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How to cite:

Bromley, John (1989) *The design and application of microprocessor based systems for clinical measurement of joint stiffness and grip strength.*, Durham theses, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/6546/

THE DESIGN AND APPLICATION OF MICROPROCESSOR BASED SYSTEMS FOR CLINICAL MEASUREMENT OF JOINT STIFFNESS AND GRIP STRENGTH.

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A thesis submitted for the degree of Doctor of Philosophy
At the University of Durham.

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March 1989

ABSTRACT

The overall aim of the project was to further the research into the objective measurement of the symptoms of arthritic disease.

There were three major parts to this study. The first part was to design a measurement system capable of making large scale, objective measurements of the stiffness of the human metacarpophalangeal joint. The second part was to design a new device to measure the grip strength of the human hand objectively. The last part was to use these two measurement systems to conduct research into the clinical manifestations of arthritic disease and study the effects of some therapeutic agents.

A new, microcomputer controlled arthrograph system was developed to measure the stiffness of the metacarpophalangeal joint of the index finger. The system proved to be reliable, easy to use and sufficiently accurate to quantify changes in joint stiffness.

A new design of grip machine was produced which enabled the forces developed during a power grip to be analysed. Measurement was made of the force contributions of individual digits and the maximum total gripping force. The machine was portable and extremely easy to use.

A study of the circadian variation of joint stiffness and grip strength, over a full twenty four hour period, was carried out. Measurements were made every two hours in both healthy and arthritic subjects. A circadian variation of stiffness was observed in the joints of arthritic subjects. Joint stiffness was elevated in the early morning and for some subjects the degree of change was profound. No significant circadian variation was observed in the joint stiffness of healthy subjects. A circadian variation of grip strength was observed in arthritic subjects. Grip strength reached a minimum value between 2.00 and 4.00 a.m. in the majority of subjects. No consistent relationship was found between changes in joint stiffness and changes in grip strength.

The effect of several forms of physiotherapy on the joint stiffness of arthritic subjects was studied in both the short and long term. The subjects were measured before, and then immediately after, treatment each time they visited a physiotherapy hand clinic. Only the results of those patients who attended the clinic for a minimum of five weeks were used in any subsequent analysis. Four different treatments were studied: hot wax and ultrasound, hot wax alone, ultrasound alone and exercise. The combination of hot wax baths and ultrasonic therapy effected temporary reductions in all joint stiffness parameters. The reductions in energy dissipation and torque range were highly significant ($p < 0.05$ and $p < 0.001$ respectively). No significant reductions were found for hot wax, ultrasound alone or exercise. In the long term, no significant change in joint stiffness was found for any of the treatments considered.

Acknowledgements

I would like to thank the following people and organizations without whose help this work would not have been completed.

The Arthritis and Rheumatism Council for their financial support.

Many thanks to the technical staff in the Engineering department. In particular I would like to thank Ian Garret for his patience and persistence in trying to make sense of my circuit diagrams and Ian Foster and David Jenkins for their work on the mark one and two versions of the arthrograph respectively. I am also grateful to Trevor Nancarrow and Peter Nicholson for their technical advice, particularly when it came to the practicalities of electronic fault finding.

I would also like to express my gratitude to the staff at Middlesbrough General Hospital and Hemlington Hospital. In particular Dr. D.I. Haslock, Sisters Cook and Leckenby, Mrs A. Robson, Mrs J. Sadler and Mrs P. Cole for allowing me to interfere with their daily routines and being generally helpful with advice and information.

Thanks are also due to the many patients, colleagues and friends who acted as test subjects for the experiments, unfortunately too numerous to mention.

Special thanks are due to Mrs Valerie Rhind for sharing half the burden of the 24 hour experimentation at Hemlington Hospital and for being brave and persistent enough to wake me in the early hours of several wonderful mornings!

I also must thank Mr P.G. Binnington for his photographic expertise and, along with Mr G. F. Willis, for putting up with me whilst writing this thesis. Many thanks are also due to my fiancee Carol for generally keeping me going, sacrificing many evenings out and helping with the proof reading.

Lastly, but by no means least, I would like to express my gratitude to my supervisor Dr. A. Unsworth for his continuous encouragement, ideas and, above all, his patience.

Once again, thank you all.

This text is dedicated to my dear father, with L.A.A..

DECLARATION

The work contained in this thesis has not been submitted elsewhere for any other degree or qualification and that, unless otherwise referenced, it is my own work.

STATEMENT OF COPYRIGHT

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CHAPTER ONE

INTRODUCTION

1.1 Assessment of arthritic disease

Literally the word arthritis means an inflammation of the joint. However, it is generally used to encompass the wider field of all pathological joint disorders which may, or may not involve inflammation. The most common categories of arthritic disease are; osteoarthritis, rheumatoid arthritis and the many forms of arthritis following from infection (Reiters' disease, Brucellosis).

Rheumatoid arthritis is an idiopathic disease. Various laboratory tests such as the measurement of blood protein levels and the analysis of synovial fluid are used in the initial diagnosis and the subsequent monitoring of the level of disease activity. In isolation these tests are not usually definitive. Heavy reliance is placed on direct clinical assessment of the inflammatory manifestations of the disease and on the accompanying structural changes occurring at the joint.

However, the task of accurately evaluating a patient's disease status by clinical impression is not an easy one. Brewerton (1966), in an introduction to the management of the rheumatoid hand, emphasised the complexity of the rheumatoid process. He commented that; (1) even when symptoms are mild, many joints, muscles and tendons may be involved; (2) the procession of the disease is continuous variable and unpredictable. His concluding remark is worthy of quotation.

> 'No two patients present the same problems, and no individual patient presents the same problem for any great length of time except in the later stages of the disease.'

In one effort to standardize the assessment of disease activity and the effects of therapy, Lansbury (1958) evaluated the relative importance of observable items in rheumatoid arthritis. He identified a group of crucially important factors and used these to develop both systemic and articular numerical indexes.

These were :-stiffness, fatigue, pain, muscle weakness, raised erythrocyte sedimentation rate (ESR), total amount of joint inflammation and joint dysfunction. The first five items were used to determine the systemic index, or the more general nature of the disease. These were quantified respectively by ; duration of stiffness after rising, time of onset after rising, daily aspirin requirement, grip strength and a standard ESR test. Although the author states that these items were objectively quantified, only in this case of grip strength, where a sphygmomanometer bag was used, and ESR could this be claimed to be even remotely true. The other three items involved clinical impression and the patient's own evaluation, which were precisely the factors which the test was designed to avoid. In fairness it should be said that the author was concerned mainly with the accuracy with which observations could be made by independent observers rather than the semantics of subjectivity and objectivity.

Summarizing his work , Lansbury said that :- 'In any scheme for evaluation of rheumatoid arthritis only parameters which can be accurately defined and measured should be used.'

The Lansbury index is just one attempt that has been made to reduce the inter-observer error in clinical assessment. Ropes et al (1958) and Ritchie et al (1968), amongst others, used rigorous verbal descriptions to introduce uniformity into the classification of patients suffering from rheumatoid arthritis . Verbal descriptions whilst useful, are entirely subjective in the same way as the parameters used in the Lansbury approach.

It is apparent that if simple, truly objective methods of measurement of the important parameters involved in assessment can be developed then this should lead to a more accurate determination of disease activity and the effects of therapy. In this text attention will be focused on the objective measurement of joint stiffness and grip strength.

1.2 Confusion of stiffness and muscle weakness

The profound increase in joint stiffness on waking experienced by many patients suffering from arthritis has been named 'morning stiffness'. In rheumatoid arthritis the duration of morning stiffness is a major diagnostic criterion(Cobb et al (1954), Ropes et al (1958)). Hollander (1953) has observed that morning stiffness is also found to some extent in many other forms of arthritis, including osteoarthritis and fibrositis.

Subjectively, it is difficult to distinguish between the resistance to movement of a joint , i.e. stiffness, and the inability to effect the movement, caused by deficiencies in musculature or the limiting effects of pain. This relationship was commented upon in a paper by Wright and Plunkett (1966) during investigations into the circadian variation of passive stiffness and grip strength. The authors mentioned that although changes in strength outweighed greatly the changes in passive stiffness, it could be that changes in both parameters combine to produce the overall feeling of morning stiffness. They went on to postulate that subjective stiffness may vary directly with objective stiffness measurements and inversely with maximum strength of grip.

