomelic children, providing a prosthesis similar to the Simpson arm with elbow flexion and wrist rotation. This type of position was found to be restrictive for phocomelic children since active motion at the shoulder of the small arm was prohibited. Enger (1967) introduced a non-axial shoulder mounting which permitted the natural arm to move with the complete prosthesis. The actuation mechanisms make use of differential area piston actuators and a considerable degree of control hardware has also been developed which will be reviewed elsewhere. No indication is given of any attempts at evaluating various control principles in practice, since force demand control has been regarded as being of superior importance.

The force demand valves developed by Klasson have been incorporated in a pneumatic arm prosthesis developed by Carlson (1971) at the University of California in Berkeley. This prosthesis utilises the valves in a position servo control system, and makes use of coupled movements, combinations of which are selected by the patient. The tackling of the prosthesis problem in this way, utilising pneumatic power, is highly significant, since the development of powered prosthetics in the U.S.A. has for a long time been inhibited by a widespread jump onto the electric bandwagon, which has not been as productive as may have been expected on a first appraisal of the situation.

Pneumatically powered prostheses have been something of a favourite in Britain, where, apart from the work at Edinburgh, comprehensive prostheses have been developed in three other centres.

The most prominent of these was the Medical Research Council Unit at West Hendon Hospital (MRC 1970) where a fully mobile pneumatic arm prosthesis was developed, chiefly as a result of the thalidomide problem. The design was based on the data obtained from an assessment of daily living requirements and as a result provided an extremely powerful arm prosthesis. However, various paradoxical decisions were made during the development of this prosthesis, in the view of the experiences of the author of this thesis during the same period of time.

The prosthesis incorporated humeral rotation, shoulder flexion, elbow flexion, pronation/supination of the wrist and hook grasp. Wrist flexion is passive, against a spring, and a small degree of shoulder abduction is achieved as a result of a linkage to the humeral rotation mechanism. Shoulder flexion is achieved by means of externally mounted (external to the arm) pistons driving a chain and sprocket arrangement. The Kiessling elbow flexion mechanism was rejected on the grounds of manufacturing complexity, but strangely enough is retained in a modified form as the wrist rotator. The elbow flexion mechanism used is an ingenious double four-bar linkage system, which is very compact, but has been the source of a great deal of trouble due to the large number of joints present.

The decisions which have resulted in difficulties with this prosthesis are related to the control and power side. One of the major problems with the Hendon arm was due to a large instability in the controls, a fact which was overcome by the introduction of hydraulic damping. In fact the instability is merely due to an incorrect choice of valves, since the poppet valves used are

inherently unstable, as they effectively help to turn themselves on once flow begins. If force-demand valves had been used in place of these poppet valves, the arm would almost certainly have been stable without the introduction of extra damping.

The second basic problem encountered by the users of this arm concerned the excessively high gas consumption realized in use. This is directly related to the size of actuators used, and to the type of valves used, since there is no direct control of drive side pressure in the pistons when poppet valves are used for the controls. It is felt that a compromise of a reduction in the power of the arm, combined with more careful control system design may have resulted in a considerable reduction in gas consumption.

The Hendon arms are being fitted to children by Mr. N. D. Ring at Chailey Heritage Craft School and Hospital and are fitted bilaterally. This presents severe problems for the establishment of an adequate number of control sites, but the fittings are carried out in this way because of the view that control sites on one side of the body should not be used to control prostheses mounted on the other side. In order to overcome this shortage of control sites Pottinger and Ring (1968) propose to use control locks to permit one control site to control more than one function.

The same reasoning has led Bottomley (1968) to propose the development of arms which have a restricted number of degrees of freedom. In this it is hoped that unilateral control of an arm may be achieved without the need for the sequential type of control proposed by Ring. This viewpoint has led to the development of prostheses at Roehampton, the mechanisms and control of which are fundamentally an amalgam of various aspects of the Edinburgh and

Hendon arms.

The one remaining major work with pneumatic prostheses is that of Bousso at Oxford. This work is of particular interest since the actuators used were not the conventional pistons used elsewhere. Bousso (1970) developed a special hinged bellows system into which gas was fed under pressure, this caused the bellows to expand, which resulted in a rotational movement of the other members of the bellows, since the side of each bellows compartment was formed by a plane radiating from the central hinge. These bellows were used in a comprehensive arm with shoulder flexion, elbow flexion, wrist rotation and hook action. The arm constructed in this way was light and, apart from the bellows themselves, very simple. However, only one of these prostheses was built, and the project advanced no further since there was no access to a patient population. The control systems were, as usual, the weak link, either being of the simple poppet valve type or solenoid operated for use with myoelectric control sites.

1.13 Conclusions drawn from the review of pneumatic systems.

This review of the major works with pneumatic arm prostheses makes one major point quite clear; the most important aspect of the prosthesis lies in the control principles to be used. This point has not been appreciated by the majority of workers in this field, who have tended to develop actuators for various modes of action and have then assembled these parts into a device with powered movements at the anatomical joints of a normal arm, expecting the patient to be able to control the complex device by virtue of a considerable training programme.

Only two of the prostheses described have been designed as a complete entity on the basis of certain control principles. The Hendon arm has achieved some success as a result, with the main problems being associated with control flaws. The co-ordinate arm developed in Edinburgh has achieved more success as a result of the use of control principles previously proven in fitting practice, and the main problems have been the engineering ones of providing a mechanism which is strong and robust enough to withstand the heavy use to which it is subjected.

This distinction between control principles and engineering hardware is an important one, since the use of a successful control principle almost certainly carries with it a heavier wear on the mechanism. It is therefore quite possible that a prosthesis which has a poor control system will have less mechanical trouble than does the successful prosthesis, and therefore considerable attention must be paid to the maintenance problems of a prosthesis lest it fail for the wrong reasons. It is therefore essential to design an arm prosthesis as a complete entity in order to preserve the qualities of the device, piecemeal development will not do.

1.14 Complete arm systems - hydraulic power medium.

The advent of hydraulic power to the powered prosthesis scene has been surprisingly tardy, and in fact has made little impression in the way of fittings to patients. Indeed, the only hydraulic system which has really been completed is the Northern Electric arm from Canada. The pump developed by Lukas at Northern Electric (1969) is a highly efficient device which is powered by a small electric motor, pumping action being due to the small, rapid lateral

displacements of a shuttle mechanism. In order to overcome the problems of large flow requirements during simultaneous use of the shoulder, elbow, hand or wrist, the control has been made sequential so that only one movement is possible at any one time. This fact, combined with the slowness of the movements, severely limits the prospects of this prosthesis. One rather surprising aspect of the prosthesis, particularly in view of the limited attempts at cosmesis in the hand, is the attention given to dynamic cosmesis. The elbow is free to swing loosely during walking, which adds a certain touch of realism to the behaviour of the arm until it begins its powered movements.

Work on the investigation of hardware for the hydraulic powering of prostheses was carried out by Godden at Oxford University on a Department of Health and Social Security contract (Final report Godden 1970). This project did not lead to the production of a prosthesis as such, but was concerned with optimising motor operating conditions, the speed of the radial piston pump, and the operation of the hydraulic accumulator energy storage system.

Similar investigations are under way at University College London, where Broome and Lambert (1972) are producing actuators and valves for use in hydraulic prostheses based on the pump used by Godden. Work at University College London has always been concerned with the control theory behind prosthetic servo systems (e.g. Lambert and Davies, 1966), and has made various theoretically biased assessments of items of prosthetics hardware (Mufti and Meachem 1968) which have not been correctly related to the practical realities of prosthetics applications. In an effort to establish

some real experience with hydraulic prostheses, the University College team is applying the hydraulic systems in the arm mechanism designed in Edinburgh. It will be interesting to see the outcome of this work, particularly as the valve to be used is a spool valve, which may offer something of a compromise between the stability conferred by a force demand valve and the instability of a poppet valve.

Hydraulic power for prostheses is also being investigated at the University of Manchester under McLeish (McLeish 1968 and McLeish and Watson 1971). The application is being made to an arm mechanism designed at Edinburgh, as at University College London, but the hydraulic power comes from a pump operated by the heel during walking or from an electrically driven swash plate pump either of which charges an accumulator with sufficient energy storage to cover the simultaneous use of the various movements.

Since the majority of practical work with hydraulically driven prostheses is still in its infancy, it is difficult to assess the situation at this stage. However, from a control point of view there are considerable advantages available to the user of position servo controlled mechanisms, since the incompressibility of the power medium means that it can also be used as an indicator of position. One major problem still remains in the form of leaks, the choice of a non-irritant working fluid is imperative, and an absolute minimum of leakage is essential before the prostheses can be considered acceptable.

1.15 Complete arm prostheses - electric power medium.

Despite the many attractions of electricity as the power medium for prostheses, it has never been really successful when used for

powering complete arms, and the reason for this has always been that of the relatively high weight of the electric motor in comparison with the power output. The one possible exception to this problem was provided by the first electric arm produced by Alderson in 1948. This prosthesis made use of one motor which could drive any one movement at a time, clearly this reduces the weight problem to a great extent, but the incompatibility of the sequential control system with that of the human operator pre-destined it to failure. Work with this arm is described in some detail in Klopsteg and Wilson's "Human limbs and their substitutes" (1954).

McLaurin (1965) at Ontario Crippled Children's Centre pioneered work with electric arms in more recent times, and most of his problems may be attributed to the excessive weight of the prostheses. Activation of the movements was achieved by means of a lead-screw driven by the motor, connection to the rotation motion then being similar in action to that of a piston actuator. This type of actuator was used in feeder arms which incorporated linked elbow and shoulder flexion motions and prehension.

Wirta and Taylor (1970) are building an experimental electrically powered arm to assess the possibilities of a promising myo-electric control system which is based on pattern-recognition principles. This project is still in an experimental phase and as a result the weight problems are not of immediate importance to the assessment of the control system. It is probable that the control system will eventually be tried on a pneumatic arm, since this will provide a better opportunity for an evaluation of the control principles in a real prosthetic situation.

Some work in Japan has also been directed towards the production of self-contained electric arms, but a film of this in action shows it to be very slow in its movements and sequential in its action patterns.

A possible future trend for electrically powered arms has been initiated by Marquardt in Heidelberg, where he has used two Otto Bock elbow units on an endoskeletal structure to provide elbow and shoulder flexion in an adult size arm. This type of approach has previously been used with Otto Bock pneumatic components, and may prove useful in cases where limited function is all that is required.

The feasibility of electric power for arm prostheses is clearly questionable under the present circumstances of power/weight ratios of electric motors, and it appears that some major discovery in electro-mechanical energy conversion is really necessary before electricity can compete on equal terms with pneumatic power. It is, of course, possible to counterbalance the weight of motors in the arm by means of springs, but arm prostheses have to be carried by the patient at all times and therefore the all-up weight of the system is a severe problem. The orthotics problem is entirely different, since in devices such as the "Golden arm" of Rancho Los Amigos Hospital (Allen et al 1970) the weight can be carried by the wheelchair frame. Another major problem not appreciated by many workers who use electric power, is that mechanical feedback systems are still necessary, since switch and potentiometer controls have no built-in facilities for displaying the physical output characteristics of the arm to the patient.

1.16 The development of items of powered prosthetic hardware.

This section of development work is concerned with isolated functional units of hardware, such as elbows which are developed without being part of a whole arm system. Various items have been adapted from the complete prostheses described previously, such as some of the Kiessling/AIPR actuators, which have been utilised in various other systems on occasions.

One pneumatic device which is of particular interest is the Swedish elbow unit (Johansson et al 1970) which has been incorporated in a myo-electric control system by means of solenoid operated valves driven by pulses of current. The mechanics of the elbow itself are interesting in that a linear acting piston is used which pushes rollers along either side of a curved beam which is attached to the elbow rotation shaft. The shape of the curved beam is designed to ensure that the torque at a given elbow angle is at all times optimal for that position, since, for example, the torque requirements are highest when the elbow is fully flexed.

The majority of the items of hardware developed in this isolated manner are elbows, and American in origin. However, the one exception to this latter fact is the harmonic drive electric elbow of Livingstone and Crecraft (1968). Following the deduction that, for an elbow unit alone, the best medium for powering an elbow is electricity (Livingstone 1965), a unit was made which incorporated the simple 'epicyclic' harmonic drive gear reduction system, driven direct from a small motor mounted axially with the wave generator rollers.

Although Livingstone's system was not designed for compatibility with any particular system, the similar harmonic drive elbow of the Veterans Administration Prosthetics Centre (1971) is designed to replace conventional cable operated or passive locking elbow units. Similar conventionally geared electrically powered units have been produced by the Ontario Crippled Children's Centre, Gilmatic and the Istituto Nazionale Per L'Assicurazione (INAIL) (Schmidl's Italian unit) who have also produced a wrist rotator.

The Boston elbow of Mann (1968) and Mann and Reimers (1970) is electrically driven with a lead screw type operation. This device was mainly the vehicle for a tactile display of information regarding elbow flexion angle, which enhances the feedback of information to the patient in the emg controlled system used for the device. The whole device is somewhat large, heavy and complex and is not compatible with existing arm systems.

Another interesting approach which seems to sum up the American reluctance to abandon conventional prosthesis hardware is the Johns Hopkins' University cable power device. This is a torque motor which acts as a 'winch' on the conventional limb cable, thereby permitting retention of the whole conventional prosthesis. Control of this device is achieved by skin motion, which moves a magnet placed close to magnetically sensitive diodes, and hence operates the motor.

These items have been recorded as an indication of the intermediate phase which is possible between conventional body powered systems and those which use external power media. There is no doubt

a place for such devices, but it seems somewhat risky to expect that the conventional prostheses can provide an optimum basis for experiments with an entirely new idea. To use the motor car analogy once again, the situation is like putting an internal combustion engine into a stagecoach and expecting successful results.

Chapter 2.

Power sources and actuators.

2.1 A fundamental choice.

2.2 The use of body functions as power sources.

2.3 The power requirements of prostheses and power storage media.

2.4 Electrohydraulic systems.

2.5 The direct use of electric power.

2.6 Pneumatic systems.

Chapter 2.Power sources and actuators.2.1 A fundamental choice.

The choice of a power medium and the type of actuator to be driven by that medium is the most fundamental decision of all in the design procedure for an externally powered prosthesis since all subsequent work must make the best use of the available power. It is therefore important that the designer be aware of the merits and defects of the various available systems, and, indeed whether or not externally derived external power is really necessary at all. This point may at first sight seem to be an anomalous one, but the fact is that it has been possible for some workers to make use of various aspects of the human system in order to provide power for prostheses. A somewhat exaggerated example of this situation is given by the use of gross body movements for the powering of conventional body powered arm prostheses. However, this macroscopic use of body functions is the situation to be avoided in powered arm prosthesis work, and it is the use of small, regular, body actions such as heart beat, which can provide power without the necessity for conscious muscular effort. It is these 'passive' processes which will be considered initially since they could, theoretically, provide a 'free' source of power.

2.2 The use of body functions as power sources.

The most 'passive' of all the attempts to harness body functions concerns the provision of electric power by virtue of the oxidation-reduction potentials of metal electrodes placed in contact with internal body fluids. Reynolds (1964) made use of platinum and

platinum black electrodes placed in various parts of rat's anatomy, and used the 'battery' created thereby to drive an oscillator. The power derived from this system was of the order of 10 μ W, and depended on the electrolytic characteristics of living tissue, since power ceased 75 minutes after death. Similar work has been pursued by Konikoff (1966), who used platinum black and stainless steel electrodes for optimum results.

The power derived from this type of system is exceedingly low (10 μ W) and could only be considered as a source of power for electronic implants used as signalling devices, operating under low load conditions.

Similar low-power electrical sources have been derived from movements of blood vessels or the heart by the use of piezo electric crystals. In these situations, the movement of the natural system physically drives the piezo electric crystal, thus creating an electric charge across the crystal. In this way Myers et al (1964) made use of the movements of a dog's aorta to drive a cardiac pacemaker, whereas Enger and Klein (1966) made use of the left ventricle of the heart driving a piezo electric system as the power supply for a pacemaker. Improvements in the efficiency of these systems have been made by Ko (1966) by operating the crystal at resonance, but the power levels may still only be considered as being of exceedingly low level.

More simple mechanical systems have been arranged surgically, so that one body function has been harnessed in order to assist another. Kantrowitz (1960) altered, by surgery, a dog's diaphragm so that the action of the diaphragm contractions squeezed the aorta

in an auxiliary pumping action. In a somewhat similar fashion Kuserow and Clapp (1964) used muscle action to power an external pump for prolonged perfusions.

Although these two systems are specialised applications of body activities, they serve as indications of the possibilities of utilising regular physical movements for pumping actions, particularly in hydraulic systems. This principle has been adopted by Heather and Smith (1962) who made use of the external body movements created by the beating of the heart to drive a small hydraulic pump. Once again, the power levels are low since the heartbeat force 9-13 oz. must be harnessed from a travel of only 0.02". This situation requires an extremely light and efficient pump, and even with the use of an accumulator to store the power the practical problems of driving the device consistently militate against its successful operation. This system is also applicable to being driven by breathing actions, but the problems of mounting the device, together with the relatively low power available would severely limit the functional capabilities of any system driven from such a source, since the number of operations in any interval of time would be severely limited.

A system which is similar in principle has been developed at the University of Manchester (McLeish 1968 and McLeish and Watson 1971) and makes use of the pressure exerted at the heel by body weight during walking. Two short stroke pumps mounted in the heels of a pair of shoes are connected in parallel and supply pressurised hydraulic fluid to an accumulator, which it is hoped can then be used to power artificial arms. The developers of this system feel

that the power developed in such a system could be of the correct order of magnitude for powering an arm system. However, since the power is necessarily dependent upon the pedestrian activities of the patient, this fact alone provides large problems, since situations involving a high rate of arm power consumptions are usually those of low leg activity (e.g. writing, eating, etc.).

This consideration of the systems for deriving power from natural body functions shows quite clearly that the majority of the power levels which can be derived cannot be considered in the same league as that required for powering an artificial arm system. The work of McLeish (1968) shows that whilst sufficient energy is available from large scale movements, unless a considerable accumulation can be achieved, the user may find that a walk is necessary before he can finish eating! The conclusion then is quite clear; at present, external power sources must be utilised in order to provide an adequately consistent supply of power.

2.3 The power requirements of prostheses and power storage media.

The logical approach to an investigation of the practically possible sources of external power would appear to be a study of the normal arm power requirements. However, the widely varying results derived from various assessments of this problem, together with certain facts of engineering expediency, make the practical choice a non-ideal one in many respects since the optimisation of the power pack in this matter is not the deciding factor.