Myers et al (1981) in a paper entitled, 'An objective measurement of morning stiffness,'actually describe a new device for measuring grip strength. Although the authors did state explicitly that stiffness was reflected in the power developed during the establishment of grip, in this text stiffness and grip strength will be treated separately.

1.3 Introduction to Objective joint stiffness measurement

Following the publication of the original papers of Wright and Johns (1960a, 1960b) and Scott (1960), a number of workers have contributed to the body of knowledge concerning the measurement of human joint stiffness. Some workers have introduced devices which provide a simple indication of stiffness, with a view to the performance of large scale clinical studies, whilst others have designed devices to study the underlying mechanisms which may cause joint stiffness.

The production of a large number of devices and a wide variety of measurement techniques led to a, perhaps, inevitable confusion of terminology. The terminology used included joint laxity, mobility, coefficient of resistance to movement and elastic and viscous stiffness. The confusion persisted and was criticised by Thompson (1978) who proposed a more consistent set of terms.

In an engineering sense stiffness can be thought of as the relationship between force and displacement exhibited by a particular material or body. As measurement of human joint stiffness has been confined to those joints which articulate in a rotational manner it is more appropriate to consider stiffness as the relationship between torque and angular displacement (these being equivalent to force and displacement in a rotational situation).

Thompson defined stiffness in the following way :

'The resistance to passive motion at a joint throughout the normal range of motion in the usual functional plane.'

'Passive 'in this sense indicating the absence of voluntary or reflex muscular activity.

This definition provides a reasonable compromise between stiffness in a strict engineering sense and its use in clinical situations and has been adopted by most subsequent workers.

However, exceptions do still persist. Wagner and Drescher (1984) in a study of metacarpophalangeal (MCP) joint stiffness refer to the ‘measurement of mobility ’and Bird et al (1986) describe the ‘hyperlaxity of joints’. Although in the latter case, as the work was concerned with subjects with abnormally supple joints, it is arguable that the ‘normal range ’element of the Thompson definition of stiffness applies.

Over twenty years after the publications of Wright and Johns and those of Scott , Unsworth et al (1981) commented that so much had been published on the relative merits of different devices and experimental procedures that the application of joint stiffness measurement to clinical research had been largely neglected. In more recent years some attempt has been made to rectify this situation with studies of the circadian variation of joint stiffness by Yung et al (1984) and Helliwell et al (1987) and an assessment of some therapeutic techniques by Yung et al (1986) but the amount of data still remains small and differing explanations of conflicting results abound.

At the time of writing, no one device for measuring stiffness objectively is commonly used as part of general clinical practice. There is a need therefore to conduct more research in this field for two reasons. Firstly, to provide new data which may help to resolve some of the outstanding arguments and, secondly, to establish the efficacy of objective stiffness measurement in everyday clinical assessment of arthritic patients.

Before proceeding further it is necessary to describe in some detail the subjects of all this measurement activity, the joints themselves.

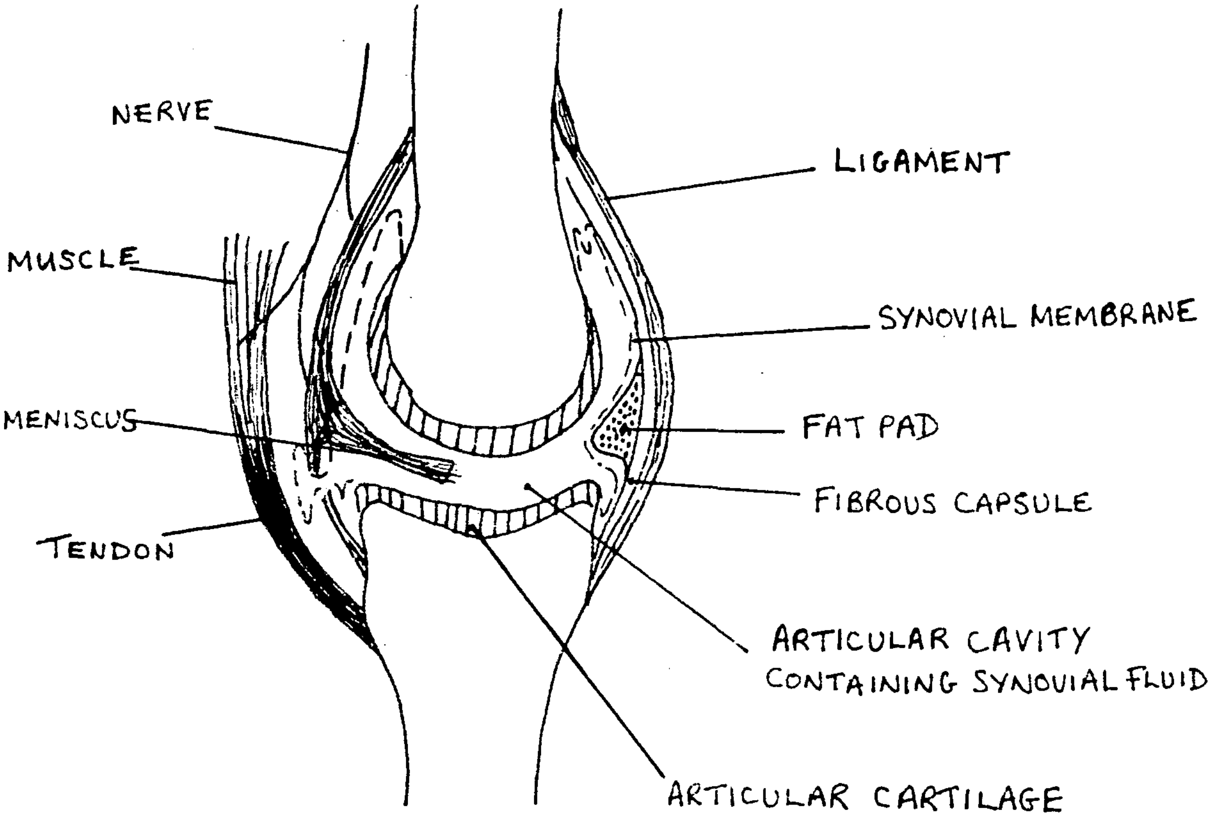
1.4 The subject of the Stiffness measurement

The material presented in this section, which has been derived from standard anatomical and physiological texts, is intended as a simple introduction for the general engineering reader who may be unfamiliar with the study of human joints.

Man has over three hundred joints in his body, each classified into one of two general types ; Synostosis, where bones are united by fibrous tissue or cartilage (as in the skull) and Synovial, which is the most common. Measurements of joint stiffness have been confined to synovial joints, particularly those typically affected by arthritis such as the joints of the fingers and the knee.

From an engineering viewpoint a synovial joint can be thought of as an elaborate but highly successful bearing, capable of providing lubrication during joint rotation and absorbing axial and radial loads. A schematic diagram of a synovial joint is shown in figure 1.1.

Fig. 1.1 Schematic diagram of a Synovial Joint



1.4.1 Synovial joints in general

The bone ends are capped by articular cartilage and contained within a fibrous capsule. In combination with ligaments, some of which may be incorporated into it, the capsule helps to maintain the joint's stability. A synovial membrane lines the capsule, surrounds the joint completely and secretes synovial fluid into the joint cavity. The membrane readily becomes inflamed by any source of irritation which may cause larger than normal amounts of fluid to be secreted.

Usually synovial fluid is only present in very small amounts. Its function is to provide nutrition for the articular cartilage and to act as a lubricant when the joint is moved. There are several theories as to the lubrication regimes within synovial joints but these form a separate field of study in themselves.

Movement of the joint is caused by muscles acting through various arrangements of tendons. The line of action of the force which is transmitted by the tendons is controlled by tendon sheaths and effects such as 'bowstringing 'of a tendon across a joint are prevented. The range of joint movement is limited by limb apposition, ligament tautness, close packing of the joint surfaces or by the effects of pain.

Further information on joint movement is better presented by consideration of a particular synovial joint. The largest body of experimental work exists for the metacarpophalangeal joint probably because of its relatively easy accessibility for measurement, the low mass and, consequently, low inertia of the digits of the hand and because it is one of the joints most commonly affected by rheumatoid arthritis. The MCP joint of the index finger of the right hand will be the subject of joint stiffness measurements in this text and it is, therefore, convenient to describe some joint motion conventions in terms of it.

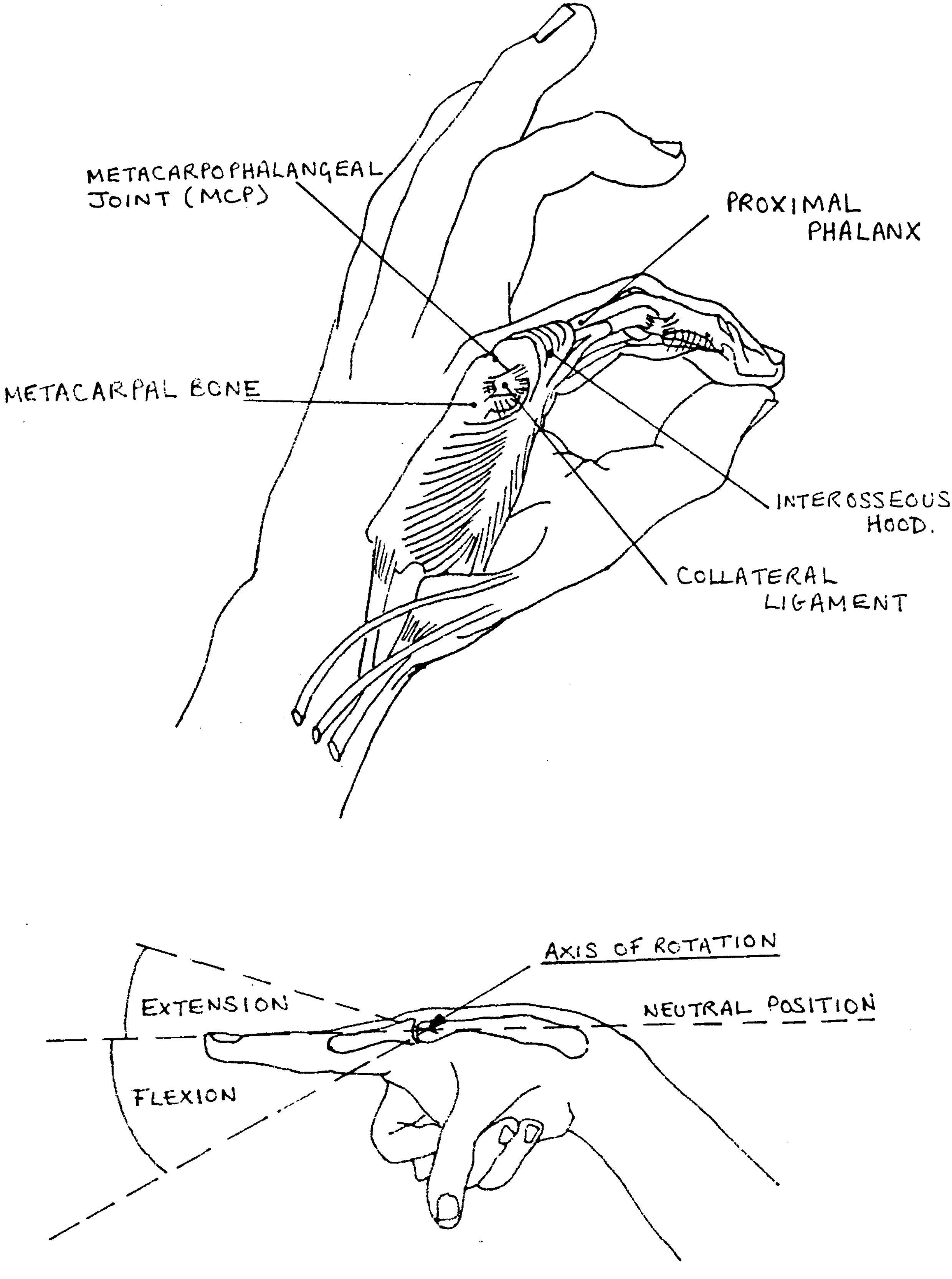
1.5 Joint movement conventions

The MCP joint is the joint between the head of the metacarpal bone and the head of the proximal phalanx. Figure 1.2 shows the position of the MCP joint of the index finger in relation to the rest of the hand.

The position whereby the proximal phalanx is in alignment with the metacarpal bone is known as the neutral position and is arbitrarily defined to be zero degrees.

If the proximal phalanx is moved dorsally from the neutral position then the joint is said to be in extension. Angular positions in extension are defined as negative. Movement of the proximal phalanx towards the palmar aspect of the hand from the neutral position puts the joint into flexion. Flexion angles are defined as positive.

Fig. 1.2 MCP Joint : Movement Conventions



The proximal phalanx is caused to move by moments (or torques) applied about the shown axis of rotation by the extensor tendon apparatus and the flexor tendon apparatus of the hand. The sum of the moments acting so as to move the joint into extension is known as the extension moment. Similarly, the sum of the moments acting to move the joint into flexion is known as the flexion moment.

If the hand is relaxed the proximal phalanx occupies a position somewhere in flexion. This position will vary from subject to subject but occurs when the extension and flexion moments are in equilibrium. Consequently, this is known as the equilibrium position.

In addition to the flexion/extension plane the MCP joint commonly moves in the abduction/adduction plane caused by spreading and closing of the fingers (spreading - abduction, closing - adduction). Loebl (1972), Wagner (1974) and Howe et al (1985) have measured MCP stiffness in this plane and it seems reasonable, therefore, to alter the phrase, 'the usual functional plane ', from Thompsons' stiffness definition to 'a usual functional plane.'

1.6 Introduction to grip measurement

Assessment of the ability of the hand to grasp or pinch has frequently been used as part of larger investigations of disease activity and to monitor the recovery of subjects suffering from trauma injuries.

The majority of workers involved in clinical studies have monitored the maximum change in pressure during an active squeeze of a sphygmomanometer cuff attached to a blood pressure manometer (Ingpen (1968) and Backlund and Tiselius (1967) amongst others). The prevalence of this method is probably due to the ready availability of the equipment within hospitals or surgeries and its ease of use. Measurements of this kind are, however, prone to inaccuracy as will be discussed in the next chapter (chap2, sec 2.3).

Specially designed hand dynamometers have been available for a number of years and, more recently, they have been incorporated as part of comprehensive microcomputer controlled hand assessment systems such as that of Jones et al (1985). However, Buchanan (1984) has noted that these specialist devices do not seem to have been favoured in general clinical practice.

1.6.1 Types of grip

Long et al (1970) cited the previous works of Napier (1956) and Landsmeer (1962) as the prime movers in distinguishing between different forms of hand grip. Grip activities were divided into two categories, power grip and precision handling.

Power grip was defined as, 'forcible activities of the fingers and thumb acting against the palm, for the purpose of transmitting force to an object.'The actual positioning of the fingers surrounding an object is determined by the shape of the object and the nature of the activity. For example the positioning of fingers when gripping a cricket ball will not be the same when gripping a tennis racquet, not only due to the differing shapes but also due to the differing requirements of each sport. Rotations, abductions and adductions of the phalanges may be required to accommodate the shape of the object.

Precision handling involves the manipulation of small objects in a finely controlled manner by one or more of the fingers acting in opposition with the thumb. Chao et al (1976) and Berme et al (1977) have studied the forces developed during various forms of pinch activity and have developed three dimensional models of the kinematic chain of the fingers to analyse them. However, such work is beyond the scope of this thesis and thus attention will be refocused on power grip.

Long et al (1970) mention that power grip is static not dynamic and isometric not isotonic. It could be argued that during the establishment of grip the deformation of the material of the object being grasped constitutes a dynamic effect. However, the deformations for most reasonably solid materials would be so small that the notion of a static or isometric power grip seems reasonable, but this brings into question the usage of the word 'power'to describe this form of grasp. Jones (1984) commented that since no motion is involved then no work can be done. As power is the rate of doing work then it follows that there can be no power. An explanation of this type seems to cause confusion, especially in clinical circles, and certainly there is good reason for doubt. If no work is being done then it seems illogical that any fatigue effects would be encountered after grip had been established. Consideration of the thermodynamics of muscle leads to the following explanation.