An assessment of the power and torque requirements in arm movements was made by Paul and Mann (1962) in which everyday movements were broken down into their constituent motions, which

were analysed for power and torque content. The extent of contribution of the constituent motions in each everyday task was assessed from existing maximal effort data in order to provide an indication of the overall average powers associated with different functional activities. In this way, the power and torque requirements of the joints of the normal arm could be assigned average values of power and torque and hence some indication was given of the losses incurred by amputations of different extents. Since the data used for the basis of this work was taken from existing work concerned with maximum powers and torques, the average powers derived are based on the high side, e.g. 265W for a shoulder disarticulation. The design of an arm prosthesis capable of delivering such power would be quite impossible if weight is to be conserved, and such a prosthesis would clearly be over-endowed with power for much of the time. It is therefore felt that a more valuable assessment would have been made by an analysis of power requirements during the majority of everyday activities which operate at a low power level.

A more practical approach to the problem is made by Klein and Montgomery (1968) who, by considering a child-size arm lifting 1 kg arrive at a power of 11.5W for one movement. They point out that due to the difficulty of obtaining precise information on the subject, it is expedient to base practical work on simple estimates of this sort in order to arrive at more accurate results by experiment with artificial arm systems.

Experience with pneumatically powered artificial arm systems with a single multi-functional powered prosthesis at the Princess

Margaret Rose Orthopaedic Hospital, Edinburgh, has shown that in a ten hour day, attending school, an eleven year old boy will use two 180g bottles of CO_2 which is equivalent to an average power level of 2.6W. This is an average consumption, but the power source must be capable of delivering at least five times this rate for short periods of a few seconds at a time.

Following their appraisal of the overall requirements of a powered arm system, Klein and Montgomery consider the merits of various power sources in terms of energy stored per unit mass of store. On this basis the pressurised pneumatic storage system scores very low at 12 Wh/kg whereas the electrical storage systems can provide of the order of 100 Wh/kg. The use of butane gas in combustion could provide 14,500 Wh/kg, whilst nuclear power could rise to 880,000 Wh/kg. The practical problems presented by the use of the latter two energy sources unfortunately prohibit their utilisation at this stage, thus effectively limiting the choice to pneumatic storage by liquification of CO_2 gas, and electrical storage in nickel-cadmium rechargeable cells. The choice of CO_2 as a pneumatic source of power is itself a practical compromise made between various other sources, as is the choice of Ni-Cd cells in the electrical case.

Various workers have made cases for their own selections of particular power media, none of which can be considered as a watertight argument. This merely proves the point that there can, as yet, be no definite selection, the choice must be made on the basis of striking a balance between the storage system on the one hand and the actuator system on the other. Some examples of the

widely varying choices are given below.

Livingstone (1965) made the choice between electric and pneumatic power on the basis of the storage weights, selecting electricity. He then selected the actuator system as a direct current electric motor, rejecting electrohydraulic systems because of their relatively low efficiency. In contrast with this Lambert and Hall (1968) chose hydraulic power because of the improved power to weight ratio of the actuators, whereas Earl (1965) can argue in favour of pneumatic power on the basis that pneumatics can provide the same maximum power at 500 psi as oil at 1400 psi in the same actuator, supplementing this by the point that pneumatics are suited for fast acting, low power situations, whereas hydraulics are better suited to slow, heavy work. Wager (1970), in a theoretical comparison of electric and pneumatic power applied to a hand and elbow, finds that the number of action cycles provided by the same system weight is worse for pneumatic systems, except for high force/low velocity situations - so the choice is still fundamentally a matter of priorities and personal opinion.

Practical work with powered prosthetic arm systems has been limited to the use of pneumatic, electro-hydraulic and electrical power, apart from the two hydraulic systems mentioned above which have used body movements to operate pumps feeding accumulator systems.

2.4 Electrohydraulic systems.

Of the electrohydraulic systems which have been investigated, only one can be considered as having reached the stage of a full prosthetic system. This was the Northern Electric arm (1969),

produced in Canada, and driven direct from a single pump powered by a small d.c. electric motor. The power source was Ni-Cd cells which are rechargeable. Similar systems have been investigated by Godden (1970) who furthered development of the Lucas radial piston pump and produced piston actuators and rotators of the helical drive type. Work of a similar nature is continuing at University College, London under Lambert. Lambert and Davies (1966) found from an analogue computer analysis that a hydraulic system should be fast enough for operation in prosthetic systems, and work has now progressed to the stage where valves and actuators are being produced (Broome and Lambert 1972). This system is expected to be powered from rechargeable batteries driving an electric motor which in turn drives an efficient pump, probably of the radial piston type.

2.5 The direct use of electric power.

The direct use of electric power in upper extremity prosthetic systems made a surprisingly early appearance in the form of the electro-magnet powered hand referred to by Borchardt et al (1919). This idea was revived in post-war years by Reiter (1948) but has not been successful because of the short distance over which electromagnets can exert high forces. This unfortunate fact has necessarily led to the use of electric motors for powering prostheses, since an optimum constant spacing between stator and rotor can be maintained at all times.

The source of the electric power required for driving the small d.c. electric motors commonly used in prosthetic systems has usually been in the form of nickel-cadmium rechargeable cells. The reasons for such a choice are given by Grahn (1965) who explains

that although the silver-zinc cells have the best energy storage characteristics, they are not available in a sealed form, a point which is satisfied by Ni-Cd cells since the oxygen and hydrogen evolved during use are recombined during charging.

In order to make the best use of an electric motor it is essential that the motor be allowed to operate under ideal conditions, which are normally associated with a rotor speed of several thousand revolutions per minute for d.c. motors. The choice of permanent magnet d.c. motors is essential on a power/weight ratio basis, and therefore all systems using electric motors must incorporate some form of speed reduction mechanism which is capable of efficiently gearing down the speed by a factor of 100 or so. The systems employed to achieve this reduction are the only real distinctions between one electrical system and the next, since all use permanent magnet d.c. motors powered from rechargeable cells.

The neatest and most compact system for achieving the large speed reduction is the harmonic drive system employed by Livingstone and Crecraft (1968) and VAPC (1971) in their elbow units. This drive unit consists of a toothed flexible belt which is situated within an internally toothed gear which has (say) one more tooth than the flexible belt. The flexible belt is held in an elliptical shape by a pair of rollers which are driven from the motor, the rollers thus cause contact between belt and gear at two points only. Thus, during one complete rotation of the motor shaft, the gear will have moved by only one tooth distance, therefore achieving a reduction in speed of 100:1 if there are 100 teeth. This single stage reduction mechanism allows an extremely compact

construction, but tends to be rather noisy in operation.

Most other electrically driven systems use more conventional speed reduction mechanisms, for example most of the electrically powered hands use worm gear drives, or toothed belt and gears for speed reductions. Exceptions to these are the 'linear actuators' used by McLaurin (1965) and Mann (1968) who utilise motor driven lead screws in piston-like fashion.

2.6 Pneumatic systems.

Pneumatic power has been most extensively used in powered arm systems, despite the unfavourable characteristics of the energy storage system in terms of energy/weight ratio and rechargeability. The reasons behind this fact are simply those of engineering expediency, the actuators are of high power/weight ratio, and the speed of response is high, even in miniaturised systems.

Although all practical pneumatic systems have utilised CO₂ gas as the power medium, the choice was not entirely an automatic one, since various alternatives are available in the form of the fluorocarbons, such as Freon for example. Tome (1961) considered the relative merits of Freon 12 and CO₂ as storage media, finding that the use of Freon would convey considerable advantages in terms of weight due to the low storage pressure which required neither a strong bottle nor a pressure regulator. However, on all other counts, such as toxicity and combustibility, for example, CO₂ was preferred. In a report for the Ministry of Health, Levell and Snowden (1968) divide the possible fluids into three categories: (i) critical temperature above operating temperature range, (ii) within operating range, and (iii) below operating range. Category (i) has the best energy stored/weight ratio but requires

a pressure reducer to overcome variations due to temperature fluctuations and latent heat requirements effectively limit maximum flow rate. Category (ii) which contains CO₂ is an effective compromise between these problems, a major advantage being the non-toxic properties of CO₂ which permit safe exhaust to atmosphere of used gas.

Although the selection of CO₂ as a power medium is relatively safe, there are important features which must be borne in mind during the design of the storage system. Pearson (1965) points out the effects of temperature fluctuations on partially filled bottles of CO₂, showing that a bottle which is more than 50 per cent full but less than 100 per cent is safe if used in conjunction with a pressure relief valve which will operate if the internal pressure increases excessively. Bottles filled in this way are then used in conjunction with pressure regulators to provide gas at a convenient operating pressure of approximately 100 psi in most cases.

The actuators driven by the pneumatic power source have taken various forms, most of which rely on the effects of pressure on a mobile plate of one sort or another. An interesting exception to this rule is provided by the device known as the McKibben muscle which relies on the lengthwise contraction of a balloon which is allowed to expand radially. The practical form of this device was developed by McKibben, a U.S. physicist, in conjunction with Nickel et al of Rancho Los Amigos Hospital, Los Angeles. The actuator consists of a flexible cylindrical rubber sac, covered by a woven braided sleeve, which is woven in such a way that lengthwise contraction occurs when pneumatic pressure is applied to inflate the sac.

The more conventional actuators take the form of pistons, with sliding or rolling seals to prevent escape of gas, cylindrical bellows and a specialised form of bellows developed by Bousso (1970) at Oxford. The action of the Bousso bellows provides directly a rotational motion and is most readily understood by imagining the old-fashioned fireside bellows operated in reverse - pressure applied at the 'spout' end causes opening of the bellows, the handle plates pivoting about the hinge near the 'spout'. The Bousso bellows are thus incorporated directly into a joint mechanism, with the hinge being situated at the anatomical joint axis. This type of actuator has not been greatly exploited, probably because of the relatively complicated construction involved when special sizes are required in small numbers. Small batches of specialised piston actuators may be manufactured very simply, and may be easily modified, which is an important factor during development work.

Piston actuators of a size and weight suited to prosthetics are not available commercially, although suitable O-ring seals are readily obtained. This has led to the individual development of specialised actuators such as the helical rotators of Kiessling (1961) and Nichols et al (1966), and the modular range of linear actuators by Harborow (1969). The linear action of conventional piston actuators is commonly converted to rotational motion by means of crank action driving gears, cables or chains.

The only specialised development work carried out on pneumatic actuators for prosthetic use has been concentrated on the McKibben muscle actuator. Schulte (1961) has provided a comprehensive range of characteristics of the device, whilst Pakusz and Gwynne (1961) have increased the output force by reduction of the helix angle of

weave. Morecki et al (1967) describe an actuator of the McKibben type with reduced hysteresis characteristics, and this approach is considerably advanced by Kato et al (1970) of Waseda University, Tokyo, who describe flexural and rotational versions of the device.

The chief problem with actuators of the McKibben type, and with bellows, in the large dead space which must be pressurised before the actuator works. This results in an increased consumption of gas, a fact which has been confirmed by Burnett and Price (1965) who, in a comparison of the McKibben muscle, bellows and piston actuators, found the piston to be more efficient, despite the need for a 'running-in' period to reduce friction. The efficiency of the piston actuator, combined with ease of manufacture by conventional engineering techniques therefore makes their selection imperative, since fully functional arm prostheses contain such complex mechanisms that no space can be wasted, individually designed actuators therefore being essential.

The problem of gas economy in pneumatic systems is a very real one, and has been the subject of various investigations. In a theoretical analysis of pneumatic piston actuators Earl (1958) finds that the differential area type piston actuators are more economical to run than those of the double acting variety. However, unpublished work at the Princess Margaret Rose Orthopaedic Hospital, Edinburgh, has indicated that, if used in a pressure demand controlled system, with position servo control, double acting pistons can conserve gas to compensate for the different type of operation. The incentive for using double acting pistons is considerable, since a double

acting piston of $\frac{1}{\sqrt{2}}$ diameter delivers the same force as a differential half area type of unit diameter, which represents a considerable saving of space.

Lönnebring (1971), in a theoretical analysis of pneumatic systems, finds, not surprisingly, that stiffness (or compressibility) in a pneumatic system is not compatible with gas economy, and regards this as a detrimental fact. However, the compressibility of the pneumatic system at the relatively low pressure of 100 psi (which is necessary for safety reasons) is almost certainly an advantage, in that impact loadings are damped and are therefore less likely to cause danger to the prosthesis or the wearer. This fact of compressibility in pneumatic systems is frequently given as a disadvantageous one, usually on the basis that control is difficult. However, if the control system is well designed, no feedback errors need be introduced as a result of the 'softness' of the mechanical system.

Chapter 3.

Cosmetic gloves and associated materials for hands.

- 3.1 The choice of materials for gloves.
- 3.2 The fundamental techniques.
- 3.3 Progress in the techniques of glove production.
- 3.4 Alternatives to pvc as the glove material.
- 3.5 The more general aspects of cosmesis.

Chapter 3.

Cosmetic gloves and associated materials for hands.

3.1 The choice of materials for gloves.

The production of cosmetic gloves has necessarily been limited to the post-war years, since the considerable developments in materials technology, particularly that of plastics, has provided workers in the field of cosmetic replacements with such a wide variety of materials with differing properties, that the problem has now become one of keeping up with the new phenomena and assessing new possibilities.

Before the advent of the now widely available plastics materials, the flexible cosmetic restorations which were produced were commonly made from natural latex rubber, coloured and hardened as required, for example Brown (1945) based his rubber prosthetic fingers and gloves on sculpted models, skilfully produced to match the natural hand. However, natural rubber presents serious problems in use, since it is not very strong in thin films when flexibility is also required, colouring is difficult, the material perishes and becomes brittle with age, and, more significantly, it is not fully resistant to a wide range of chemicals, even such common-place liquids as mineral oils causing rapid deterioration of the material.

3.2 The fundamental techniques.

Despite these considerable disadvantages, Clarke et al (1947) produced latex rubber gloves, and also used latex rubber for the manufacture of moulds for further work, paving the way for many years of future glove production by the use of a dipping process to build up the thickness of the latex mould. Clarke also refers to

electroplating techniques for producing metal shell moulds, plating onto wax replicas of hands and cadaver hands, in the former case removing the original by melting out the wax, the latter requiring the more grisly technique of maceration! By 1949 the techniques began to involve the use of pvc (Clarke and Weinberg 1949), when it was found that the pvc plastisol curing temperatures destroyed the rubber moulds. This was initially overcome by part curing the pvc, removing the rubber mould, and completing the pvc cure in a glycerin bath. However, the hollow shell metal moulds were found to be more convenient and were produced by plating onto a filled pvc glove sprayed with conductive paint, or by the spraying of molten metal direct, although in the latter case the moulds were found to discolour the pvc gloves produced from them. Clarke found considerable difficulty in achieving release of the gloves from within the shell moulds and went to considerable lengths to concoct release agents to relieve the situation. The effect of one application of such release agents, together with detail lost as a result of spraying conductive paint for plating, is to considerably reduce the amount of detail reproduced which is a very serious drawback in the production of good quality reproductions of hands.

3.3 Progress in the techniques of glove production.

When Dembo and Tane-Baskin (1955) found that the public tended not to notice the cosmetic gloves then available, a distinct inertia seemed to settle upon the development of improved processes, for as late as 1968 Klopsteg and Wilson's "Human Limbs and Their Substitutes" Leonard describes what is basically Clarke's process with the introduction of a new casting material in the form of

sodium alginate. In fact, so retarded had the development become that Leblanc (1971), as a result of a symposium on the subject, produced a comprehensive specification for cosmetic gloves in the hope of engaging the help of commercial enterprises.

However, two attempts have been made to improve the quality of both the glove and the production process. The first of these was carried out as part of the Swedish project for the production of a functional hand prosthesis. The specification for the glove covering (Lynmark and Mohl 1967) was given on the basis of the extreme flexibility required for use with a fully articulated hand. This fact meant that the gloves would necessarily be thin and disposable after three to five days use. Klasson and Winderlich (1968) describe some of the processes used in an attempt to produce these gloves. Apart from making use of plating techniques similar to that of Clarke, they describe a procedure which makes use of ceramic materials. By stuffing an everted glove and taking a plaster impression of the everted glove, it was possible to make a split mould for the casting of a ceramic mould which could be used for subsequent dipping in latex. The detail reproduced by this process was poor, and included split-lines from the mould, a fault which cannot be accepted in true cosmetic gloves.

An independently developed, but fundamentally similar, process has been described by Kenworthy and Small (1974), details of which are given in the practical section of this thesis. The significance of this work is that gloves of intricate shape and almost perfect detail can be faithfully reproduced from simple moulding and casting processes followed by the dipping of a mould into pvc latex

which is subsequently cured by the application of heat.

3.4 Alternatives to pvc as the glove material.

After having extolled the virtues of the materials collectively known as 'plastics', it is perhaps surprising to note that pvc has proved to be the only such material suitable for use in cosmetic gloves. The number of alternatives is seriously reduced by the requirements of extreme flexibility and high strength, together with a necessity for existing in a readily usable form such as a latex or plastisol. The only practical alternative to pvc has been polyurethane, which was evaluated for this purpose by the U.S. Army (Hodge et al 1971) but was found to be lacking in flexibility and colour retention properties. However, this presents no serious problems, since pvc is almost ideally suited to the function, apart from a low tear resistance once damage has begun, and a tendency to become easily soiled, although this could be almost eliminated if wearers of prostheses would wash the gloves as frequently as normal hands are washed.

3.5 The more general aspects of cosmetics.

In an overall appraisal of the work on the development of cosmetic gloves it must be said that, until quite recently, surprisingly little effort has been made to arrive at even an approximation to the definition of a cosmetic covering for a prosthesis; which is that the cover must, as far as is compatible with mechanical requirements, approximate to the appearance, texture and gripping qualities of the normal skin covering of the hand. It would clearly be quite impossible to introduce such sophistications as the peculiar stress-strain relationship of normal

skin described by Ridge and Wright (1966) for example, but the works described above have provided some solutions to the problems of appearance.

The problems of texture and gripping quality are substantially different from those of appearance, although the reproduction of fine fingerprint details clearly must affect gripping to some extent, however small. Various workers have introduced soft spongy areas onto fingertips in prostheses, and rubber coverings for hooks, for example the Ontario Crippled Children's Centre (1969) used polyurethane foam, and Ralph and Bowden (1969) used highly plasticised epoxy resins. However, very little emphasis has been placed upon the necessity of achieving realistic texture in hand prostheses, and more important still, no emphasis has been placed upon the functional qualities of such texture, apart from the work of Simpson (1971). Simpson shows the functional importance of the pulp of the fingers and describes powder filled sacs which achieve an improved functional equivalent of the pulp. Development work with this system is described elsewhere in this thesis, but the point to be noted is that the cosmetic qualities of the cover for the hand prosthesis can and should be directly related to functional properties at all times.