If muscle were perfectly elastic then, after contraction of all the muscle groups during a grasp, all the energy that was required to deform the material of the object would be stored as strain energy within the muscle and associated structures. But muscle is not an elastic material and, once contracted, energy is dissipated in the form of heat (Alexander 1968) and this must be replaced if the level of grip is to be maintained. From a thermodynamic viewpoint the net rate of flow of energy into the muscles does not constitute power but it will, ultimately, lead to fatigue. Despite these explanations there seems little point in trying to change terminology that is so well established and so the name of 'power 'grip will be retained in this study.

1.7 Factors affecting power grip

Tubiana (1981) suggested that a typical gripping activity consisted of three phases. The first stage being the opening of the hand which requires the simultaneous action of the long extensors and intrinsic muscles. The second phase involves the flexing of the digits to grasp the object. In power grip the thumb is very useful as, in combination with the palm, it resists the forces applied by the other digits. Intrinsic muscles control the flexion of the MCP joints and adduction of the thumb. However, Tubiana stated that the intrinsics tire easily and so in a power grip the extrinsics become more important.

In an essay on the functional relationship between the fingers and the thumb Harrison (1981) mentions that, in the position of power grasp immediate loss of 'power'in gripping is noticed when the middle finger loses function either from limited movement or pain. The author also notes that the ring and little fingers supinate towards the middle finger to provide reinforcement.

Many authors have noted that the hand does not function in isolation but is dependent on the positions of wrist, elbow and shoulder. Simmons et al (1981) emphasised that the position of the wrist being midway between the origin and the insertion of the long flexors dramatically influences their effectiveness.

Some of the mechanisms that act in a 'power grip 'have now been mentioned, and as it is this function that has been used as one of the indices of the rheumatoid hand, it is pertinent to describe how the changes in the structure of the hand and wrist in rheumatoid arthritis may influence the strength of grip.

Burke (1984) in a larger treatise on the effects of rheumatoid arthritis commented that weak grip in the rheumatoid hand may arise for a variety of reasons.

Wrist synovitis or tendon rupture may result in a flexion deformity of the carpus. The relative lengthening of the flexor tendons when the wrist is flexed thus reduces their effectiveness. The persistent pain during the course of the disease may lead to the disuse of many of the joints and hence the atrophy of the muscles. Flexor synovitis, triggering or tendon rupture may all present as weakened power grasp. Joint synovitis, subluxation or intrinsic muscle tightness may also reduce finger flexion and so reduce the ability to grip.

1.8 A starting point

It has been noted that none of the specialist devices designed thus far for the objective measurement of joint stiffness or grip strength have been widely adopted for use in general clinical assessment of the arthritic diseases of the hand. Initially an attempt will be made to establish why this is so. In the next chapter some measurement devices and procedures and what they have revealed about the nature of arthritic disease will be analysed.

CHAPTER TWO

A REVIEW OF MEASUREMENT METHODS AND CLINICAL FINDINGS

2.1 Some objective methods for measurement of joint stiffness

2.1.1 Constant torque devices

Scott (1960) in a paper entitled 'morning stiffness in rheumatoid arthritis 'measured the passive stiffness of the metacarpophalangeal joint of the index finger.

The subject's hand was fastened to a horizontal platform by two retaining straps with the palm lowermost and the fingers free to move. A spring of known stiffness was suspended vertically a measured distance above the platform and directly over the skin crease of the distal interphalangeal joint of the index finger. The spring was extended and attached to the finger, the subject was instructed to relax completely and then the spring was released, so moving the MCP joint into extension.

Joint stiffness was described simply in terms of the vertical distance through which the finger was displaced.

A number of readings were taken in a short space of time to test the repeatability of the measurement and it was found that the vertical distances recorded increased. This indicated a lessening of stiffness with repeated extension of the joint. Scott noted that the variability of successive measurements was not excessive amongst those subjects with healthy joints but was unacceptable in subjects suffering from rheumatoid arthritis (RA).

It is immediately evident that joint stiffness is not a simple matter of applying a known torque about the joint and measuring the resulting angular displacement. Previous rotational history must also be taken into account and this appears to be especially important in the case of diseased joints.

The quantity being measured by this technique is a representation of the torque at the MCP joint which resists the movement into extension, caused by the torque applied by the vertical spring. For meaningful comparisons to be made between subjects the applied torque should be consistent. In this method the applied torque was dependent on the length of the of the subject's fingers and therefore comparisons could not be made. Additionally, it must be assumed that the subject was relaxed when measured and not contributing any added resistance to extension through voluntary or involuntary muscular contraction.

Scott appeared to recognise these drawbacks and did not attempt to make comparisons between subjects. He was mainly concerned with the circadian variation of joint stiffness in individuals. Bearing in mind the simplicity of the apparatus and its ease of use, this measurement method has merit if it is used solely for this purpose.

Loebl (1972) in an investigation of what he termed 'metacarpophalangeal mobility 'devised a measurement method which gave an indication of stiffness in the abduction/adduction plane. The hand was held in an instrument in such a way that the MCP joints were flexed to 90 degrees. A spring balance and pulley arrangement applied equal but opposite torques to the MCP joints of the middle and ring fingers so the fingers were forced to abduct. Protractors, positioned on the centres of rotation, measured the degree of abduction.

A similar method was used by Wagner (1974) to measure 'passive finger flexibility '. The only real difference in this method to that of Loebl being that the MCP joints were abducted from the neutral position. Wagner's device could also perform measurements in the flexion/extension plane. In this case a constant torque was imposed on the MCP joint causing it to move into extension from the neutral position. When equilibrium was achieved between the applied and the resistive torque at the joint, the angle of elevation of the finger was read off a scale. The angle of elevation was termed a measurement of 'passive hyperextension '.

Measurements of MCP joint stiffness at the limits of normal range were also undertaken by Jobbins et al (1979). The joint was moved into extension from the neutral position by manually rotating a drive mechanism aligned with the axis of rotation of the joint. A slipping clutch was part of the mechanism and could be preset to slip at any given value of torque at which time the angle of rotation was noted. The device was termed a 'joint hyperextensometer 'and was used to measure 'joint laxity '.

All of the devices described use the principle of measurement of a rotational displacement arising from the application of a preset torque. By calculating the ratio of applied torque to rotational displacement a value for joint stiffness is obtained for a particular angular position in the range of motion of the joint.

If the relationship between torque and angular displacement could be assumed to be linear then a single stiffness measurement of this kind could be taken as representative of stiffness throughout the whole range of motion. However, analysis of further work will show that this assumption cannot be made.

2.1.2 Measurement of resistance to a standard rotational cycle

In 1960 Wright and Johns published two papers (1960a, 1960b) which described their work with a new device to measure MCP joint stiffness. The device was later named the MCP joint arthrograph. A rotary motion was imposed on the MCP joint of the index finger in the flexion/extension plane by means of a heavy pendulum which rotated a shaft. The shaft was carefully aligned with the axis of rotation of the joint and the finger was attached to the shaft via a strain gauged lever. When the pendulum was set in motion the joint was thus cycled sinusoidally. By alteration of the length and amplitude of the pendulum swing the frequency and amplitude of oscillation of the joint could be varied. Resistance to the imposed motion by the joint was monitored at all points in the cycle by recording the change of strain in the lever. Rotational displacement was recorded by a potentiometer attached to the axis of the shaft and instantaneous velocity was measured by a moving coil velocity transducer (fig. 2.1).

By displaying the strain and rotational displacement on the vertical and horizontal axes of a dual beam oscilloscope a hysteresis loop was generated (fig. 2.2). From the shape of the loop it was clear that the relationship between resistive torque at the joint and rotational displacement was non-linear. Furthermore, the very fact that hysteresis was present indicated that energy was dissipated during the course of one rotational cycle.

Studies of the relationship between resistive torque and angular velocity revealed a similar non-linear relationship.

Joint stiffness has been defined as the resistance to passive motion of the joint (sec 1.3). From the original experiments of Wright and Johns it can be seen that joint stiffness depends not only on the amplitude of the motion but also on its velocity.

The basic arthrographic measurement technique has been used by a number of other workers for studies of MCP joint stiffness and knee joint stiffness. Long et al (1964a, 1964b), Backlund and Tiselius (1967) and Unsworth et al (1982) have applied the method to measurement of MCP joint stiffness in the flexion/extension plane. Much of the basic apparatus has been modified. In particular there have been changes in : torque transducer design; the drive mechanism to produce the oscillation; experimental procedure and data collection and analysis.

Figure 2.1 Apparatus of Wright and Johns (1960)

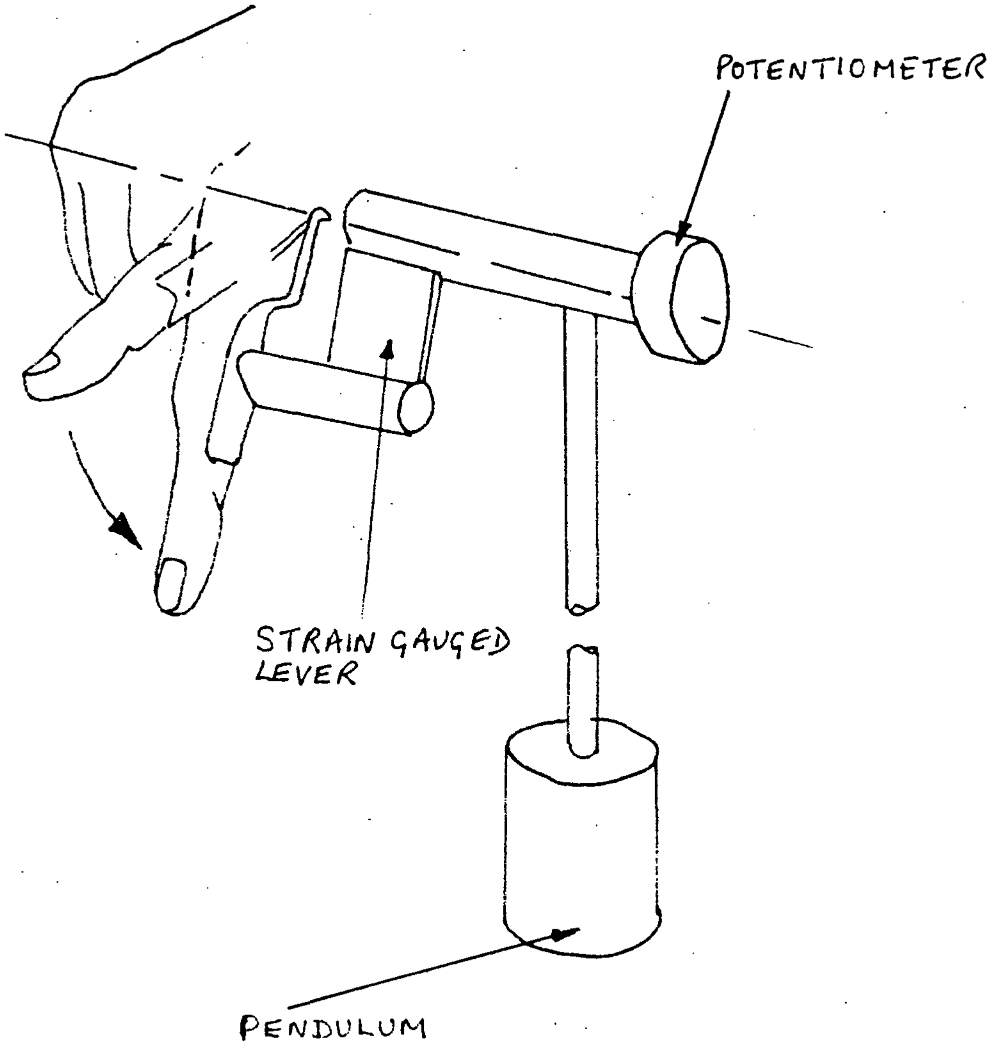
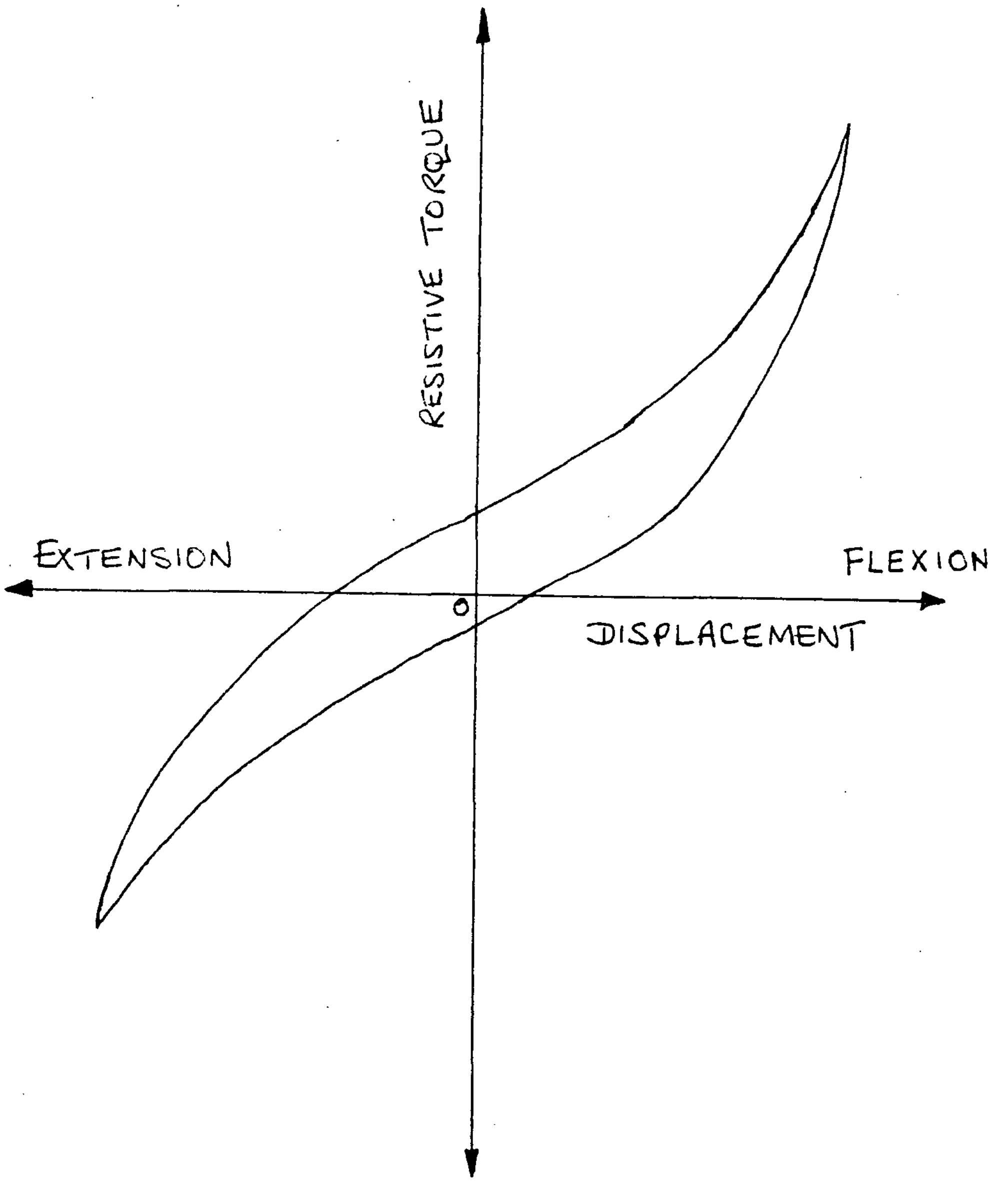


Figure 2.2 Hysteresis loop due to Wright and Johns



Of these, variations in experimental procedure and data analysis are perhaps the most significant as they make comparisons between different groups of workers difficult.

Wright and Johns imposed large amplitude cycles of 30 degrees about an angular position in flexion, which was estimated to be the mid-point of joint range. In contrast, Unsworth et al (1982) imposed small amplitude oscillations of 4 degrees at intervals of 10 degrees from 4 degrees to 94 degrees of flexion.

Analysis methods borrowed from rheological work on elastomers were used by Wright and Johns to quantify joint stiffness into elastic stiffness, viscous stiffness, plastic stiffness and frictional stiffness. The pertinence of this analysis method and others related to it are discussed in detail in Chapter three. For the moment it is sufficient to say that resistance to motion at a joint can be divided broadly into two categories, elastic resistance and dissipative resistance. A perfectly elastic joint would be capable of recovering completely from an imposed rotational displacement, there being no energy loss. Contrarily, a joint that provided resistance to motion by purely dissipative means, such as friction, would not be able to recover to the starting point of the displacement at all.