Chapter 4.

Control - theoretical considerations.

- 4.1 The basic problem.
- 4.2 General solutions.
- 4.3 The variables.
- 4.4 Compatibility with the operator.
- 4.5 Control sites.
- 4.6 The significance of information feedback to the operator.
- 4.7 Normal human motor control systems dynamics.
- 4.8 The problems of the interpretation of body 'signals'.
- 4.9 Position awareness in the natural system.
- 4.10 The importance of designing for patient compatibility.

Chapter 4.Control - theoretical considerations.4.1 The basic problem.

The title of this section implies that the problem of control has been the subject of serious study in relation to prosthetics situations. Unfortunately, very little emphasis has been placed upon the importance of specific types of control, in the belief that the highly adaptable human system can be taught to control virtually anything by dint of a considerable amount of training. This may be true to some extent, but the point is that the patient has to live with his prosthesis, not control it. A point which has been made by Schmid (1965) emphasizes this for children in particular since he notes that a child's concentration time for one task is limited to a few minutes and therefore it is essential that controls must be simple and subconscious in order to permit play, etc.

4.2 General solutions.

The wide variety of control techniques which can be used for the control of externally powered prostheses must necessarily be based upon certain low force movements or other phenomena of the body, and the number of ways in which these effects can be harnessed is potentially as large as the number of systems man's ingenuity can devise, for example Waring et al (1965) list fourteen esoteric systems which can make use of refined body motions. In addition to those control systems which make use of the physical action of the body, there is the much renowned use of the body electrical systems, where it has been possible to detect and make (limited) use of the electric potentials associated with muscle

actions in control systems which are collectively known as electromyographically (emg) based systems. These systems have evoked so much interest and subsequent research that they will be considered separately from the physically based controls.

4.3 The variables.

The control of a prosthesis is concerned with a vectorial problem in time and space, and thus controls can be devised which affect the time of action t in the direction of $\underline{x}$, vectorial position $\underline{x}$, vectorial velocity $\dot{\underline{x}}$, acceleration $\ddot{\underline{x}}$, etc. These, or combinations of these, are fundamentally the only controls which are possible, and the optimisation of any prosthetic control system lies in the choice of variable control which is made. One further complication is possible, however, which concerns the use of one control site for the control of different vectors, this arrangement being referred to as a sequential mode of control. The selection of which particular control quantity to use has largely been a matter of engineering expediency, the theory being that visual monitoring of the behaviour of the prosthesis is an adequate check on the operation. McLaurin (1965) made extensive use of switch operation on this basis, whereas Marquardt and Hasfner (1956) used a system which fundamentally controlled the velocity of the prostheses.

4.4 Compatibility with the operator.

However, the operation of these systems required considerable mental effort and training, a fact which was not apparent in conventional limb systems, which certainly required physical effort, but less training and concentration. This point is made by McKenzie (1965) in his assessment of the qualities of conventional limbs when he states "all amputees know without looking how far

the hook is open within fairly fine limits and know how firmly they are grasping". The importance of the principle of an active physical feedback of information to the operator was realized by Simpson (1965), with the incorporation of a position servo control system. Simpson (1971) has since expanded the theory behind the use of position control more fully, showing that since this system is able to behave as an extension of the patient's proprioceptive system, then control of the prosthesis is merely an extension of normal activities, requiring virtually no special attention on the part of the operator. The point is also made elsewhere in this thesis that the information content available in a position control system is superior to that of the other types, thereby conveying considerably more movement parameters to the operator.

The essentially subconscious nature of arm control has also been referred to by Nichols (1965) who noted that a normal subject's consciousness is directed towards the position of the hand in space, rather than the position of the arm. Simpson's work has confirmed this to a considerable extent, since the success of the prosthesis fitted at Edinburgh is largely attributable to the subconscious control being achieved by the wearer of the prosthesis, thereby allowing the children to perform tasks and play in a substantially normal manner. The problem of matching prosthetic control systems to the operator requirements extends to hand control to an extent which is not quite as clearly defined as for the arm. Although position information is almost certainly fed back from the normal hand, the positional requirements are less demanding, becoming second to the need for gripping force information. However, neither

of these points has been the subject of any investigations, controversy only having arisen over the choice of a voluntary opening, or voluntary closing mode of action for terminal devices. This dichotomy has probably been over emphasised, since the change over from one to the other is easily made, some patients preferring voluntary opening because the maintenance of prehension is due to a spring action, thereby relieving the fatigue of continued grip, whereas other patients find voluntary closing more attractive since they can achieve a finer control in this way. A point which may have considerable significance, however, has been noted by Ritter and Sammons (1965) who found that young amputees learned the use of hooks more readily when the change from voluntary opening to voluntary closing was made. It is therefore felt that no hard and fast rules should be applied in this situation, the optimum technique being easily established in individual cases.

4.5 Control sites.

One further general problem which occurs with the control of prostheses, concerns the utilisation of available control sites. The problem arises with the application of multi-function prostheses, which require operation by many control sites, of which there is a strictly limited number satisfying the requirements for use in a position control system. Since each of the more comprehensive arm prostheses requires at least five independent controls, the provision of functional arms bilaterally demands a minimum of ten sites. This is practically impossible in cases of bilateral amelia, and there are different schools of thought concerning the way round the problem. Simpson (1971) has taken the unilateral approach, on the

basis that a unilateral amputee is capable of a majority of daily living tasks one active functional arm is fitted in conjunction with a passively mobile second arm which has active prehension. In this situation control sites from both sides of the body are used to control a prosthesis on one side of the body. This has proved to be quite successful, as have the conventional body-powered systems which have 'mixed' the controls, such as those described by McLaurin and Sammons (1963). However, other workers have made determined efforts to avoid such 'unphysiological' controls, Bottomley (1968) advocating bilaterally fitted functional arms each with limited functions. Pottinger and Ring (1968) hoped to overcome the problem by providing control 'locks' by which one control site could successively operate different functions, a system which detracts from all the merits of a low level of consciousness in control, since continuity and uniqueness of feedback information is completely lost at the changeover.

4.6 The significance of information feedback to the operator.

The importance of the feedback of additional information, apart from that acquired by the normal visual pathways, has been the subject of various studies, such as that of Battig (1954) who found that 'artificial' visual cues during training for a particular task considerably improved learning rates. In addition he found that the best results for learning a particular task were obtained with direct learning of the task itself, rather than with special training tasks. Similar results have been obtained by Lincoln (1956) with a task concerned with achieving a specific turning rate for a wheel, learning being more rapid and accurate with verbal cues

or displayed visual error information. Howland and Noble (1953) varied the physical characteristics of the controls in tracking tasks, altering spring rate, viscous damping and moment of inertia, and found that the best results were obtained with the controls which benefited from the augmentation of position information provided by the spring rate controls. Similarly, Weiss (1954) found that in tracking tasks where visual feedback was absent, the position factors in the force/displacement characteristics of the control gave the most useful information to the operator.

Although these experiments tend to confirm the necessity for active feedback of information, some conflicting evidence appears to be provided by Carruthers and Pottinger (1968) and Craske (1968). Carruthers and Pottinger carried out tracking task experiments with cutaneous feedback of position information, and failed to find a significant improvement in results. However, due to the unusual nature of the technique for displaying information, this result is not surprising. Since the human system is not designed to interpret positional information from skin vibrations, and the feedback signals are remote from the control input region, significant delays in information retrieval would occur, thereby reducing the effectiveness of the feedback. Craske's approach was based upon the introduction of visual feedback errors by means of viewing through prisms, noting the compensations made by the control systems to allow for errors induced in this way. He then makes the point that position awareness (non-visual) is then not sufficient to provide accurate motions on removal of the prisms, using this fact as an illustration of the inadequacies of the non-visual feedback.

pathways. The fact is quite true, but the interpretation is too extreme, since all the normal systems for updating the information stored in the human 'computer' are still active, the situation for controlling a prosthesis is exactly the same as for controlling a real arm, and therefore no unusual problems arise in the use of prostheses controlled on this basis.

However, the reasons behind the lack of success of Carruthers and Pottinger's experiments are extremely important, since delays introduced into a feedback system can, at best, nullify the advantages of feedback, and, at worst can have the negative result of causing confusion of the operator. Conklin (1957) found that feedback delays of 0.25 seconds caused a significant detrimental effect in a control task, Held et al (1966) finding similar descriptions with delays of 0.3 seconds. These delays are simple transfer delays, but the situation is further complicated by Rudd's (1970) findings that second order lags are also very significant in tracking tasks, thus showing that the problem of provision of feedback information to the human operator must be studied in some detail if successful results are to be achieved and the full potential of the active feedback of information is to be realised. The importance of accuracy in the time domain has been shown by the above workers, but there appears to be a less demanding situation in the position domain, since the control systems used in the working prosthesis developed at Edinburgh (Simpson 1965 and Simpson and Kenworthy 1973) are strictly of a rather low accuracy in position. However, this appears not to affect performance seriously, and therefore it may be that the human operator can more easily

accommodate consistent defects in position information than delays in the presentation of the information. The design of the feedback system used in these prostheses ensures that time delays are very small, since the control is directly linked to the movements being monitored.

4.7 Normal human motor control system dynamics.

The importance of active feedback of dynamic information to the operator of prostheses emphasises the extreme importance of an understanding of the requirements and capabilities of the human motor system for use in future improved designs. Research projects covering a variety of disciplines have provided information which is relevant to the design and control of powered prostheses, but it appears that little attention has been paid to considering such work in the light of prosthetics. However, it must be stated that, from a practical point of view, it is risky to try to follow the mechanisms of the body too far, since highly conflicting results occur when the internal control system in the normal human being is investigated, for example Stiles and Reandall (1967) lay emphasis on the fast response obtained with a second-order servo system, the characteristics of which they find similar to the results of experiments with hand tremor frequency; whereas Baits et al (1968) emphasise the force and slip control aspects of hand behaviour. Several modes of human control systems have been made on the basis of widely different sources of experimental data, Vodovnik (1971) making use of the re-learning which occurs during artificial electrical stimulation of muscle in drop-foot cases. On the basis of data obtained in the results with retention of such

learning after removal of the stimulation, Vodovnik used a logic model to form a model in which stimulation causes some resultant feedback to the brain, which can ultimately reinforce low level output motor signals to provide a newly active system. Tomovic (1960 and 1965) has considerably widened the field of possible mechanisms which may be postulated with the incorporation of the fact that the conventional minimum error feedback systems may not necessarily be applicable in biological situations. He also points out that the problem is in another way the reverse of the conventional since a few transducers and much processing are replaced by many transducers and less processing. However, although this may be true for the transducer aspect, there is no definite evidence to suggest that the processing mechanism is in any way simplified in human systems, since Craik (1947) and Navas and Stark (1968) have shown evidence to suggest the operation of intermittent control systems, whereas Gibbs (1954) is convinced of an active continuous error feedback control system. This disagreement in no way affects the practical utilisation of the end result of whatever the control system does, since both points of view indicate mechanisms which are fundamentally position servo in nature.

4.8 The problems of the interpretation of body 'signals'.

The differing mechanisms postulated above serve to illustrate the difficulties to be encountered in attempts to decode the infrastructure of human control systems. The problem is that we understand to a limited extent how a command signal can arise, and we know the end result, but of the processes in between we know virtually nothing. This is the root cause of the difficulties underlying eng control, since these systems take the body-coded

signals at an intermediate stage and hope to make some sort of sense from them in order to drive our conventional electronic systems. Tanner (1963) has pointed out the 'statistical' basis of regulation of biological processes which necessarily make use of large numbers of individual units, working in a more or less co-ordinated fashion. This means that the control signals for such processes are also organised in a highly complex fashion, which only the muscle, for example, can decode into the relatively simple message of motion of particular characteristics. The solution to these problems is quite simple, either intercept the message before it has been 'coded' or after it has been 'decoded'. The former of these solutions will require considerable instrumentation and planning to cater for various dynamic situations, and it seems logical therefore to adopt the second choice of making use of the advanced 'free' computer in the shape of the existing human system by applying the 'decoded' movements in the best way possible. This, together with the feedback of the maximum amount of information to the human system in a suitable fashion, makes the best possible use of the naturally available mechanisms with a minimal use of the fundamentally limited man-made information processing systems.

This approach to the control of prostheses is essentially simple, and removes the need for answering many of the esoteric questions concerning the intrinsic operation of the human machine, but introduces various other difficult problems in the form of establishing the best ways for providing the human system with an adequate supply of information.

4.9 Position awareness in the natural system.

Fortunately, much of the basic knowledge about the sort of

information which is used by the normal movement control systems has been available for some time. For example, Matthews (1933) put forward the idea of position awareness being derived from tendons and muscles, and although this has been found to be incorrect in detail, the concept of the importance of position awareness was appreciated. The existence of a definite built-in position awareness system was shown by Cleghorn and Darcus (1952) who tested the sensitivity to passive movement of the elbow, finding that the direction of motion could be sensed in as little as 1.8° of motion. Work by Boyd and Roberts (1953) confirmed the active nature of this feedback mechanism in cats with an emg analysis of the output of certain nerve fibres supplying the knee joint corresponding to different joint angles, finally tracking down the source of the impulses to groups of receptors located in the joint capsule. Cohen (1958) has studied the effects of internal position feedback mechanisms in the human, finding a high level of position accuracy to be possible in the absence of visual feedback paths. Cohen also 'blocked' different groups of possible receptors by stages until he established that the main receptors must be located in the joint capsule of the shoulder in this case. He did find that, in addition, skin receptors play some part in positional knowledge, a mechanism which is advocated by Moberg (1972) in relation to fingers in particular.

The practical success of fitting prostheses based upon this type of control system acts as further confirmation of the existence of this feedback mechanism. Operation of prostheses on this principle then presents further questions for the optimisation of

design characteristics relative to the control sites which are to be used as the interface for control matters. In particular, the dynamic properties of muscle present problems, since the behaviour of the control site is followed exactly by the prosthesis in a position servo controlled mechanism where use is made of the natural proprioceptive system by effectively extending it by a constant amount (Simpson 1971). Unfortunately, information about the dynamic properties of muscle is not generally readily quantified, although Hill (1939) has simply related maximum exerted force and velocity, a work which has later been confirmed by Wilkie (1950). Some work has also been recorded by Elftman (1966) showing a radical difference in the tension/length characteristics of muscle fibres with different speeds of contraction. It is felt that this type of characteristic relationship between force and velocity in muscle can play a distinct part in the behaviour of the prosthetic servo mechanism since the muscle action of the control site necessarily becomes part of the control loop, and some preliminary work is described in this thesis which may show the significance of such factors in prosthesis design.

4.11 The importance of designing for patient compatibility.

The work which has been reviewed above shows the importance of giving direct consideration to the requirements of the human operator and his body behaviour. In this way it has been possible to design systems which are simple and directly applicable to the human system, unlike the systems proposed by Johnson (1965) and Freedy et al (1967) who advocated automation of the control system itself, the latter group of workers making their choice of control

system on a mathematically derived minimum information content basis, ignoring the fact that although the operator does not have to put in much information, he does not get much out either! Similarly Kiessling (1965) suggested that proportional control was unnecessary since visual feedback is all that is required, ignoring the fact that visual attention is conscious and specific which would make the control of a prosthesis a task in itself, leaving a reduced level of attention available for the everyday tasks of living and manipulating the environment. It is therefore felt that the lesson to be learned from these studies is that a great deal of attention should be directed towards the requirements of the human system, particularly in an inward direction, that is to say, further studies of how information is acquired by the normal system will provide the necessary data for further augmentation of prosthetic devices by the addition of extra feedback pathways.

Chapter 5.

Practical control systems.

5.1 Introduction.

5.2 The utilisation of body movements as control sites.

5.3 Control valves.

5.4 Conclusions.

Chapter 5.Practical control systems.5.1 Introduction.

The various theoretical considerations mentioned previously have led workers to develop many different practical control systems, with varying degrees of success. Since the subject of myo-electric control has evoked such a considerable degree of development, this is reviewed as a topic independent of those systems to be covered here, which are largely concerned with the harnessing of body movements for control purposes.

5.2 The utilisation of body movements as control sites.

The direct use of body movements for powering prostheses automatically provides the ideal control situation, since the operator is making use of many feedback paths by virtue of his direct link with the prosthesis. The link between patient and prosthesis for powering a prosthesis has been achieved in two ways, firstly by strap-like harnessing of movements of mobile body segments, and secondly, by tying in to the muscle movements direct by means of the techniques of cineplasty, first introduced by Vanghetti (1906) and later improved by Sauerbruch (1916). The harnessing technique is not directly applicable to the control of powered prostheses, due to the small displacements required, whereas the cineplasty technique has received some attention as a control site for externally powered systems. The cineplasty technique involves the creation of a skin-lined tunnel through a muscle, thus allowing attachments to be made to a peg pushed through the tunnel.

Practical examples of this technique are illustrated by Platou (1923)

who powered a hand prosthesis and Kessler (1939) who used cineplasty connections in preference to strap harnessing for the powering of an arm system. However, due to the complications of operative techniques, discomfort in use, and various other problems, cineplasty has become a relatively rare method for powering prostheses.

Despite these disadvantages, some attention has been directed towards the use of the cineplasty as a control link between patient and prosthesis, Lyman (1965) recording the investigation of cineplasty sites, whereas Perry (1965) notes some of the disadvantages and proposes another operation for the enhancement of muscle movements by means of a surgically induced hernia by cutting the fascia around muscle.

The number of surgically introduced control sites could be quite considerable, but in all cases the result is unsightly, adding to existing disfigurement, the operative trauma and recovery time are significant, adjustment of incorrect sitings is virtually prohibited and a considerable degree of specialised hygiene is necessary. The use of such techniques has therefore been on a very minor scale, and consequently the majority of the practical work has been directed to the external harnessing of body movements.