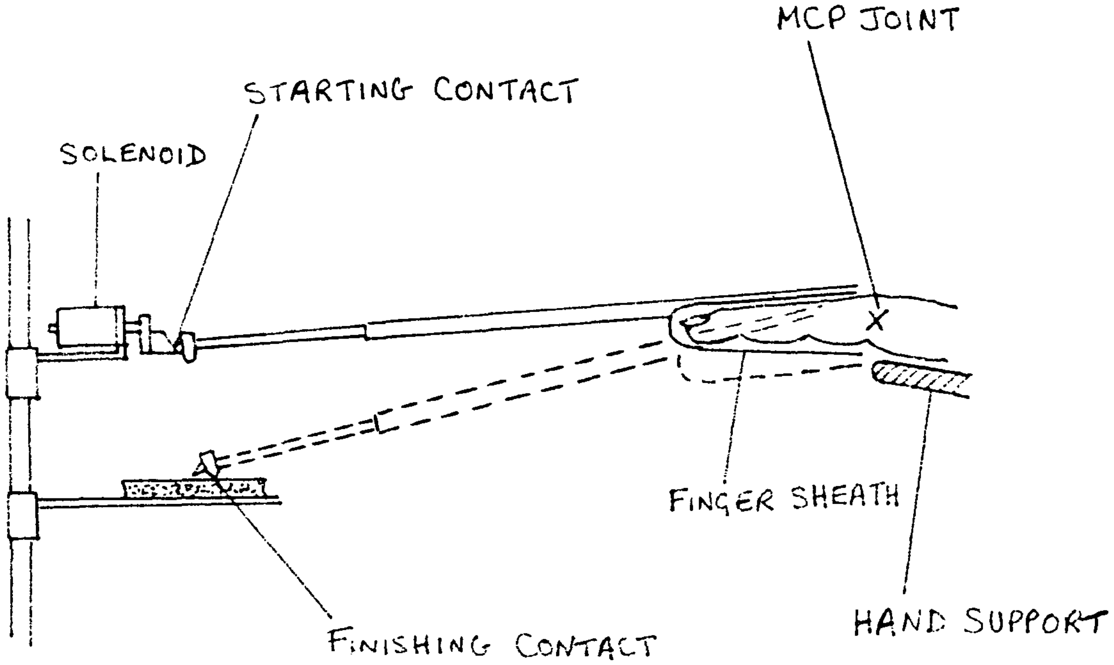
The dissipation of energy during joint motion has been seen as a major indicator of joint stiffness by some workers and has formed the basis of their measurement techniques.

2.1.3 Measurement related to energy dissipation

In a paper entitled 'muscle tension and joint mobility ', Barnett and Cobbold (1969) describe an elaborate piece of apparatus with which the decay of amplitude of a pendulum, attached to the distal interphalangeal joint, was used to determine the 'coefficient of resistance to movement 'at the joint. If impedance of the motion of the pendulum due to the drag of the air is neglected, the decay in its amplitude of oscillation must be due to dissipative effects at the joint.

Inpen and Hume-Kendall (1968) recognised the need for a simple device to measure joint stiffness which would be independent of pain and voluntary muscular action. They adopted an idea proposed by Hicklin (1967) which was based on the measurement of fall times of a weighted lever attached, via a sheath to the MCP joint. The lever was telescopic, so that the distance between the centre of rotation of the MCP joint and the end of the lever could be held constant for different finger lengths. A schematic diagram of the apparatus is shown in figure 2.3.

Figure 2.3 Apparatus used by Ingpen and Hulme-Kendall (1968)



The time taken for the lever to fall through a ten degree arc from the neutral position was measured by a digital frequency meter, which was started and stopped by the opening and closing of contacts at either end of the ten degree arc. The complete system was capable of measuring fall times accurate to one millisecond.

The authors contention was that increased fall times would indicate increased resistance at the joint. However, it has been mentioned that the equilibrium position of the joint (the point of zero nett torque) lies somewhere in flexion (sec. 1.5). Unsworth et al (1981) showed that in a group of young adults this position varied from 16-44 degrees of flexion depending on the subject. Hence in this experimental method, where neutral position was the starting point of the fall, it is reasonable to assume that there would be an elastic restoring torque assisting the motion. Stiffer joints in purely elastic sense would therefore have caused decreased fall times. Conversely, dissipative effects, such as friction, would impede the motion causing increased fall times. This experimental method does not permit a discrimination between elastic and dissipative resistance at the joint.

2.2 General Clinical findings

During their early arthrographic experiments, Wright and Johns (1960) observed that patients with active R.A. involving the MCP joint showed an increase in elastic resistance to motion when compared with undiseased controls. Experimentation was also carried out on two female subjects suffering from systemic sclerosis (hardening of the connective tissue). For these two cases the authors observed a marked increase in elastic resistance. It should be noted that subject numbers in these preliminary experiments were small but the results did appear to demonstrate that arthrographic measurement could be used to differentiate between diseased and undiseased conditions.

Backlund and Tiselius (1967) made objective measurements of MCP joint stiffness using a similar arthrographic technique to that of Wright and Johns. Comparisons of the results from 16 patients suffering from R.A. with those from 10 undiseased controls showed that elastic resistance to motion and energy dissipation were of a similar level in both groups. This finding was obviously in contradiction with the preliminary results of Wright and Johns.

In a general review paper on joint stiffness measurement, Goddard et al (1969) introduced a knee arthrograph and also presented some findings from MCP joint stiffness measurements. For the MCP results no differentiation was made between elastic and dissipative stiffness but the general 'stiffness 'findings are worthy of discussion.

From studies of two age-matched groups of 31 women and 31 men, it was observed that men showed greater MCP stiffness than women. Measurements were also made for a group of women ranging in age from 6 to 66 years. No subject numbers were stated but it was reported that there was a 300 % increase in stiffness from youngest to oldest. The authors speculated that increasing joint size in reaching maturity may have been a factor in the latter findings but that increasing stiffness after maturity was probably due to age changes of the collagen of which the periarticular structures are composed.

It is interesting to compare the comments on factors affecting MCP joint stiffness made by Goddard et al with similar work on the knee joint. Such et al (1975) conducted well defined experiments on 70 knee joints using a modified version of the knee arthrograph introduced by Goddard. The subjects selected had no clinical history of joint problems and ranged in age from 21 to 65 years.

It was found that the energy dissipated during rotation of the knee increased with advancing age but that elastic resistance to motion did not. The division of stiffness into elastic and dissipative components made the following explanation possible. It was suggested that the changes in surface roughness of articular cartilage and a decrease in the viscosity of synovial fluid with age may have caused a decrease in the effectiveness of the lubrication mechanisms acting at the knee joint and, consequently, an increase in energy dissipation.

Such et al explained that the lack of change in elastic resistance with age was possibly due to the tendency of ligaments and tendons surrounding a joint to become lax with age, thus causing an area of 'slack 'during the knee rotation, which would negate the increasing rigidity of collagen with age.

Further studies of the knee joint were undertaken by Thompson (1978). Thompson used a horizontal arthrograph which was designed to eliminate the influence of lower limb mass on the stiffness measurement. Experiments on 25 male subjects in the age range 21 to 73 years revealed that there was no correlation between elastic stiffness or energy dissipation with age. These findings were obviously inconsistent with Such et al and Goddard et al. Therefore the effect of advancing age on joint stiffness is not certain.

An explanation of age effects, such as changes in the surface roughness of articular cartilage leading to decreased lubricative properties, may be plausible for a large, load bearing joint like the knee. In a smaller joint, which does not bear major loads, such an explanation is less likely. Indeed, Wright and Johns (1962) have demonstrated that the major contributors to the MCP stiffness measurement are probably the passive properties of muscle and the joint capsule (see chapter 3, section 3.8)

2.2.1 Diseased joints and the effects of therapy

There is scanty information about the effects of therapy on joint stiffness. Wright et al (1969) observed that the MCP joint stiffness of patients with active R.A. decreased markedly on administration of cortico-steroids. In view of future discussions, it should be noted that the patients considered showed increased joint stiffness, compared with healthy subjects, before administration of the steroid. The effect of short wave diathermy was also investigated in patients suffering from osteoarthritis of the knee. Wright et al observed that the overall stiffness of knees was reduced by about 20 per cent ten minutes after treatment, but that the beneficial effects were transient.

Short wave diathermy was also shown to have beneficial effects on MCP joint stiffness by Yung et al (1986). This was just one of five physiotherapeutic modes considered, the others being, wax baths, ultrasound, ice and exercise. Stiffness measurements were made before and then immediately after one treatment in a group of healthy subjects and in patients suffering from R.A.. Both short wave diathermy and ultrasound significantly reduced the amount of energy dissipated in the joints of the patients.

Perhaps the most interesting finding of Yung et al was that patients suffering from rheumatoid arthritis did not exhibit increased elastic stiffness or energy dissipation when compared with healthy subjects. It was suggested that whatever the patients were feeling as stiffness was not the same as the actual objective stiffness, measured in terms of energy dissipation and elastic resistance.

Recent work by Howe et al (1985) and Helliwell et al (1987), measuring MCP joint stiffness in the adduction/abduction plane, supported this view. When comparisons were made between healthy subjects and patients suffering from R.A. no significant difference was found in elastic resistance. More remarkably, the energy dissipated in the joints of the patient group was significantly less than that in healthy subjects.

Evidence to show that arthritic joints are actually less stiff than healthy joints is a fairly recent development and has been made possible by testing greater numbers of joints than in earlier arthrographic studies. Decreased energy dissipation in diseased joints has been explained by the tendency of the joint capsule and ligaments to become lax following cycles of inflammation and remission. The mean duration of disease in the arthritic subjects tested by Helliwell et al was 12.4

years and thus it is reasonable to suppose that the majority of diseased joints had undergone several inflammation/remission cycles.

From the work of Yung et al and Helliwell et al it seems probable that, in the majority of patients, what is perceived as stiffness is not stiffness at all but possibly due to the inability to move joints due to pain or muscle atrophy. These recent developments are in agreement with the observations of Backlund and Tiselius (1967) but appear to be contradiction with the earlier findings of Wright et al, and Ingpen, both of whom observed increased stiffness levels in arthritic joints. However, Wright et al (1969) did stress that markedly increased joint stiffness was found in those patients with active R.A. and only to a small extent in patients in whom the disease was in remission. The possibility remains therefore that objective measurement of joint stiffness is still useful as an indicator of disease activity and has advantages over subjective impressions gained from dialogues with arthritic patients.

2.3 Some objective methods of grip strength measurement

The techniques used to measure grip strength in power grasp can be divided into two categories, dynamic and isometric. During an isometric muscle contraction the grip force is generated in the initial stages and then maintained without any shortening in the length of the muscle fibres. Conversely, during a dynamic or isotonic contraction the force is developed during the continuous stretching of the muscle. As the muscles are shortening during an isotonic contraction work is therefore being done on whatever type of grip transducer is being used to measure the grip force.

Lansbury (1957) measured grip strength as part of his evauation of an articular index for rheumatoid arthritis. A double folded blood pressure cuff, inflated to a pressure of 20 mm of mercury, was connected to a standard mercury , blood pressure manometer. The patient was asked to grip the cuff and to exert their maximum grip for a predetermined period of time. Lansbury introduced an element of competition which he referred to as 'beat the doctor 'to encourage the patients to sustain their maximum effort. A competitive element is important for repeatability in an active test of this kind where the results are affected by psychological as well as physiological factors. The average of the highest pressure readings for two consecutive tests was recorded for each hand. The author found a reasonably good correlation between grip pressures and the other parameters of his index, namely subjective stiffness, fatigue and pain.

This type of measurement technique has been used by many workers and although the test and pressure recording methods have varied the inflated cuff or Davis bag (inflated rubber bag) have retained their popularity as the grip transducer. A number of problems have been noted concerning the accuracy of pressure readings taken from a fluctuating mercury column. Lee et al (1974) investigated the inter-observer error that could result from this form of measurement technique. The authors concluded that there was a considerable inconsistency in measurement of grip strength when conducted by different physicians and that some account should be taken of this error when making deductions from other experiments. Results from an investigation of circadian variation showed that evening values of grip pressure were significantly higher than morning values but the differences between the means were of the same order as the inter-observer error.

In a preliminary study to evaluate the use of the inflated cuff, Jones (1984) commented that the mercury column was very sensitive to small jerky movements of the fingers during the course of the grip. The large amplitude oscillations that resulted made judging an average pressure value difficult and also negated the use of a tell-tale indicator since the final position of the tell tale would not represent a steady state condition.

From these observations it therefore seems desirable that the element of uncertainty of pressure measurement is taken away from the observer and is handled automatically. A number of devices have been designed which will perform this type of operation.

Wright and Plunkett (1966) used a slight variant of the method used by Lansbury by connecting a rubber bag, inflated to 20mm of mercury, to a bourdon gauge pressure transducer which itself was connected to a pen recorder via a transducer. In this way the authors were able to generate pressure/time recordings automatically which enabled them to conduct their analysis at leisure at a later date. It was not stated explicitly what value of pressure was extracted from the pressure time curves but it is reasonable to assume that either the maximal values or the mean value of the pressure for the duration of the grip were calculated. The possibility that pressure/time curves actually contain much more useful information about the nature of gripping activity was exploited by Myers et al (1980).

The apparatus consisted of a sphygmomanometer cuff connected to a semi-conductor pressure transducer. The transducer fed signals into a unit which analysed the pressure/time curves. Various parameters were derived, these were :- maximum grip pressure, 95% rise times (time taken to reach 95% of the maximum grip pressure), work done during attainment of the maximum grip and the maximum power developed.

Work and power were calculated in the following manner. It was assumed that work was done by the subject by compressing the air within the cuff transducer system. Further, it was assumed that the grip caused an isothermal, reversible compression of the contained air. Pressure and volume change continuously during the grip, in going from the initial pressure (P_1) to the final maximum pressure (P_2), and so the work (W) input was calculated by evaluation of the following integral,

$$W = \int_{V_1}^{V_2} P dV$$

where V_1 and V_2 represent the initial and final air volumes respectively. The power output was determined by dividing the work done by the time taken to achieve the maximum pressure.

However, the total work done during the grip is not simply reflected in the compression of air alone. The changes in stress and strain in the material of the cuff must also be taken into account. That is,

$$W = \int_{V_1}^{V_2} PdV + \int_{\epsilon_1}^{\epsilon_2} \sigma d\epsilon$$

where σ and ϵ represent the stress and strain functions that will vary continuously during the deformation of the cuff. Consideration of the magnitude of the forces in the material of a cuff when digging in the finger ends suggests that the value of the stress/strain integral is not trivial.

Experiments conducted by Jones (1984) with cuffs of different sizes showed that the grip pressure depends on the size of the cuff, pressure reducing with increasing cuff size. This result was expected, since the larger the cuff, at equal pressures, then the larger the force per unit surface area. Hence a larger force must be applied to the cuff to produce the same pressure change.

Thus it can be seen that not only do grip pressure reading depend on initial cuff or bag pressures but they are also dependent on the stress/strain properties of the material of the cuff and its size. Carus et al (1985) and Jones et al (1986) have also commented that different techniques of squeezing the cuff of bag will give rise to different pressure readings. For example digging in the finger ends as opposed to lying them flat against the shape of the cuff will produce a greater pressure change for the same grip force since the force is acting over a smaller area.

All these factors throw doubt on the results that have been obtained from inflated cuffs or bags. However, it is reasonable to suppose that grip techniques will, with practice, be reasonably consistent for a particular subject and thus variations in grip pressure exhibited by the same subject, with the same apparatus, at the same ambient air pressure, are valid reflections of changes in grip function, although not an absolute measurement of gripping force. It is apparent that considerable care must be exercised when attempting to compare actual pressure values from different groups of workers and it is more appropriate to consider the general trend of pressure change.

2.2.1 Other types of dynamic grip measurement

Bowers et al (1961) investigated the use of three different types of grip strength dynamometer. These were, the Stoetling adjustable dynamometer, the cable tensiometer and the Narangansett hand spring dynamometer. Of these devices only the cable tensiometer did not provide for adjustment for individual hand size. Apart from this factor the operation of the devices was similar, all involving the gripping of a handle which was attached to a spring balance arrangement (or in the case of the tensiometer a pre-tensioned cable). Readings were taken by eye from a graduated scale.