In almost all situations concerning the control of prostheses, the number of control sites available is limited, and as a result some functions must be sacrificed in order to permit the use of a single site for a single movement. This has been found to be a desirable factor in the control of prostheses, and therefore some workers have introduced automatic facilities into the prosthesis in

order to overcome this problem to a certain extent. This approach has been made particularly in the development of multi-function hand prostheses, for example Rakic (1964), Salisbury and Colman (1967), Baits et al (1968) and Ring and Wellbourn (1968) have all introduced automatic gripping procedures within a prehension device, making use of slip detectors which provide the system with the information necessary to achieve a 'just holding' action. The danger with this type of automation is that the designer is tempted to overcome the inadequacies of his system by introducing more and more automatic procedures, each of which is decreasing the communication between patient and prosthesis. This problem is typified by the system envisaged by Freedy et al (1967) who, after making an incorrect choice of control principle from the human operator viewpoint, introduced a self-teaching control system which modified its characteristics as a result of errors previously experienced. Automation of this type rapidly becomes 'top-heavy' until the situation is reached where the patient is operating a machine rather than living with a prosthesis. However, limited amounts of automation are both useful and necessary in order to permit satisfactory function of a prosthesis, for example, McLaurin had successfully used linked motions in an arm prosthesis, as have the arms developed in Edinburgh and at the Medical Research Council Unit in Hendon.

The general practical problem, then, boils down to the choice of a control site and the development of the means by which the site activity can be harnessed. The problem of harnessing the movement of a control site is the one which has exercised the minds of the

developers, ranging from simple systems such as the muscle bulge techniques used by Kotzenberg (1920) for the operation of a hand prosthesis, the pneumatic bag linkage used by Wilms (1950), the Bowden cable introduced by Simpson (1965), and the hydraulic link used by Frank and Jaksic (1970), to the highly complicated intra-oral system stimulated by tongue movements used by Bontrager et al (1970). Waring et al (1965) list some fourteen systems for controlling electrical systems, but the variety must be as large as imagination permits, with Arp (1969) assessing fluidic control possibilities, Grunert (1968) using the variation of oscillator frequency by alteration of coil characteristics by the movement of a plate nearby, Hammond (1972) using capacitance loading of a tuned circuit in a similar manner and the team at John's Hopkins University (1972) using the effect of magnets on the conductivity of magnetically sensitive diodes. One electrical system which is of particular interest is that devised by Yamada et al (1969) since it incorporates important mechanical factors which are absent in most electrical control systems. Control of electric motors is achieved in this case by the compression of a liquid filled cell in which is situated a pressure sensitive resistor, the mechanical resistance allowing smooth, stable control of the motor without any oscillatory tendencies.

5.3 Control valves.

Because the majority of successful arm prostheses have been pneumatically (or hydraulically) powered, the most significant hardware developments have been concerned with the production of suitable valve systems for the control of the fluid power medium. In attempts

to satisfy control requirements in this field, a considerable variety of operating modes have been experimented with, providing many different operating characteristics which have led to a significantly varying degree of success in use.

The design of valves for the control of powered prostheses presents many specialised problems, the majority of which are related to the degree of miniaturisation which is demanded by the strict constraints imposed by the requirements of the appearance and shape of the prostheses. However, the basic forms of the valves are essentially the conventional poppet valve (aperture control), the force (or pressure) demand valve and the spool valve, all of which are well known in conventional systems. In addition, several departures have been made from these conventional systems, some being of particularly ingenious and interesting construction.

Consideration of the approaches made to valve design on conventional lines leads to some interesting facts, since a difference of opinion appears once more between those who favour the electrically based projects and the advocates of more simply based mechanical solutions to the problem. This division has taken the form of a choice between poppet valves and force demand valves, the electrical solution being to provide solenoid operation of poppet valves, whilst the 'mechanical' solution has been to make use of the inherent stability conferred to a system by force demand valves.

The spool valve has received relatively little attention largely because of the high frictional forces introduced by the large number of sliding seals and the relatively large movements required for operation. However, Kinnier Wilson (1965) has used balanced

spool valves with orthoses and Klasson (1967) experimented with spool valves before adopting force demand valves as his basic control. In addition the Department of Mechanical Engineering at Oxford University has experimented with electromagnetic spool valves and Broome and Lambert (1972) are at present using a spool valve in an hydraulically driven system. The problem with spool valves is largely due to the relatively large movements required to achieve adequate flow conditions, the valve of Broome and Lambert requiring 0.5mm movement for full flow in comparison with less than 0.1mm in well designed poppet and force demand valves.

The use of poppet valves in pneumatic control systems has proved to be something of a problem since these valves are by nature unstable. The majority of such valves rely on the opening of an aperture which is normally maintained closed by virtue of the pressure differential due to supply pressure acting across the sealing area, but problems arise when opening commences, since the closing force tends to reduce as output pressure rises, thereby allowing opening to proceed more readily and rapidly. For this reason, the majority of poppet valve systems have been concerned with electromagnetic operation when electrical 'correction' factors may be readily introduced. Therefore various electromagnetic valves have been made for use in pneumatically powered systems, Morton (1968) describing several types, Gavrilovic and Maric (1969) using solenoid operated valves in a type of position servo mechanism and Bousso and Ishai (1970) using electrically operated valves in an emg controlled pneumatically powered system. Johansson et al (1970) make the best use of poppet

valve characteristics by using the rapid turn-on to advantage in a pulse width modulated control of gas flow, even controlling stiffness by simultaneous driving of both sides of an actuator. This system has been used for the control of an elbow mechanism.

Attempts which have been made to utilise poppet valves directly in control systems cannot be considered as successful, since such severe stability problems have ensued. This difficulty is exemplified by the adoption of the poppet valve in the arm developed at the Medical Research Council Unit at Hendon (1970), which required the introduction of hydraulic damping to make control feasible. Such stability problems were also encountered in work with poppet valves described in this thesis, and led to the exclusive adoption of the force demand valves which were not significantly more complicated and conferred great stability on the system being controlled.

The force demand valve (fdv) has been extensively used in the control of prostheses since its introduction in 1965 following co-operation between Elliott Automation and Simpson in Edinburgh. Bottomley's (1966) SABU valve appeared later, and this, together with Klasson's (1967) version, was subsequently modified in Edinburgh (Kenworthy and Jolly 1973) to suit the specific requirements of the prostheses being developed. Klasson (1967 and 1970) has made particularly extensive use of the fdv, adapting it to many specialised tasks such as pressure regulators, etc. The valves used by Marquardt (1965) were fundamentally force demand valves used in a sequential fashion, although the design may appear at first sight to be a poppet valve, a feedback diaphragm acts in opposition to the operator, tending to turn off the flow at all times, which

explains the stability obtaining in all such systems.

The conventional valve systems described above have formed the mainstay of control systems in all successful pneumatic arm and hand prostheses, with one notable exception - the systems introduced by Kiessling (1961). The valves associated with Kiessling's piston actuators took the basic form of a spool valve, but with the major difference that adjacent ports were connected, not by the sliding of the spool, but by a lateral movement of the spool which caused a leak past the O-ring seal between inlet and outlet ports. These valves provide no force feedback, but stability was adequate because of the high return spring rate of the compressed and distorted O-ring seal. A later modification and more sophisticated version of this valve has been described by Lichtarowicz (1968).

Probably the most simple valve of all has been used by Engen and Spencer (1969) in the form of a direct constriction imposed upon a thin walled flexible tube. This type of valve, however, relies upon gross distortion of the tube and hence does not have the reliable characteristics which are essential for good servo-mechanisms in control systems. Cool (1970) with a typically simple, but ingenious, system has also made use of a tube in the basic form of the old type of bicycle valve which consisted of a flexible stretched tube covering the inlet port. Cool's valve consists of a coil spring maintaining the compression of such a tube over two holes in a metal rod, one hole being the inlet port, the other being the outlet. By effectively unwinding the coil spring by the action of a 'clothes peg', line pressure gas leaks under the slackened tube to the adjacent outlet port. Once again, this system provides

no active force feedback to the operator. Cool and Pistecky (1971) have also described another ingenious valve which is fundamentally a poppet valve, which is maintained closed by a tensioned wire. When an electric current is passed through the wire, the wire extends and thus allows line pressure to force the seal open, thus allowing flow to commence. In addition to these ingenious valves, Cool has also produced a very small force demand valve 'of non-conventional design', but unfortunately no details are available apart from the rather high price of £25.

Another valve system which has been investigated is the rolling diaphragm type. This system was investigated at the Royal Aircraft Establishment, Farnborough, and at Oxford University, but was found to be unsatisfactory in respect of leakage, which caused rejection of the system by the Medical Research Council team at Hendon (1970), despite various alternative sealing materials being tried by Ralph and Bowden (1969).

5.4 Conclusions.

The conclusion to the review of practical control systems is rather discouraging, since it is clear that a totally inadequate amount of attention has been paid to this problem. This phenomenon is probably the result of a tendency which prevails in all circumstances where patient fitting is required urgently; hardware is produced first, and the control system is added later, usually too hastily. It is felt, therefore, that considerations of control details should be the initial design factor, upon which the rest of the mechanisms are based.

Chapter 6.

The use of muscle electric potentials for control.

- 6.1 Historical background.
- 6.2 The 'pros' and 'cons' of emg control.
- 6.3 The electrodes.
- 6.4 Signal processing.
- 6.5 Emg control applied to non-electrical systems.
- 6.6 Conclusions.

Chapter 6.The use of muscle electric potentials for control.6.1 Historical background.

Knowledge of the association of muscular activity with electricity is long-standing, going back to the classical experiments of Galvani (1737-98) with the electrical stimulation of frog's legs. By 1951 experimental work had become so sophisticated that Merton (1951) was investigating the relationship between electrical stimulation and the recorded electromyograph (emg) signals indicative of muscular activity, in an attempt to gain an insight into normal muscle control. In the following year Berger and Huppert (1952) introduced the possibility of using emg signals as a source of control information for prostheses, by considerations of the results obtained using copper electrodes and electrocardiograph jelly to pick up the signals, and this work heralded the most publicised and misguided development in the history of powered prosthetics work, the use of electrical signals for the control of prostheses seemingly providing the electronic age with the answer to all its prosthetic problems. On reflection, it seems almost incredible that such a variable and apparently haphazard phenomenon should have been assessed as a possible control site. Some of the immediate problems were well summarised by Wagnan and Pierce (1965) who, in an assessment of the possibilities of emg signals make the points that artefacts occur due to electrode placement relative to muscle fibres, dispersion effects occur through the muscle, the shape of the electrodes affect the signals, some muscle fibres have slower responses than others, 'adjacent' motor unit signals interfere with one another, and from all this a coherent 'message' is to be

deciphered! However, work by Basmajian (1963) showed that individual motor unit control could be achieved with training, and Moore (1965) was able to use single neuron action to control an artificial breathing system for an anaesthetised cat. Work of this nature tended to help the converted to justify their choice of control signal, although practical work had already commenced in 1955 with the system of Battye, Nightingale and Whillis (1955) which used the average level of the emg signal to operate a switch controlling a pneumatically powered system.

6.2 The 'pros' and 'cons' of emg control.

In a review of emg controlled systems Scott (1966) gives reasons for this choice of control which have seemed convincing to many other workers in this field, namely that the use of myo-electric signals is 'more direct' and less subject to external influences. This type of argument has been put forward by many other workers, such as Voskoboinikova and Slavutsky (1967), who were associated with the development of the Russian emg controlled hand, and state concerning myo-electric control "It is the most functional, as it is nearest to the natural method of controlling a health limb". All workers who have been directly concerned with the fitting of emg controlled prostheses and have described the circumstances of the fittings, have laid considerable emphasis upon the necessity for extensive training programmes in the use of emg control. This fact alone shows that emg control is neither easy nor natural, a point which is clarified by Radonjic and Long (1970) who, as a result of considerable experience with emg systems, concluded that they were based on, at best, very shaky foundations. They attribute the

difficulties to the fact that the normal system is based, not on muscle control, but movement control in which, according to a pattern for each movement, various muscles participate. The relationship of muscles to particular movement patterns is specific, since tendon transfer experiments showed that the re-training of a muscle into a new function was very difficult. In addition Radonjic and Long point out that there is no definite relationship between muscle tension (upon which the emg signal depends) and muscle position (which is required for the execution of skilled movements). The conclusion is, therefore, that emg control lacks any significant degree of proprioceptive feedback to the patient, thereby making learning a difficult, conscious task requiring a considerable learning time before good control is even remotely possible.

In addition to the above general drawbacks to the emg control system, some workers have questioned the specific applicability of emg control to cases of congenital abnormalities. Ladd and Sumard (1969) found that, compared with 90 per cent of normal children, only 25 per cent of congenitally malformed children could achieve successful control of single motor units. Childress and Billock (1970) also query the potential of the emg system in this situation, pointing out that there is no 'phantom limb' sensation to aid training.

Despite, or perhaps being unaware of, these drawbacks, a very large number of researchers have invested considerable effort and expense in the development of some extremely sophisticated electronic systems, and it remains to review the various approaches which have been made to the problem.

6.3 The electrodes.

The necessary starting point for any emg work is the pick-up of the signals, and this has been achieved in several ways, the simplest of which involves the placement of electrodes on the skin surface over the muscle whose activity is being monitored. In an assessment of the requirements of such electrodes Greatbatch (1965) shows that a great deal of random variation in signal with, say, a silver electrode is attributable to the impossibility for the reaching of an equilibrium potential since there are no silver ions in the body. This problem is overcome by using a silver-silver chloride electrode, when saline can be used to form a good body contact and thus a stable electrode becomes possible. However, by contrast, Scott (1967 and 1965) prefers to use implanted electrodes (transmitting information by telemetry) due to fewer cross-talk problems, or percutaneous electrodes from which the pulse-repetition rate is used to control a prosthesis. Kedefors (1970) also used implanted electrodes, as do Herberts and Petersen (1970) who transmit the signals by frequency modulation of an implanted oscillator. Even the use of implanted electrodes is fraught with problems, however, since Pollak (1971) has shown that radically different signals may be produced from the same source by the use of different types of electrode.

6.4 Signal processing.

The interpretation of the emg signals has always been difficult and has been made in various ways, the earliest of which (Battye et al 1955) has been mentioned previously. This was followed in 1960 by the celebrated 'Russian' hand (Kobriniski 1960) which used the emg

signal level to operate level sensitive switches controlling the hand. Similar level discriminatory systems have been used by Skachkov (1967) who incorporated pressure feedback to the operator by vibratory stimulation of the skin, Scott (1967) who achieved 3-state control of a hook, Beeker et al (1967) who level discriminated 4 signals to give pulse control of solenoid operated pneumatic valves, Childress and Billock (1970) who, from simple electrodes built into the stump socket, provided 3-level control for a prosthesis, Dillner and Hagg (1971) who describe three ways of gaining several outputs from one site, and Bousso and Ishai (1971) who used 2 level signals for on/off control of pneumatic valves in an arm prosthesis.

A greater degree of reliability and sophistication was introduced by Bottomley and Cowell (1964), with the incorporation of a 'backlash' facility in the control circuitry. This was a measure taken to overcome the random variations of the emg signal and effectively meant that the switching level was in fact a band of a width dependent on muscle tension (amplitude of emg signal). In this way a considerable degree of smoothing could be achieved, since the band width could be adjusted so that random fluctuations of the emg signal would not initiate inadvertent switching. This type of system was adopted by Suzuki and Suenatsu (1969) in a hand control system which also incorporated a velocity feedback facility within the control system. The training technique utilised by Suzuki (1966) is of interest since he made use of a visual analog display of emg levels in order to accustom the user to this type of control.

The technique of internal velocity feedback used by Suzuki as mentioned above is typical of many emg control systems which make use of various forms of internal feedback in an attempt to improve control properties. Alter (1965) introduced velocity control by emg, and Bottomley (1967) incorporated force feedback for strain gauges together with velocity feedback for the motor, a technique which was adopted by Fyson et al (1969) in the Aldermaston device. This type of system uses the emg signal to create a drive error signal derived from the difference between emg and the feedback information, but the use of the emg signal is really somewhat incidental, since any electrical signal would serve. The system used by Mann (1968) for control of the Boston elbow is one of the few which incorporates any form of active mechanical feedback of information to the operator. Whereas velocity and force feedback is arranged within the electronics package, position information is actively displayed to the user by the variation of the position of a phantom sensation created by two vibrators stimulating the skin. As an illustration of the variety of techniques available for use in emg control systems, Henninger's (1970) use of pulse width modulation in achieving force control is a useful example, and by contrast, Sullivan and Martell's (1964) use of torso emg signals in servo control systems shows the wide variety of available signal sites.

Emg control has also been used in so called position servo control systems, which are achieved once again by internal feedback within the control packages. Hall and Lambert (1968) found that the signal to noise ratio of their system was unsatisfactory and

prohibited the successful use of the controls. Seamone and Hoshall (1970) have also used this type of feedback in an electrically driven version of the APRL hand, but make no attempt to provide active feedback of information.

There is virtually no end to the degree of sophistication possible with electronic systems, and since the recognition by Bottomley (1965) of the possibilities for the use of spatial emg patterns, there have been various advanced uses of many control sites simultaneously assessed. Finley (1965) used a computer to analyse the normal emg output of pronation/supination and elbow flexion in an attempt to relate patterns of emg activity to standard movements, in the hope that a prosthesis might be controlled by recognition of a suitable pattern on an amputee. Similarly Morecki et al (1967) hoped to use recorded emg signals from a normal functional arm to control an artificial arm or one with motor control defects. Wirta and Taylor (1970) have described a control system which uses ten sites, each weighted according to data obtained from the normal human operator, although the applicability of control information from one individual to control by another individual seems highly unlikely, some ease of control is reported.

The advantage of these multi-site control systems lies in the removal of the effects of random signal fluctuations, since it is unlikely that all sites will vary in the same way, at random. However, another possibility is the use of correlation techniques which tend to reinforce regular events and hence diminish the effects of random occurrences. Schmidt (1971) claims to be able to isolate the firing of single motor units in this way, which may

help to overcome the problems of cross-talk and interference which are encountered in normal systems.

6.5 Emg control applied to non-electrical systems.

In concluding the review of the work with emg controlled systems it should be pointed out that such control is not confined to the use of electrical power. During and van Miltenberg (1967) have used pulse control of a solenoid operated valve to control pneumatic systems, and Bousso and Ishai (1971) and Ho, Kwe and Bache (1969) have also used solenoid operated pneumatic valves in various ways associated with emg control.

6.6 Conclusions.

As an overall assessment of the use of emg control it must be said that it is really very poor, for the reasons which have been summarised by Radonjic and Long (1970). It is unfortunate that the existence of myo-electric potentials has led so many workers up a blind alley, where the effects of so much sophisticated electronics are completely limited by the lack of comprehensible information in the original control signal. Many of the complex systems outlined above could be driven equally well from a microswitch activated by muscle action, with the same results. Even then, the fact remains that any amount of proprioceptive information can be fed into the electronic computer, but if none of that information is physically available to the operator, he will be unable to control the prosthesis with the ease which is the fundamental requirement of any prosthetics control system. The problem is a common one in all computer systems - if the programme cannot incorporate all the possible situations which may arise, then the computer is beaten

when presented with the unusual. The solution to this problem in the case of prostheses should be to present the available information to the human computer, which is highly adaptable, can perform predictor tasks, etc., and allow the natural computer system to take all problems as they come, since it is far better suited to this type of work than any artificial intelligence is likely to be for many years to come.

Chapter 7.

The effects of the drug thalidomide.

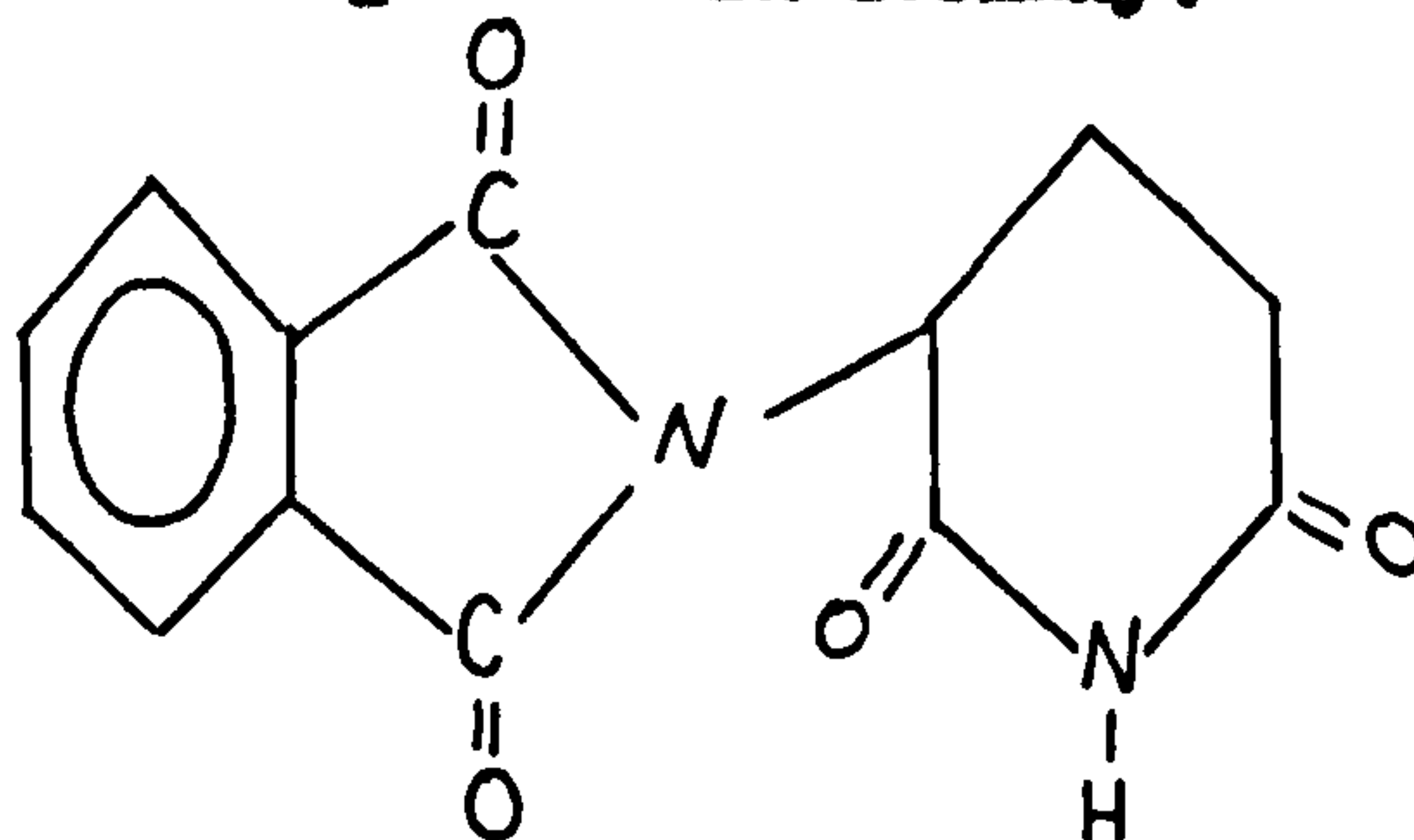
- 7.1 Historical background.
- 7.2 The effects.
- 7.3 The fitting of prostheses.
- 7.4 The problem of objective evaluation.
- 7.5 Design data for prostheses.
- 7.6 The 'self-adaptive' design philosophy.

Chapter 7.The effects of the drug thalidomide.7.1 The historical background.

The disastrous effects resulting from the taking of the sedative drug thalidomide by mothers during pregnancy are by now well known, and have been the cause of much public heart-searching and controversy.

The bibliography of work concerning the mechanisms of the effects of the drug is extensive, for example consider the list of references made in Swinyard (1969). This type of work does not directly concern the problem of the provision of prostheses for children affected as a result of the drug, and the review here will be confined to a history of the appreciations of the problems facing the deformed children and the relationships between these problems and the fitting of prostheses.

The drug thalidomide, whose structure is given below, was marketed under various trade names, such as 'Contergan', 'Distaval', 'Quieton', etc. and originated in Germany.



According to Taussig (1962) the drug was initially available without prescription until it was found to induce polyneuritis; tingling of the hands, sensory disturbances and atrophy of the thumbs. The drug was available in Germany from late 1958 until it

was withdrawn late in 1961, as the increased proportion of malformed babies came to be related to the use of the drug. Thalidomide was marketed in the U.K. by the Distillers Co. Ltd. and was withdrawn at the end of 1961 (Hayman 1961) following reports from overseas which associated thalidomide with harmful effects on the foetus.

It is perhaps surprising that the association of an increased incidence of malformation of babies with the use of a drug should have taken so long to be made, McBride (1961) reporting a 20 per cent incidence of malformation in babies from thalidomide-taking mothers as opposed to a normal 1.5 per cent incidence rate, and Wiedemann and Aeissen (1961) reporting similar effects as late as 1961. However, the widely varying nature of the deformities, together with the dispersion of the population and the subsequent realisation that the effects of the drug are associated with a specific period during pregnancy, may account for the delay in noticing these effects. Even experiments with animals were not consistent, Taussig (1962) records that the drug did not induce sleep in some animals, whereas Rodin et al (1962) quote some experimental proof of the effects of the drug. However, during 1962, evidence accumulated that the malformations were associated with thalidomide, Speirs (1962) finding that eight from ten malformations occurred with mothers who had taken thalidomide. He also checked for incidence of rubella and other diseases, nutrition and radiation, but the spread of the pregnancies tended to discount these causes. It was also appreciated at this stage that malformations were associated with a specific phase of foetal development, McBride (1961) having noted that the

malformations tended to be associated with structures developed from mesenchyme (i.e. bones and musculature of the gut) and Woollam (1962) noting that the timing of the use of the drug during the morning sickness phase coincides with the period of greatest mitotic activity in foetal development. On reflection, it is easy to look at the work of Warkay and Takacs (1959) and Kalter and Warkay (1961) with the effects of salicylates and Vitamin A during pregnancy, and say "why did no one check?" However, this sort of recriminative speculation is not constructive except as a reminder to avoid the recurrence of similar events, the most important fact being the rehabilitation of those children affected as a result of the use of the drug; the numbers are quite considerable, there being 3000 survivors in Germany and 340 in Britain alone.

7.2 The effects.

The malformations are considerably varied and complicate each individual case in a specific manner. Gillis (1962) records haemangiomata on the forehead or face, depressed bridge of the nose, coloboma affecting one or both eyes, phocomelia of varying extent as the most common limb deformity, cardiovascular defects and defects of the urogenital system or intestinal tract. Lenz (1962) records similar defects: amelia, atypical phocomelia, aplasia of the radius, leg defects, absence of the auricles, haemangiomata of nose and upper lip, atresia of the oesophagus, duodenum or anus, cardiac anomalies, aplasia of the gall-bladder and appendix. In view of this disastrous list of abnormalities it is surprising that such a high survival rate has been possible amongst the thalidomide children, and this has given a considerable impetus to the development

of powered artificial limbs, since most conventional prostheses have been inapplicable to the thalidomide problem. There is little to be gained from a detailed analysis of thalidomide anatomy, since this is peculiar to the individual, it suffices to say that most of the amelic group possess substantially normal clavicle movements and most of the phocomelic group have sufficient mobility and strength in their digits to manipulate controls. Beyond this, it is essential to fit the harnessing and control of prostheses to each individual, and any prosthesis must be developed with this fact in mind.

7.3 The fitting of prostheses.

The problems involved with the fitting of prostheses to congenital amputees are somewhat different from those of the traumatic amputee, and are in some respects easier to solve, whilst others prove to be more difficult. In one respect, at least, the congenital amputee has an advantage - he has not lost an arm, he merely has to learn to live in a world designed for people with arms. The traumatic amputee, however, has to completely revise his whole way of life which can often prove to be prohibitively difficult. These points make one fact quite clear, that early fitting of prostheses to congenital amputees is essential for their future development. This point is made by Aitken (1964) who adds that the motivation of feeding can prove to be of considerable assistance in the training of children in the use of prostheses. This early fitting is important in the development of the 'body image' referred to by Kenedi (1969), and in particular of the dynamic aspects of the body image as conferred by a prosthesis.

Kenedi's emphasis on training the body up to a standard to meet the prosthesis half way, as it were, is a debatable point, however, since the need for training implies that the control task is not easy, and it should be achieved at a subconscious level if everyday tasks are to be achieved (Simpson 1970). Another important aspect in the fitting of prostheses generally is made clear by the results of a survey carried out by Lambert and Sciora (1959) which concluded that the poor functional capabilities of cosmetic hands caused the high rejection rate recorded. The psychology of rejection of prostheses is extremely complex, the real reasons for rejection often being obscured by superficial factors, and for this reason experiments with new prostheses must be very carefully scrutinised, and the new devices on trial should have some obvious functional benefits for the patient in order to give him an incentive to try a new prosthesis for a period which is sufficient to provide a useful assessment.

7.4 The problem of objective evaluation.

The problem of obtaining an accurate report about the success of a prosthesis is a very real one, since results obtained in a clinic are often loaded in favour of the prosthetist. This fact has been recognised by workers at the Rehabilitation Institute of Montreal who have, in their thalidomide programme, made a special point of assessment in the home, by therapists, and, where possible, obtaining information from parents and friends about the use of the prostheses. The thalidomide problems are complicated, however, by the psychological involvement of the parents, often in the form of a feeling of guilt. This phenomenon is noted by Gillis (1962)

who finds that the children adapt fairly well to prostheses, but finds the parental acceptance to be more of a problem.

The fitting of prostheses, then, is a complex task, not only involving the provision of hardware, but also a considerable amount of careful planning in the fitting programme itself. This latter aspect of prosthetics work has been found to be the vital key in successful fitting of powered prostheses, (Simpson and Kenworthy 1973), with the back-up service being an integral part of the fitting programme.

7.5 Design data for prostheses.

The problem of the provision of powered prostheses has inspired many workers to investigate in some detail the functional capabilities of the normal systems. The necessity for such work is questionable, however, and the correct utilisation of the results obtained is almost impossible, since no-one can know the functional requirements of a prosthesis before it is in existence! Clearly, some design data are required, but these can be set almost arbitrarily, provided that they bear some relationship to the normal requirements, there is no need for a statistically based survey which, after all, can only cater for the rare 'average' individual. Even after considering 180 selected tasks McWilliam (1967) feels that rigid requirements should not be set, since individual patients will use different patterns of motion, concluding that experimentation with prostheses will provide the best solution. Design criteria of this somewhat arbitrary nature, based roughly on anatomical and daily lifting requirements formed the foundations for the arm developed in Edinburgh (Simpson and Kenworthy 1973)

which was then able to enter a type of self-modifying continuous development which ultimately resulted in the optimisation of the functional requirements according to the demands of the operators.

The dangers which can arise from the interpretation of 'normal' operational data are well illustrated by the effects of the work of Keller et al (1947). On the basis of results obtained from observations of normal activities it was concluded that the majority of prehension activities of the hand occurred in the pincer grip mode, which led to the development of the APRL hand prosthesis, which has dominated the hand prosthesis scene for 25 years. Another case of data which should not be applied in advance to an unknown quantity such as powered prostheses, is given by Paul and Mann's (1962) assessment of power requirements, which, being based on 'maximum effort' data, gave power requirements of an order of magnitude in excess of the power used satisfactorily in practical prostheses.

Concerning the range of motion of the joints in the normal upper limb, there have been a multitude of publications related to ranges of joint movement and their use in assessment of disabilities which is quite valid in that context. There is therefore no necessity for a detailed investigation to establish the same requirements for a prosthesis, and anyway, an adequate indication can be given by asking any passer-by to perform a few simple movements.

Various complex projects have been carried out in an attempt to establish definite 'patterns of movement', in a manner similar to the prehension pattern theories described elsewhere in this thesis.

Furnee (1967) and Murphy et al (1967) have used television cameras linked to computers, Engen and Ottnat (1967) have used complex photographic analyses, Marsolais (1966) has made a computer analysis of cine X-ray film, and Wijnshenk (1967) has even derived complex differential equations for arm motions in an attempt to achieve computer control of an artificial arm.

7.6 The 'self-adaptive' design philosophy.

The inapplicability of such data to individuals is quite clear, particularly in the case of congenital deformities, and the task of the developer of powered arm prostheses is therefore to provide a device which does not have fixed operational characteristics, and is capable of being operated as an extension of the patient himself, so that natural prehension can develop with the prosthesis, subject to practical balances being attained between strength and weight, speed and lifting power, etc. In successfully fitting prostheses to active children the first criterion must be robustness and reliability, a point which has been made by Smithells (1965) in a less complex context:

"As soon as you fit children with any sort of elbow flexor, the limb below the elbow is immediately used as a hammer and it must be robust as well as being light and free from trouble".

Chapter 8.

Tactile feedback.

- 8.1 The importance of tactile feedback.
- 8.2 Previous studies of the tactile sense.
- 8.3 The response to vibratory stimulation.
- 8.4 The mechanical aspects of skin vibration.
- 8.5 The receptors for tactile information.
- 8.6 Theories of touch perception.
- 8.7 Summary of the practical implications of the background work.
- 8.8 Practical applications of vibratory stimulation.
- 8.9 Alternatives to vibratory stimulation.
- 8.10 The prospects for future development.

Chapter 8.Tactile feedback.8.1 The importance of tactile feedback.

The importance of tactile feedback in the normal human system is to a large extent underestimated by the majority of people and it is only when this facility is lost through disease or amputation that the useful nature of the touch response becomes evident.

It is therefore of considerable importance to assess the possibilities for the introduction of a degree of tactile feedback into prostheses, since this feature would considerably augment the control and precise use of such a device. Indeed, the requirement for tactile feedback is so great that surgical restorations or modifications are attempted wherever possible in order to provide an element of function with the benefit of natural tactile feedback. One example of this approach is the unsightly, but functional, Krukenberg operation.

However, such arrangements are not always suitable and an alternative procedure has been used by Kuhn (1971) whereby a hook prosthesis can be turned aside on a hinge, exposing the stump with its normal fleshy covering and associated touch responses.

This direct use of the natural systems available cannot be applied to more severe levels of amputation and it is therefore necessary to consider the touch response with a view to extending the tactile sense from one part of the body to the end of an arm prosthesis.

8.2 Previous studies of the tactile sense.

Unfortunately, no directly relevant information is available, the majority of previous work being in the form of psychological studies or investigations intended for the utilisation of the skin as a medium of communication (Geldard 1960, Hahn 1968, and Hawkes 1962). However, much of the basic work from such sources is useful, albeit fraught with many contradictory items such as that provided by Elithorn et al (1953) who note fundamental errors such as mistakes in the perception of which finger is being touched, whereas Zubek et al (1964) note that marked improvement in cutaneous sensitivity follows within one week of blindfolding a subject. Thus, on the one hand we clearly have a system with faults, whilst on the other hand it is flexible enough to adapt to new circumstances.

8.3 The response to vibratory stimulation.

The greater part of the experimental work which has been carried out on the tactile response, has been concerned with the reaction to vibratory stimulation, since it is well known that the skin adapts rapidly to permanent deformations, a response only being elicited during the changing phase and for a short period thereafter. Vibratory stimulation is not 'adapted out' in this way, although Wedell and Cummings (1938) reported that the sensitivity to vibration was reduced after prolonged stimulation, the loss being greater at greater frequencies. Furthermore the effect of prolonged stimulation at one frequency was to reduce sensitivity at the higher frequencies to a greater extent than at lower frequencies.

These reductions in sensitivity are not sufficient to preclude the effective use of vibratory stimulation and there has been a considerable variety of investigations into the effects of vibration on the skin, the majority being concerned with the effects of amplitude and frequency upon the threshold of perception. Thus Knudsen (1928), Bellows (1936), Stevens (1959), Werner and Mountcastle (1965), Talbot et al (1968), Janig et al (1968), Verrillo (1970) etc. variously showed that the threshold of sensitivity S is related to the amplitude of stimulation A by the relationship $S = kA^n$ where n is less than unity and varies with frequency, being larger at low frequencies and smaller at high frequencies e.g. $n = 0.95$ at 60 Hz, $n = 0.83$ at 120 Hz. There are different peculiarities noted by different workers, for example Stevens (1959) notes that the power law applies to the fingertip, but not on the arm; Werner and Mountcastle (1965) note that some six distinct levels of amplitude can be discriminated; Talbot et al (1968) found that the skin receptors produced pulses at frequencies greater than that of the stimulus frequency; the results of Janig et al (1968) were obtained with the foot pads of cats; whereas Verrillo (1970) was able to show that the experimental method of subjective assessment of intensity in human subjects on a scale of 1-10 gave results comparable with those of matching tests.

Similarly Mowbray and Gebhard (1957) investigated the perception of changes in frequency at different frequencies, finding $\Delta f/f = 0.05$ in the 1 - 320 Hz range, whereas Goff (1967) corrected for the subjective variations of intensity with frequency and found that, above 200 Hz, considerably greater frequency

changes were required before they could be perceived; and in addition, that Δf was smaller for greater intensities.

Information more directly relevant to the mechanics of stimulator design is provided by Sherrick (1953) who notes no difference between tangential and normal stimulation, together with the fact that there is a maximum subjective stimulus at approximately 200 Hz, which is attributed to a resonance of the tissues of the skin and underlying structures. Similarly Verrillo (1965) found no difference between inwardly and outwardly directed stimuli, also suggesting that the response depends upon tissue velocity rather than absolute amplitude. Verrillo (1966) also finds that the threshold decreases directly as the protrusion of the stimulator into the skin increases and that threshold is inversely proportional to contact area.

8.4 The mechanical aspects of skin vibration.

The mechanism of the tactile perception of vibration appears to be provided by a combination of the peculiar resonance and dispersive properties of the mechanical system composed of skin and underlying tissue, together with the response characteristics of different receptor bodies in the skin. The importance of the skin and underlying tissue was illustrated by Weitz (1939) who altered the mechanical properties by anaesthetising underlying tissues and noting the alterations in subjective response, confirmation being provided by the modelling techniques of von Gierke et al (1952) who, following measurement of the complex mechanical impedance of thigh tissue, were able to derive a mathematical model based upon an elastic, compressible, viscous material which agreed

satisfactorily with experimental evidence.

8.5 The receptors for tactile information.

The analysis of the various types of receptor is still the subject of some disagreement, although Lindblom (1965 and 1970) advocates three main types of receptor which he refers to as Intracutaneous (IC), Pacinian corpuscles (PC) and touch pads (TP) in hairy skin. To the IC group is attributed a rate of velocity sensitivity, being active for tissue velocities 0.5 - 50 mm/sec with following of repetitive stimulation ceasing before 200 Hz. The PC group is regarded as being sensitive to deep reflections from bone etc. The work of Janig et al (1968) with the effects noted in cats' feet adds to the confusion by attributing all responses to the PC group only, whereas Iggo and Muir (1969) find the response of Merkels disc (surface) type receptors respond in a linear fashion to the amplitude and velocity of the stimulus. Rogers (1970) notes the high sensitivity of PC at 200 Hz, but compares this with a very poor localisation ability at frequencies above 40 Hz, although in practice pattern recognition ability improved with frequency.

Thus it can be seen that the understanding of tactile responses is far from complete, and that, in practical terms, there is available only a small amount of immediately useful information and this comprises data concerning contact area, the amplitude of the stimulus and to some extent an indication that the frequency of the vibratory stimulus can be optimised.

8.6 Theories of touch perception.

The formulation of theories to encompass the various data

outlined above has necessarily been somewhat vague, but has generally taken the form of advocating the principle of the natural system making an analysis of the responses of many receptors, which, of course, respond locally in different fashions to a stimulus dispersed via the type of mechanical model postulated by von Gierke et al (1952). Thus Gibson (1966) regards the senses as responses to an appreciation of an overall 'picture' from all receptors, whilst Quilliam (1971) is slightly more specific in postulating that a variety of similar receptors with different sensitivities will all be stimulated close to the stimulus, but those more remote will respond according to the level of the stimulus in their own area following dispersion, thus permitting the dominant feature of the stimulus to be 'weeded out' from the general background level of stimulation. Similarly Talbot (1968) found that the pulse rate of receptors was frequently greater than that of the stimulus, and he proposes that the response is linearised over many receptors, with frequency discrimination possibly occurring by an appreciation of the dominant period between pulses rather than by a frequency measurement.

The simultaneous analysis of many receptors would appear to be necessary in order to explain the fact that the fingers can resolve roughnesses which have a characteristic spacing of less than the average distance between touch receptors in the skin, a problem which also arises in the performance of the eye. In the case of the eye Findlay (1973) has proposed a solution which uses the concept of sensory channels, introducing an element of order into the organisation of the many receptors and it is felt that this may

be applicable to the tactile sense.

The work of von Bekesy (1955, 1957, 1958 and 1962) also appears to indicate the existence of a form of correlation of responses over a number of receptors, since the skin responds to 'stereophonic' effects, with the apparent position of a stimulus being variable according to the stimuli applied at one or more sites. In addition, the work of Verrillo (1965) in satisfactorily applying the Zwislocki (1960) theory of temporal auditory summation to tactile responses, shows that the system certainly operates on a basis which is outside the effects of probability alone by showing evidence that a summation process explains the experimental results with the perception of the tactile equivalent of closely spaced 'clicks'.

8.7 Summary of the practical implications of the background work.

In conclusion it may be said that there is little information available concerning the way in which an artificial extension of touch may be made, particularly when one looks for an indication of the way in which stimulation could be 'matched' to suit the requirements of the skin. However, should all further experiments fail to produce such an indication, it may be that the 'sensory plasticity' of Bach Y Rita (1967) may save the day by allowing the natural system to modify itself to suit the inadequacies of any artificial tactile extension.

8.8 Practical applications of vibratory stimulation.

The application of vibratory stimulation in practical situations has been of an essential analogue nature, with the tactile sense being used as the medium for the transfer of non-tactile information.

Thus, Lindner (1937) used electromechanical vibrators for

teaching deaf-mutes to communicate using filtered speech with the high and low frequency components remaining. Similarly the work of Geldard and Sherrick (1965) with the subjective effects of variable locus patterns on many vibrators together with that of Bliss and Crane (1966) and Bliss et al (1970), using air jets and piezo electric mechanical stimulators in a matrix on the skin, has shown that the transfer of 'pictures' via the skin is a feasible proposition. This is confirmed by Bach y Rita (1969) who showed that pictures from a television camera could be transferred in a similar fashion, and reported that the patients began to 'see' the picture rather than 'feel' the vibrators after continued use.

Another analogue application has been the use of the skin as a medium for the feedback of information from prostheses, and in this application the results have also been significant. Carruthers and Pottinger (1968) used several vibrators to indicate tracking responses, finding that, in the absence of an alternative, the vibratory feedback was useful, but not to a marked extent. A similar system has been employed by Mann (1968) and Mann and Reimers (1970) with the position feedback system in the Boston elbow, and here successful results in position awareness tests are indicated.

The skin has also been used as the medium for the feedback of force information, with Skachkov (1967) relating pulse duration to hand grip pressure, whilst Yamada et al (1969) have altered the pressure on the skin in relation to motor torque in an electrically powered hand. Also, Engelhardt and Quenzer (1972) achieved force feedback by ranging the pulse repetition rate from 0.6 - 30 Hz, using 200 Hz pulses, whilst Hill (1972) proposes complex feedback

systems using air jets and piezo-electric bimorphs linked to a computer.

Thus, it can be seen from this brief review, that the use of the skin has been limited to the transfer of non-tactile information, and very little attention has been paid to assessments of the possibilities for the extension of the tactile sense itself. In order to be able to pursue this aspect of development adequately, more information is required concerning the way in which the tactile discrimination of objects is achieved, and hence some guide as to the ways in which remotely acquired tactile information can be presented to the skin.

8.9 Alternatives to vibratory stimulation.

An additional condition imposed upon touch systems for prostheses is that of the power required to drive the vibratory stimulators, which are necessarily damped by the skin itself. Furthermore, information transfer is affected by the variable nature of the contact between skin and stimulator during all but the most static of conditions, and it is factors such as these which have led various workers to look at electrical stimulation as an alternative.

The chief difficulty with electrical stimulation of the skin lies in the fact that the band of stimulation level between the detection threshold and the pain threshold is narrow and variable, and it is therefore of considerable importance to introduce suitable safeguards into the system. Nevertheless Hawkes (1960 and 1962) advocated electrical stimulation for aerospace applications on the basis of its greater compactness in comparison with vibratory

stimulation. However, a drawback appeared to be the fact that only two levels could be discriminated in the acceptable range at 100 Hz, with only three levels even at 1500 Hz. However, Beeker et al (1967) applied electrical stimulation to a tactile extension system, using current pulses related to the pick up from a piezoelectric crystal in a gripping device, and reported that a touch-like sensation was perceived. No clinical application reports were available at that time, but some, admittedly second-hand, reports indicate that the system has been rejected in some cases by patients who find the stimulation painful.

Detailed investigations in the detection threshold to pain threshold band of skin stimulation have been rather limited, in contrast with the considerable work which has been directed towards muscular stimulation, of which the work of Pennacchiotti et al (1966) and Morecki et al (1967) are prosthesis related examples. However Pfeiffer (1968) and Pfeiffer et al (1969) have given some consideration to this subject, particularly remarking upon the small range of acceptable stimulation levels, although Kato et al (1970) have used electrical stimulation for the feedback of pressure, finding that stimulation pulse width is an important factor in affecting detection thresholds.

A still more advanced system has been used by Clippinger (1971) who utilised an implanted stimulator driven by induction from outside the skin, stimulating the median nerve for the feedback of force in an APRL hook. This work represents an important aspect of tactile stimulation in general, since, to some extent, the variable nature of skin contact is removed. This is particularly important

with electrical stimulation, since the thresholds appear to be related to current density on the skin, i.e. a given current over a small area generates a higher stimulus than over a large area, and variations in area of contact can occur readily under all but the most closely controlled conditions. The implantation of electrodes is one way of overcoming this difficulty, but cannot be regarded as an adequate solution for general use, and it is therefore necessary to introduce adequate safety mechanisms into the electronics package for surface stimulators.

8.10 The prospects for future development.

Thus, as a general conclusion to the review of tactile feedback in general, it can be said that electrical stimulation appears to offer a more compact and lower power system than does vibratory stimulation. However, further investigations are required into the protection against stimulation rising to the level of the pain threshold, and also further information is required concerning the subjective sensations created by electrical stimulation and their relationship to normal tactile responses.

Chapter 9.Theoretical analyses of position servo control systems.

The inclusion of a review section concerning the theoretical analyses rather implies that this topic has been the subject of a significant amount of work. However, this has not been the case, with only limited studies being made, each of which has resulted in solutions which have not led to useful practical guidelines for future development. Unfortunately, therefore, this review is an account of a non-event, rather than of previous accomplishments.

The reason behind the lack of success in work of this nature is the fact that virtually all prosthetic development programmes have been carried out either by groups committed to the provision of prosthetic hardware directly for patients, or by groups removed from the practical realities of patient requirements. In the former case, the intricacies of control systems have usually been considered not at all, whereas the latter situation has led to an element of oversimplification. Thus Brann's (1966) analysis of a pneumatic servo system did not include the stabilising effect of force feedback, and therefore precluded the incorporation of additional stabilising factors such as the dynamic properties of the operator. Similarly Burrows et al (1972) analysed a pneumatic system which used on/off valves, finding it to be oscillatory in nature, which is true enough for practical systems using such valves, but a prosthesis with this property is of little use unless large scale damping is introduced as in the arm developed by the Medical Research Council (1970) at Hendon. An equivalent approach was made in the analysis of a hydraulic system by Davies and Sillito (1970), who made no attempt to introduce

practical valve characteristics, thereby invalidating the relevance of the analysis in real terms.

The necessity for considering operator, servo system and actuators as a complete practical system in these analyses has been highlighted still further by the work of Mufti and Meachem (1968) who analysed the frequency responses and stability criteria for various pneumatic valves, finding some to be inherently stable and others unstable, the most intriguing fact being the recorded instability of the Edinburgh force demand valve, which operates in the most stable of practical arm prostheses!

Thus, it was apparent from this limited amount of analytical work that useful theoretical considerations could only be made by using close approximations to the individual components of a real system, and considering them together, taking account of their mutual interactions.

Chapter 10.

The normal upper limb - a brief assessment.

- 10.1 Introduction.
- 10.2 The function of hand and arm.
- 10.3 The arm in its capacity as a positioning and direction determining device.
- 10.4 The shoulder joint.
- 10.5 The arm as a folding strut.
- 10.6 The elbow joint and associated structures.
- 10.7 The wrist.
- 10.8 The hand.
- 10.9 Muscle action.
- 10.10 Muscle control.
- 10.11 An overall view of the natural hand/arm system.

Chapter 10.The normal upper limb - a brief assessment.10.1 Introduction.

The provision of an artificial hand-arm system must naturally be associated with an assessment of the behaviour and functional capabilities of the natural system. Such a review is necessarily complex and, to a large extent incomplete, particularly with regard to many aspects of control mechanisms and the feedback of information from the limb to the central nervous system of the operator. However, an attempt will be made to describe and explain those aspects of the natural system which are of particular interest to the development of complete upper extremity prostheses. Since other levels of amputation present specialised problems of musculature and control, no attempt will be made to relate aspects of normal arm function to these situations.

10.2 The function of hand and arm.

Functionally, the arm and hand may be regarded rather more simply than may be expected on first inspection. A very large proportion of the arm functions are concerned solely with the task of providing a stable mounting, of almost infinitely variable position, for the hand in its capacity as a prehension device. Of course, it is not possible to ignore entirely the important arm functions exhibited in its capacity as an aid to balance, as a protection in falling, as a nudging or pushing device using the elbow, or as a stabiliser in complex gripping operations where the forearm is used as a weight. Such a list may be made as long as time permits, but these functions are at all times insignificant in

comparison with the most important function of providing the hand with its platform from which prehension is derived.

The hand and arm may therefore be regarded as 'symbiotic union' of two essentially functionally independent units. The fact that the motive power for the majority of hand functions lies within the arm in the form of the extrinsic hand musculature, is incidental since a hand removed from an arm at the wrist can still be operated 'normally' by operation of the tendons which pass through the wrist into the hand. It is therefore convenient to consider the hand and arm systems independently from a bio-engineering standpoint. This in no way contradicts the argument for the concurrent development of a complete hand-arm system; rather it tends to confirm the fact that in order to achieve a successful end result, the respective parts must be compatible to the greatest extent whilst clearly existing as individual entities. The folly of designing a hand prosthesis without a directly compatible arm would be like fitting a foot onto an arm; clearly the foot has developed to be walked on, as the arm has developed in its capacity as a hand carrier. Therefore, it must be borne in mind that although an artificial separation of the hand and arm systems is made in this chapter, their relationship to one another is important at all times.

10.3 The arm in its capacity as a positioning and direction determining device.

The arm is basically a folding strut which incorporates rotation and flexion facilities at the distal end. The strut is attached to the body by means of a universal joint of the ball and socket type, which permits the strut to be rotated either in a vertical plane or

in a horizontal plane, or in a combination of both such motions.

The mechanism for the provision of the rotational facility at the distal end of the folding strut is such that the rotation occurs along the length of the distal member of the strut, whereas the flexion facility is provided at the extreme distal region of the strut. It is therefore convenient to divide the functional parts of the arm into three sections which can be considered separately:-

- (i) the shoulder joint.
- (ii) the folding strut incorporating elbow flexion and pronation/supination.
- (iii) the wrist flexion in the distal regions of the distal member of the strut.

10.4 The shoulder joint.

This joint is usually simply described as being a ball and socket joint which is only true as a brief description of functional type. The joint is in fact a complex structure which bears no real resemblance to the engineering concepts of ball and socket joints since the socket itself is a complicated arrangement of rigid sockets, ligamentous structures and a formidable array of musculature. Indeed the joint is so intricate that it is not even possible to consider the ball and socket joint alone; since this joint is somewhat loosely hung on a girdle draped round the spine, neck and rib cage, there being only one articulating surface with the main body skeleton at the sternum.

The shoulder structure, when seen in terms of bone structure alone, appears to be highly unstable. The large head of the single upper arm bone, the humerus, articulates with the glenoid cavity

of the scapula (Fig. 10.1) in a liquid lubricated joint capsule. The scapula is an approximately triangular bone structure which is attached to the spine and rib cage by muscular and ligamentous connections only. The triangle is oriented apex downwards, and has two protruding structures (processes) at the angle distal from the body mid-line. One of the processes projects forwards - the coracoid process; the other process - the acromion projects laterally, and below this process is a concave region - the glenoid cavity - to receive the head of the humerus. The effective area of the glenoid cavity is increased by a triangular ligamentous band extending from coracoid to acromion process thus providing an arch to accommodate the large head of the humerus.

The scapula articulates with the clavicle at the acromio-clavicular joint. Once again this joint is bathed in synovial fluid and possesses a retaining capsule which is thickened in its upper part to form a ligament which ties the clavicle and acromion together. The clavicle to scapula bonding is further strengthened by the coraco-clavicular ligament which binds the lateral part of the clavicle to the coracoid process. This ligament limits the range of motion of the acromio-clavicular joint and in practice forms the chief support by which the scapula, and hence the other parts of the arm, are suspended from the clavicle.

The sterno-clavicular joint forms the only direct jointing between the upper limb system and the main skeletal structure of the trunk. The joint itself is synovial and consists of a shallow socket formed by the sternum and rib cartilage. Since the joint is so heavily loaded it is strengthened by powerful ligaments. In

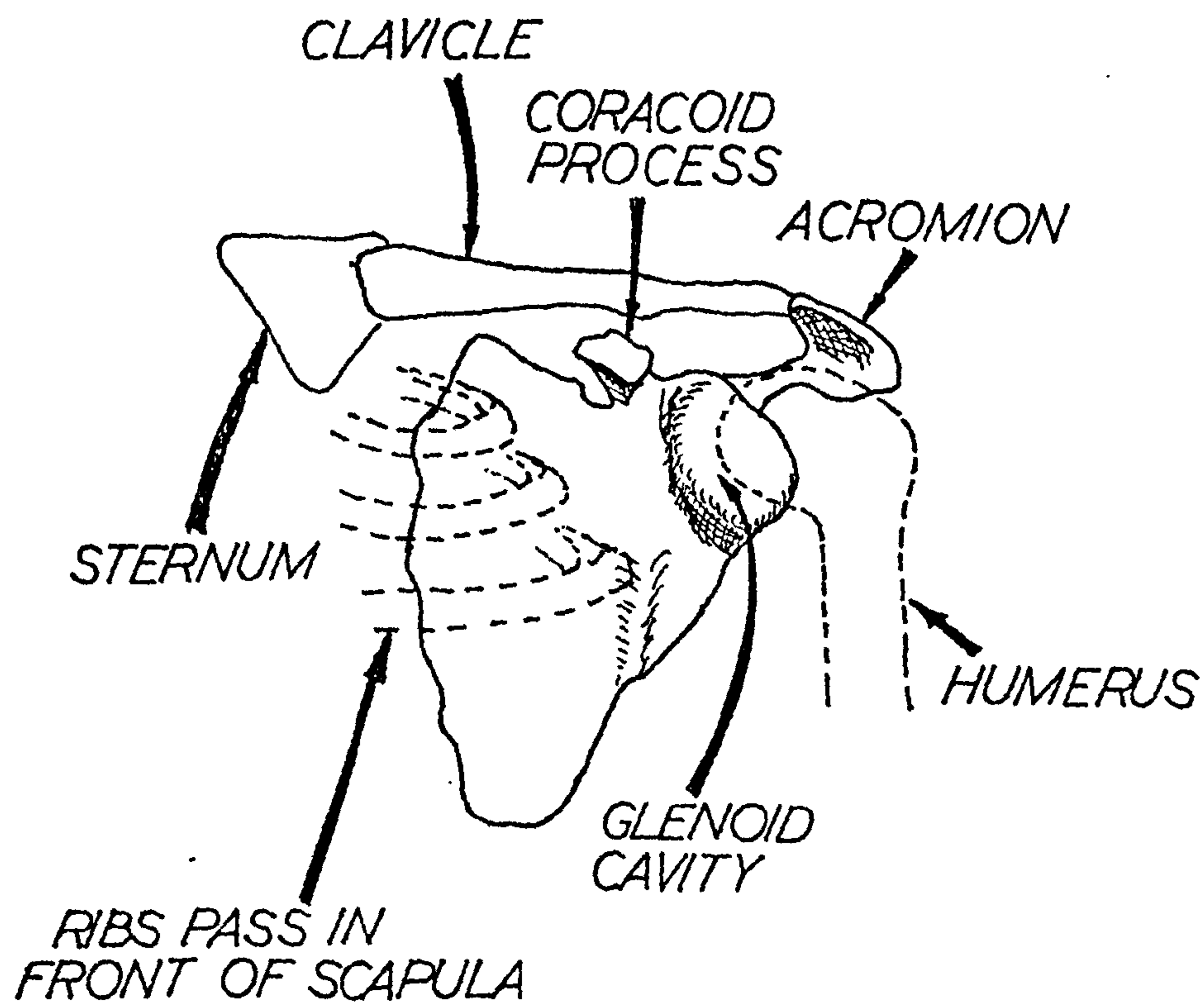


Fig. 10.1

The bones of the shoulder.

addition the joint capsule is fibrous and very strong, especially in the fore and aft directions where it is ligamentous in nature. The joint cavity is divided into two parts by an articular disc which also acts as a ligament and prevents upward motion of the medial end of the clavicle.

The relative instability of a system of bones as described above would seem to contradict the obvious extreme resilience and strength of a shoulder joint which in practice can support the weight of the human body, even when subjected to impact loads of that magnitude. However, the musculature of the upper body and shoulder is so extensive and powerful that most of the stability and strength is provided from this source. The muscles are so arranged that some support the skeletal structures, some contain the otherwise weak humero-scapular joint, and all participate to some extent in movements of the upper arm. This formidable array of muscles forms a web of powerful materials woven around the shoulder mechanisms and apart from the movements activated by these muscles, they also provide support and load bearing capabilities for the whole shoulder girdle, thereby conferring great strength upon a relatively weakly jointed system.

From these considerations it is apparent that the shoulder is by no means a simple ball and socket joint. The extremely large range of motion available in the normal upper arm is the result of a relatively limited range of motion due to the ball and socket action of the humerus in glenoid cavity joint, superimposed upon the overall movements of the joint itself. By means of scapular movements, restricted by the action of the clavicle and associated

joints, the orientation of the glenoid cavity can be varied, thus increasing the effective range of motion of the humero-scapular joint.

10.5 The arm as a folding strut.

Following the assessment of the shoulder joint it is possible to consider the upper limb in its own right, subject to the operations of the shoulder mechanisms outlined above. The upper limb itself consists of three major bones, the humerus, the radius and the ulna, which articulate in such a way that they form a hinged folding strut which terminates, at the distal end, in a manner which permits the pronation and supination of the remaining mechanisms which are attached still more distally. The configurations of the constituent bones are shown in Fig. 10.2.

10.6 The elbow joint and associated structures.

The elbow joint is basically a hinge joint formed by the articulation of the humerus with radius and ulna. More specifically the head of the radius articulates with the capitulum of the humerus and the humeral trochlea articulates with the trochlear notch of the ulna. Since the joint is effectively a simple hinge, it is maintained medially and laterally by strong ligaments which ensure that the integrity of the joint is preserved in all states of flexion of the joint. The anterior and posterior ligaments are less strong but more flexible, so that no restrictions are placed on the range of action of the hinge. The joint is lubricated in the usual way by means of a synovial capsule and fluid.

In addition to the elbow 'hinge' joint, there is a joint between radius and ulna in the region of the elbow. This joint,

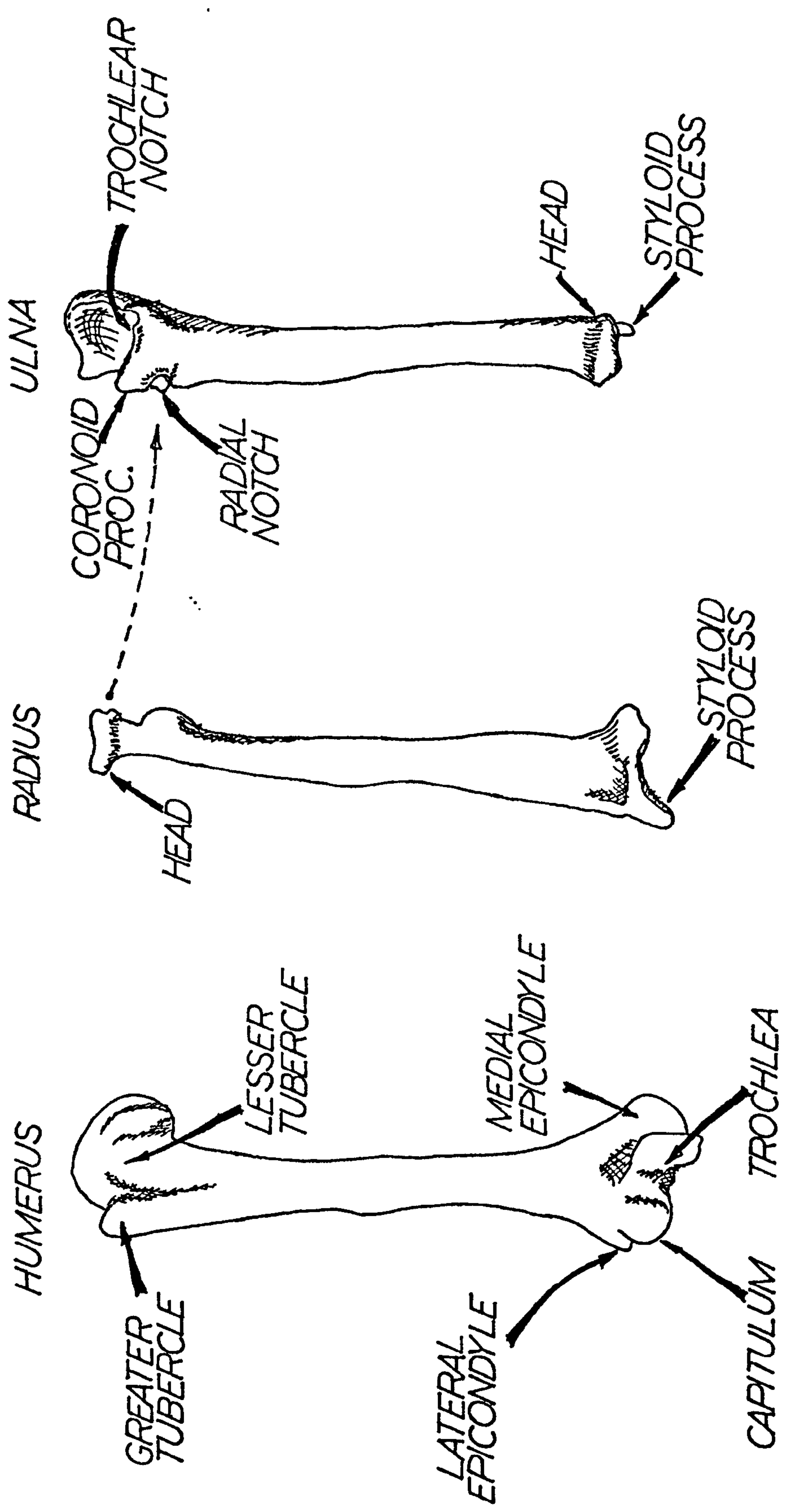


Fig. 10.2

The bones of the arm.

in conjunction with a similar one at the wrist, is active during pronation/supination actions when radius and ulna rotate relative to one another.

The proximal radio-ulnar joint is formed between the side of the head of the radius and the radial notch of the ulna. The joint is maintained by the annular ligament which encircles the radial head and the ligament is attached to the ulna, thus forming a tie between radius and ulna. The ligament forms smaller loops more distally from the elbow which ensure that the radial head is held close to the humerus at all times, since the annular ligament is assisted by, and fused with, the lateral ligaments of the elbow. The synovial capsule for the radio-ulnar joint is an extension of the remainder of the elbow joint capsule. Thus the overall action permitted by the proximal radio-ulnar joint is that of rotation of the radius on the surface of any cone whose axis lies in the direction of the resting radius bone (i.e. parallel to the direction of the axis of the ulna).

The distal radio-ulnar joint occurs between the ulnar notch of the radius and the head of the ulna. This joint is unusual by virtue of the fact that the bone between the bones is formed by the articular disc, a fibrocartilage plate which separates ulna from the bones of the wrist. By means of the articular disc attachments to the radius and ulna, the radius can rotate around the styloid process of the ulna at a radius determined by the length of the articular disc.

The combined effects of proximal and distal radio-ulnar joints thus permit the radius to rotate relative to the ulna, and around it,

resulting in a crossing of the bones to achieve the necessary pronation/supination range of almost 180° . The two bones are further related by the interosseous membrane which is a fibrous sheet between the radius and ulna long their lengths, consisting of oblique fibres which transmit proximally directed forces, applied at the hand, from radius to ulna. In addition, the oblique nature of the fibres allows the unrestricted alteration of spacing between radius and ulna which must result during pronation/supination actions.

10.7 The wrist.

Although it has been stated that functionally the wrist may be regarded as a unit separate from the arm, this is only the case from an operational point of view. Anatomically, the musculature is arranged in such a way that elbow and wrist are connected by various muscles. Therefore, in order that an appreciation may be gained of the action of the various muscles, it is necessary first to explain the structure and action of the carpal region of the limb.

The carpal region of the arm consists of eight small bones arranged roughly as in Fig. 10.3. The jointing is complex and variable and will thus be considered in stages.

The radio-carpal joint is formed between the distal end of the radius together with its extended region due to the articular disc, and the proximal aspect of the carpus. Normally the articulating part of the carpus consists only of the scaphoid and part of the lunate. However, during adduction, the triquetrum also comes into contact with the articular disc and thus becomes an active part of the joint. In the normal way, the joint possesses a capsule with

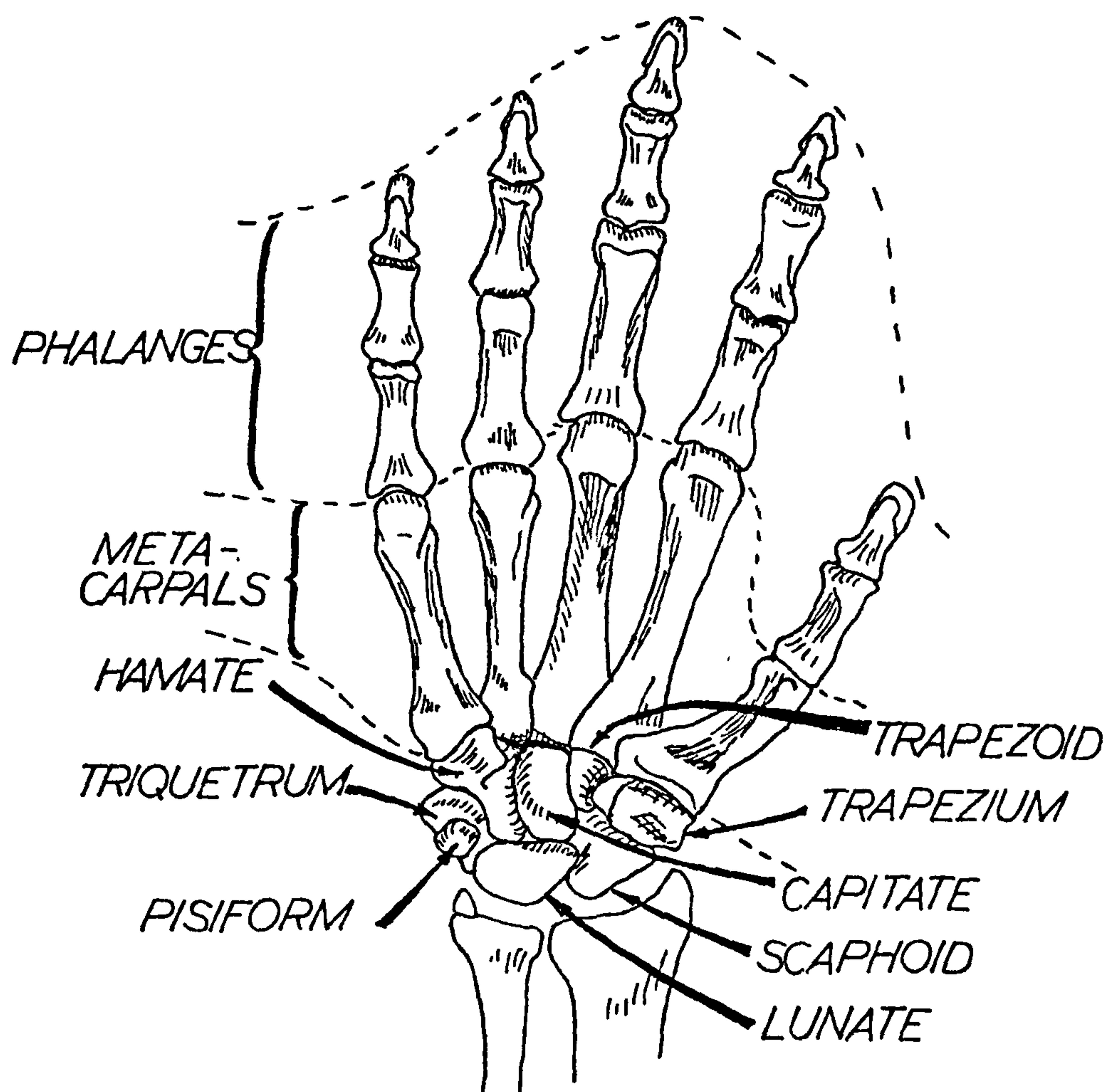


Fig. 10.3

The bones of the hand.

strengthening ligaments and a synovial membrane. The major movements achieved at this joint are extension and adduction, whilst flexion and abduction occur to a large extent at the intercarpal joints.

The intercarpal joints, apart from the pisiform-triquetrum joint, share a complex cavity, also common to the carpo-metacarpal and intermetacarpal joints of the fingers. The fibrous capsule and synovial membranes are common to all the joints, with the capsule appropriately thickened at individual joints to form strengthening ligaments. The overall effect of these joints is to provide a further range of flexion and extension together with some side-to-side sliding which effectively increases abduction and adduction movements.

As a result of this brief description of the carpal structures, it is apparent that muscles attached to the carpal bones, or distal to the carpus, will necessarily have an effect on the position of the wrist mechanism.

10.8 The hand.

The bone structure of the hand is very simple to describe, but provides a considerably more difficult problem for the consideration of the ways in which the structure may be controlled. The bone arrangements in the hand may be briefly described as a group of five digits, four of which consist of four roughly cylindrical segments jointed together, the fifth consisting of three similar segments also jointed together (Fig. 10.3). These five digits articulate with the distal carpal row, the thumb doing so in a fashion which is of paramount importance in its contribution to the versatility of the hand.

The proximal segments of the digits form the metacarpal area

('back') of the hand. This metacarpal area has two distinct functional parts, namely that pertaining to the fingers, and that associated with the thumb. These two regions are readily distinguished by the degree of mobility achieved at the carpo-metacarpal joints since the four finger metacarpals have a very restricted range of motion, whereas the thumb metacarpal possesses a very large range of motion. The remaining hand joints at which significant degrees of movement are possible are the metacarpo-phalangeal and interphalangeal joints. Each of these joints is capable of approximately 90° of flexion in a largely fixed plane of movement.

Therefore the hand may be regarded as a mechanism consisting of fourteen separate uni-planar 90° flexion hinges together with a more complex joint between the thumb metacarpal and the trapezium in the carpus. Clearly, the muscular and tendinous organisation necessary to provide the stable function and control of such an array, must be formidable indeed.

However, it is first necessary to consider the joints themselves in order to show how the muscles and tendons can function in relation to these joints. Since it is the most significant contribution to the overall function of the hand, the carpo-metacarpal joint of the thumb merits particularly close attention. The joint is formed between the thumb metacarpal and the trapezium which is situated in such a way that it can move more readily than the other carpal bones. Each of the articulating surfaces takes the form of a saddle, the interlock of the joint being created by means of a quarter turn of one saddle relative to the other so that the convex surface of one bone mates with the concave surface of the other and vice versa.

The joint capsule is slack thus permitting a large range of unrestricted movement in each of the two mutually perpendicular directions of rotation permitted by the interlocking saddle configuration. The overall effectiveness of the thumb movements are further accentuated by the fact that they do not occur in the same plane as finger movements. This situation arises as a result of the curvature of the carpal arch which is maintained by the tension of the flexor retinaculum, a dense fibrous band which stretches from the scaphoid and trapezium to the pisiform and the hook of the hamate bone. The length of the flexor retinaculum is less than the distance across the free standing carpal bones, and the band thus acts as the string of a bow formed by the carpal bones. Because of the independent nature of the trapezium bone, the articular surface is pulled round by the flexor retinaculum so that the plane of flexion is at 90° to the plane of flexion of the fingers. The overall effect of this peculiar joint is to provide the thumb with four basic types of motion; laterally in extension, medially in flexion, towards the palm in adduction and away from the palm in abduction. These movements may be combined in sequence to provide circumduction or opposition when the thumb is moved to meet the fingertips. In fact, the opposition movement may be regarded as a direct consequence of the non-linearity of the saddle-shape along one axis, since some abduction is automatically created by the joint profiles during flexion.

The carpo-metacarpal joints of the fingers are considerably more restricted in their movements, particularly in the cases of the index and middle fingers. The index metacarpal fits around the distal surface of the trapezoid in a manner not unlike that of the

thumb carpo-metacarpal joint. However, most of the motion is prevented by the lateral and medial articular characteristics with the trapezium on one side and the metacarpal of the middle finger on the other. The fourth and fifth carpo-metacarpal joints are slightly less restricted in their movements whilst the fifth metacarpal makes use of an opponens muscle to achieve a limited amount of flexion and rotation in a small scale imitation of thumb action. An overall degree of co-ordination between the metacarpals is provided by the intermetacarpal ligaments between all adjacent metacarpals.

Each metacarpal bone has a convex head which articulates with the concave articular surface of the appropriate proximal phalanx. These articulations form the metacarpo-phalangeal joints which possess a degree of versatility of motion which is significant in the considerable versatility of gripping modes available in the normal hand. For the fingers these joints provide the base for the operations of the less versatile hing-like interphalangeal joints. Therefore it is apparent that the metacarpo-phalangeal joints must provide such additional motions as are necessary for satisfactory orientation of the individual fingers relative to one another. Briefly, the metacarpo-phalangeal joints of the fingers provide the fingers with the functions given to the thumb by the carpo-metacarpal joint, the only real difference being that the extent of abduction and adduction is considerably reduced.

The joint capsules of metacarpo-phalangeal and interphalangeal joints are thickened on the palmar and side aspects to form strong ligaments, whereas the extensor tendon replaces the function of the

capsule on the dorsal side. The joints are further strengthened by collateral ligaments passing down and forwards from the sides of the head of the proximal bone to the sides of the base of the distal bone. The palmar ligament is a strong fibrous plate which attaches loosely to the neck of the proximal bone and attaches to the base of the distal bone. It also provides part of the socket for the head of the proximal bone on its palmar surface.

The distribution and effect of the ligaments described above, applies equally well to the interphalangeal joints, which operate as simple hinges. Sideways movement is restricted by the collateral ligaments and by the construction of the joint itself. The articular surfaces are 'keyed' in the middle by the effect of the prominence of the base of the distal phalanx locating in a groove in the head of the proximal phalanx, thereby preventing rotation along the length of the phalanges and also effectively eliminating abduction and adduction.

The terms synovial joint and synovial fluid have been used several times without explanation, thus a brief note will be made concerning these matters. The term synovial joint refers to any joint which possesses a cavity enclosed by a synovial membrane and containing synovial fluid. The membrane can be separated both from bone and capsule, but adheres to fibro cartilage and tendons which enter joints. Synovial fluids and membranes also are present in tendon sheaths. The prime function of synovial fluid appears to be one of lubrication, but it may also serve as a form of nourishment for the articular cartilage. The mechanical properties of synovial fluid are non-linear and well suited to lubrication since the

viscosity decreases as shear rate increases, (Davies 1966). In this way the fluid can provide the best lubrication under all conditions of motion.

Before mentioning the various details of hand function and control it is necessary to describe certain intrinsic hand structures which govern the special behaviour of the complex articular system. A structure particularly important for the action of the extrinsic hand muscles has been mentioned previously in the description of the carpal area. This band, the flexor retinaculum, acts as a pulley around which all the extrinsic palmar acting muscles function. The movements of tendons round the flexor retinaculum within the fingers and palmar areas is facilitated by synovial sheaths which surround the tendons wherever they pass through the fibrous canals which bind the tendons to the appropriate underlying bone structures. In particular, the fibrous sheaths of the fingers ensure that bowstring effects cannot occur, by binding the flexor tendons to the phalanges between joints.

The extensor apparatus of the fingers is complex and beautiful in its operation. By means of ingenious alterations in the line of action of various tendons and muscles relative to the position of the interphalangeal joints, extensor muscles can also double as flexors under certain conditions, and maximal use can be made of the limited excursion of each muscle. The complex action of this apparatus is well described by Bunnell, and can only be briefly mentioned here. The long extensor tendon can, by virtue of its stage of tension, alter the position of fusion of the lumbrical and interosseus muscles relative to the metacarpo-phalangeal joint (Fig. 10.4). Thus, when the long extensor tendon is slack, the

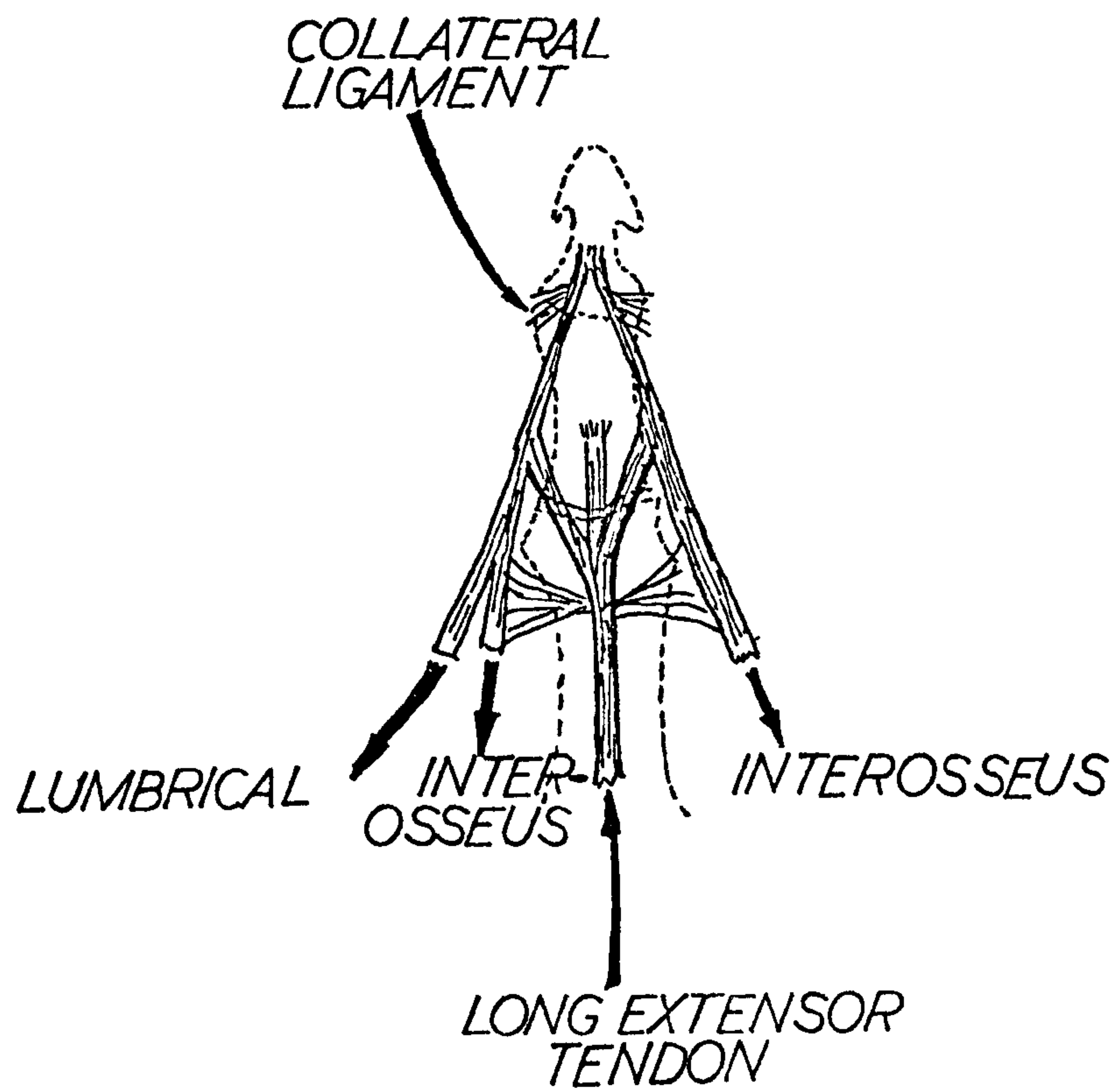


Fig. 10.4

Finger extensor apparatus.

lumbrical and interosseus can only act as extensors of the distal joints via the lateral bands, or provide sideways motion by asymmetrical action. In order to prevent bowstring effects on the dorsal aspects of the wrist the extensor retinaculum exists to perform the equivalent functions of its flexor counterpart. Once again the tendons pass through synovial sheaths to permit low friction movements through the 'pulleys' provided by the retinaculum and similar structures.

10.9 Muscle action.

In order to gain at least some information about the method of controlling the actions of all the joints and muscles described above, it is necessary to consider the internal organisation of muscles themselves of which there are three basic forms in the body; visceral, cardiac and somatic. Somatic muscle forms the muscles associated with motion of joints and bones, and thus no account will be made of the other two types.

A muscle is made up of fibres of up to 30cm in length, each containing several nuclei and surrounded by a connective tissue sheath, the sarcolemma. The nuclei lie close to the sarcolemma, to one side of the fibre and each fibre is loosely bound to its neighbours by a layer of connective tissue called the endomysium. This type of connection holds together a group of fibres, a fasciculus, which is surrounded by a stronger sheath called the perimysium, the fasciculi being bound together to form the 'muscle' by a sheet of collagenous material called the epimysium. Thus, the muscle as normally seen is a composite material made up of contractile fibres in a special connective tissue matrix.

The behaviour of the individual fibres holds interesting consequences for the control of the muscle. Each fibre is largely composed of the protein myosin, which has a spirally shaped molecule. During a process which is triggered by the action of the appropriate nerve cell, the fibre contracts, making use of energy released by the reduction of ATP to ADP (adenosine tri (di) phosphate).

10.10 Muscle control.

The contraction induced as a result of the above process is total, there are no intermediate resting stages, either the fibre is contracted, or it is not. The familiar continuous contraction of muscle is achieved by the statistical result of the on/off ratio of the fibres at any moment. This control is achieved as a result of the grouping of fibres into individual motor-units, each of which is stimulated by a particular nerve cell. The fibres belonging to a motor-unit are not physically adjacent, but are dispersed throughout the muscle, even though they are triggered from the same source.

The electrical activity indicated above provides the basis for the technique of electromyography which can prove to be a useful tool in the study of muscular activity. The electrical action associated with muscles can be detected on the surface of the skin by the use of special silver-silver chloride electrodes and sensitive amplifiers. However, the somewhat random appearance of the signals which result from the combined effects of many different motor units, make interpretation virtually impossible except on an 'average change of activity' basis. It has been possible for various workers to isolate the effects of individual motor units by the precise placement of an electrode probe inserted into the body of

the muscle. Basmajian (1963) has found that by the visual display of motor unit activity from such a source, a volunteer has been able to learn voluntary control of an individual motor unit.

However, the insertion of such percutaneous electrodes, and the maintaining of a consistent position of the electrode during movement, are extremely difficult problems which have virtually precluded all forms of electromyographic control except that by means of skin contact electrodes.

The mechanisms concerned with information processing and the investigation of movements in the human system are extremely complex and not at all well understood at an intermediate level. The end result is adequately comprehended as the arrival of a series of command pulses down the motor nerves which induce muscular action. Also appreciated is the fact that a continuous supply of information is fed from the muscles, joints, skin, etc. to the central processing unit, and this information is used to modify and control the behaviour of any muscular actions throughout all phases of action. Due to the complexity of all these systems it has only been possible to arrive at crude models of the types of control system likely to be in action in the functioning of muscles. Navas and Stark (1968) have shown the existence of position servo type control mechanisms by the application of automatic control techniques in tracking tasks, a fact which bears out the findings of Rose and Mountcastle (1959) regarding the joint angle receptors of the cat. However, as pointed out by Gibson (1966), any specific sensory or control feedback channel is only a microscopic piece of the total information continually being processed by the natural control systems.

The complexity of the actual behaviour of the natural system is so considerable that there is little of immediate practical value that can be gained from a brief review of the subject, apart from the few indicative factors mentioned below. However, an important factor mechanically in the behaviour of any one muscle is the state of other muscles concerned with the joint being operated and this fact is represented by the existence of muscle tone, apparently caused by the feedback of information from stretch receptors in muscle to the central nervous system which in turn issues 'orders' about the state of tension to be maintained in order to overcome gravity, or maintain the stability of a particular joint.

Further information which is of importance to the control of muscles and joints is provided by the sensory facilities in the skin. Once again, the precise behaviour of these transducers is not well understood, although it is known that they produce a series of pulses when stimulated, it is not clear how the stimulus is related to the pulse train which follows. Nevertheless, it is evident that some degree of coding must exist, since many of the smaller nerve receptors are attached to the same fibre, and there are various types of these receptors which seem to specialise in tactile matters. Thus, Merkel's discs, Meissner's corpuscles and the Pacinian corpuscles are all concerned with touch or pressure and are also affected by temperature changes. Nerve endings surrounding hair follicles also provide much tactile information in the hairy regions of the body. To add to the confusion still further, Moberg (1972) suggests that a large portion of position awareness is provided by

skin receptors, rather than by the joint capsule receptors advocated by Boyd and Roberts (1953), Cohen (1958) and Rose and Mountcastle (1959). The difference of opinion here may be related to the joints considered, since Moberg's prime concern was with human finger joints, whereas other sources referred to used animal knee joints, human shoulders, etc. for their experiments. However, the precise nature of the source of joint position information is not relevant to immediate prosthetic applications since it is sufficient to know that it exists and to use the natural systems available, although additional information about the natural processes may well eventually lead to an improvement of the control systems in prostheses.

10.11 An overall view of the natural hand/arm system.

This brief review of the major mechanical aspects of the upper limb shows that it is fundamentally an arrangement of struts of various lengths, interconnected by a variety of joints with particular properties which determine the type of motion made by one member relative to the next.

Thus, in the hand, we have the four jointed struts of the phalanges of the fingers, each finger being capable of curling and straightening in a plane determined by the action of the joints which may be considered as behaving as simple hinges. These four struts are attached to the 'base' of palm of the hand via four more hinge joints which are 'slack' insofar as they allow some lateral and rotational movement of the fingers. Also attached to the palm of the hand is the thumb, which is another simple hinge jointed strut but the attachment to the palm occurs via a 'universal joint' which

allows comprehensive movement around the fingers, although not permitting rotation of the thumb along its own axis.

The palm (metacarpals) as the stable platform of the hand is attached to the forearm via the universal joint of the wrist, this universal joint being fully universal, since it permits rotation to be transmitted through it, whilst allowing lateral and up and down motions of the hand to occur. The rotation is provided by a rotation facility which operates around the long axis of the forearm.

The forearm attaches to the upper arm in the simple hinge joint of the elbow, and the system is completed by the loose attachment of the upper arm to the body via another fully universal joint at the shoulder.

Thus, schematically we have the situation of Fig. 10.5 where the figures by each box indicate the degrees of freedom at that joint.

This system comprises 31 independent degrees of freedom, each of which is driven by its appropriate musculature, the end result being a degree of control of impressive accuracy, the task presented to the designer of prostheses being the provision of a mechanical substitute. Clearly the natural system has a considerable amount of duplication of movements, this being the key to the versatility of the normal arm and hand. Many of the extra movements provided by the large number of joints are used in special circumstances in order to avoid obstructions. For example, theoretically the hand can be positioned anywhere in space by the use of only three degrees of freedom, but during feeding the chest interferes with the upper arm unless the elbow is lifted away from the body. Thus, additional

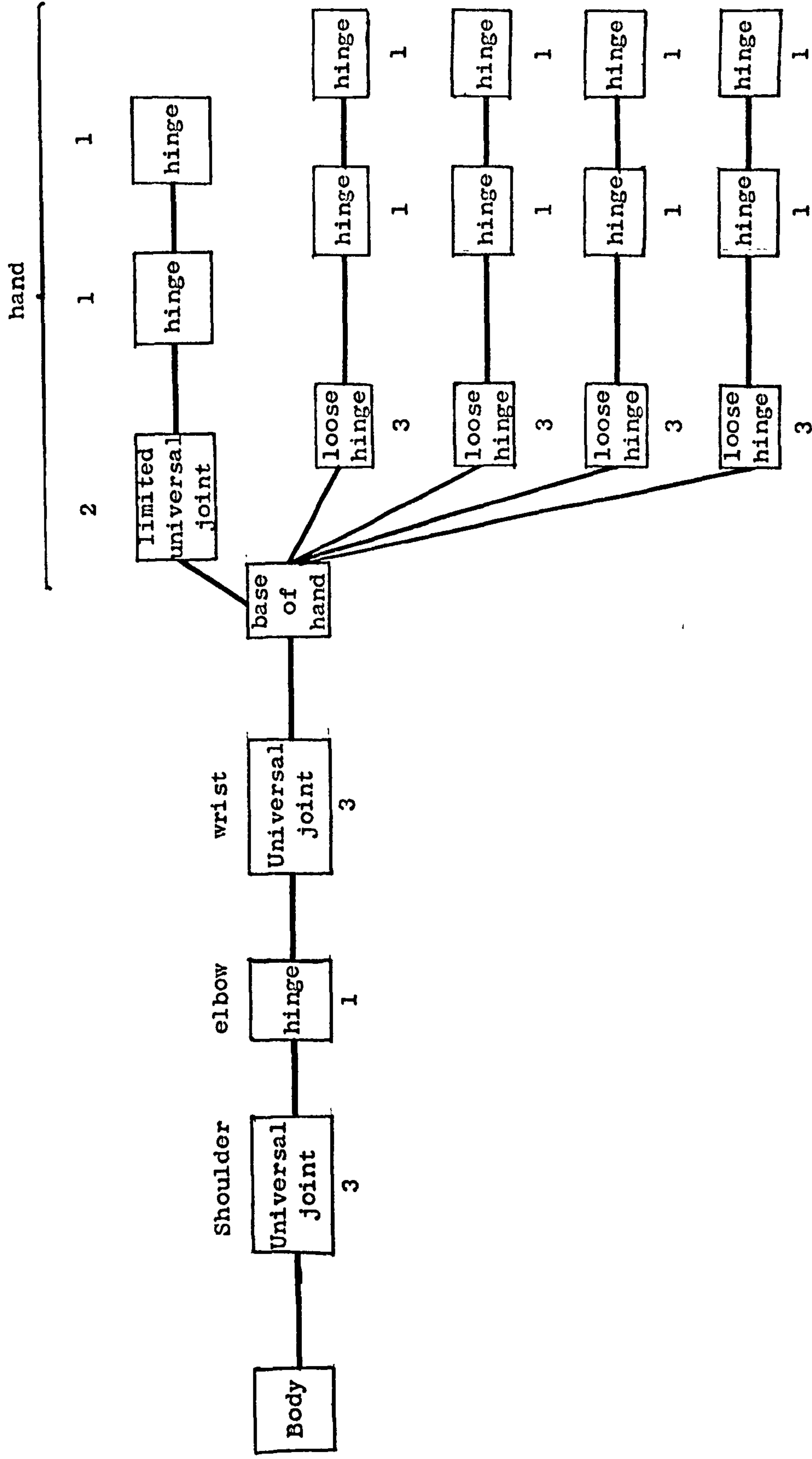


Fig.10.5 Schematic of upper limb joints.

movements come into play in order to account for the peculiarities of everyday problems.

The main problem for the design of prostheses is that only a limited number of control sites are available for working a prosthesis, say five sites for an arm controlled by an amelio amputee. Therefore, the major problem of prosthesis design is the reduction of the number of degrees of freedom from 31 to 5, whilst retaining the largest possible range of functional properties. Thus the purpose of the practical work of this thesis may be considered as the reduction of the degrees of freedom in the hand from 24 to 1, whilst losing as little function as possible.

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