Bowers took anthropomorphic measurements from a group of 100 healthy young adults. Measurements were made of hand length, middle finger length , length of the first phalanx of the middle finger, wrist girth, forearm girth and hand width. The correlation between these measurements and the greater forces produced by the adjustable dynamometers suggested that adjustability permitted the subjects to take advantage of their full leverage and therefore the adjustable dynamometers more closely reflected the true grip strength of the hand. The high correlation between the forearm and wrist girths were not surprising since the flexor and extensor muscles which account for a large proportion of the hand grip strength, are located in the forearm and pass over the wrist to the fingers.

A similar study was undertaken by Montoye and Faulkner (1964). In this case the authors found that a slight advantage was gained by adjusting the grip size and this only had an effect for very small or very large hands. The authors noted that hand width appeared to be the best method of judging the degree of adjustment to make.

From these papers it appears that there is some argument as to the importance of adjustable grip sizes in this type of dynamometer. In view of the small magnitude of the advantages to be gained from this, and the extra experimental variability which it entails, then perhaps the best method to adopt would be to have a grip transducer of standard size which would be suitable for the majority of hands.

Heyward et al (1975), in yet another comparative study, investigated the qualities of the Stoetling adjustable dynamometer and the linear variable differential transformer (LVDT) for measuring maximal grip strength. Both the devices were dynamic but whereas the output from the Stoetling depended on the displacement of a spring, the LVDT produced an electrical analogue voltage which was proportional to the movement of the core of the transformer.

It was found that the mean grip force values for the Stoetling were less than those for the LVDT. Heyward suggested that the reason for this was directly related to the difference in range of movement of each device. As the spring device moved further for the same force then this could possibly mean that there may have been a larger degree of flexion of the interphalangeal joints. The change in joint angle and angle of pull of the muscles may have resulted in less force production due to the disadvantageous position of the hand and fingers. There is also evidence to suggest that dynamic grips are less efficient than isometric ones (Elder and Trueman 1980) and as the LVDT device approximated more closely to an isometric grip than the Stoetling this may also be part of the explanation of the difference in mean grip forces of the two devices.

Not to be omitted from the plethora of comparative studies that have been made, Sheehan et al (1983) looked into the relationship between grip strength and what they referred to as 'hand function '. Grip strength was measured by a proprietory (Boots) grip meter which was simply a rubber bag connected to a dial pressure gauge. Hand function was measured by a Winthrop torquometer. The torquometer was a device which involved the tightening of an internal spring which provided an increased resistance as the top of the device was twisted. Calibration of the torquometer was in arbitrary units and by the nature of its action was not a measurement of power grip but an indicator of the effectiveness of the hand, wrist, elbow and shoulder combination. The torquometer was used both on an adjustable stand and also bimanually (the other hand providing the opposition to the twist grip).

Both the devices were used to study the grip strength and hand function of the 33 subjects, all of whom were defined as classic RA by the American Rheumatism Association definition (Ropes et al 1958). The authors found a high correlation between the two devices when compared with other subjective methods of assessment. They noted that the torquometer had advantages in speed of use and size but there were question marks over its robustness and durability. It should be mentioned that the final reading that was taken from an individual measurement was the best of three attempts but no data was available as to the observer errors or the repeatability of either device.

2.2.2 Isometric grip measurement

Perhaps because of the disadvantages of the dynamic devices already mentioned and because the more natural form of power grip is isometric (Long et al (1970)) a number of isometric devices have been designed.

Bechtol (1954) introduced the Jamar dynamometer. This dynamometer was adjustable to accommodate different hand sizes and gripping of the handle was resisted by a sealed hydraulic system. As the movement was small, less than one eighth of an inch, the grip was taken to be isometric. The Jamar dynamometer was also used by Schmidt (1970) and by Swanson (1970) in investigations of the factors which effect the strength of the hand.

The conclusions of the three groups of workers were generally in agreement but there were some areas of conflicting opinion. It was found that the force of grip was influenced by many factors:- the size of the hand spacing, the effect of previous exercise, age, state of nutrition and pain. Swanson noted that there was little difference in the force readings if the subjects were sitting or standing or if the extremity was supported or unsupported. Bechtol placed quite a lot of importance on the differences between the dominant and the non-dominant hand but Swanson concluded that from his results there appeared to be little difference between the two. This latter conclusion is most interesting as all workers who have been referenced so far, including those working with dynamic devices, have, in the main, commented that the dominant hand (the one used for most activities) produced significantly greater force pressure readings than the non-dominant one.

Pearn and Bullock (1979) recognised the need for an instrument which was very sensitive, yet robust and one which had a wide range of force. They employed strain gauges in the measurement of isometric muscular contraction. Subjects were asked to grip a U-shaped steel handpiece to which strain gauges were applied towards the bottom of the arms of the U. The authors stated that as the length of the moment arm was so long then this meant that inadvertent misapplication of the centre of force at the top of the arm did not give an error exceeding 4%. If two gauges had been connected so that they measured the difference in strain rather than the absolute value then this error should have been eliminated completely. However, it may be that the former method was preferred because of its greater sensitivity. The strain gauges were connected to a standard strain indicator unit which was battery powered.

A pilot study showed that 90% of all subjects fatigued after the second of three consecutive maximal hand squeezes. The fatigue effect is important but it should be noted that subjects in this study were young children and not adults as in the others. Results from comparison of the dominant and non-dominant hands supported the view of Swanson that the force registered by the two hands was not significantly different.

The contributions from both hands was also investigated by Ohtsuki (1981) but from a completely different viewpoint. Ohtsuki was concerned with the decrease in grip strength that may be observed during a bilateral exertion. In other words, are the forces generated when both hands are used simultaneously simply the vector sum of the individual grips or do the two grips interfere?

Forearm, palm and the proximal phalanges were kept immobile by a plaster cast. In this way only the two finger flexors (digitorum and profundus) could apply force to the transducers. The maximum voluntary isometric strength developed by both hands was measured. The individual contributions of the digits was measured in one of the hands whilst the other simply clasped a handle in the same manner as some of the earlier dynamometers. The force transducers were small load cells and axial force was applied to them via nooses into which the individual fingers were hooked.

Electromyographic readings were taken by sensors placed on the skin over the finger flexors' muscle bellies between the flexor carpi ulnaris and the flexor carpi radialis, in line with the long axis of the forearm. The author found that simultaneous bilateral exertion reduced the maximum isometric muscle strength of the individual grips and that the electrical activity of the finger flexors decreased in parallel with the decrease in grip force following successive exertions. Perhaps more interestingly, it was noted that the contribution from the individual fingers varied, from highest to lowest, in the following manner; middle, ring, index and little.

This latter finding was confirmed by the work of Jones et al (1986) who used a more convenient method of assessing the individual finger force contribution (this will be discussed in more detail in chapter four). Experimental results based on a group of 20 normal subjects and 38 patients suggested that this pattern of grip was remarkably similar between patients and normals, although the average gripping force was about one third of the mean normal value and the spread of values was greater. The lack of dominance of either the right or left hands was also commented upon which lends credence to the conclusions of Swanson et al (1970) and Pearn and Bullock (1979).

2.4 Circadian variation.

The application of the aforementioned objective measurement techniques to clinical assessment of arthritic conditions has been discussed. In the following section particular emphasis is given to the measurement of changes in joint stiffness and grip strength throughout the course of one day.

An understanding of this circadian pattern is crucial for two reasons. Firstly, if comparisons are to be made between subjects, either healthy or arthritic, it must be ensured that circadian changes are eliminated or at least taken into account. A good example of this would be the use of stiffness and grip strength as indicators of the effectiveness of a particular form of drug therapy in alleviating arthritic symptoms. If measurements were made prior to drug administration at one time of day, and then post administration at a different time, it would not be possible to determine whether any changes in stiffness and grip strength were due to the drug alone. Hence the effectiveness of the drug therapy would be in doubt (Harkness et al (1982)). Secondly, morning stiffness, which constitutes one part of the pattern of circadian stiffness variation, has been identified as an important indicator of disease activity and diagnosis in rheumatoid arthritis (Ropes et al (1958)).

The mechanism which causes subjective feelings of morning stiffness is unknown but measurements of passive joint stiffness and grip strength may help to target other clinical investigations to a specific physiological area.

2.3.1 Circadian variation of stiffness and grip strength

In this section the terms 'joint stiffness 'and 'grip strength 'will be used in their widest sense, to avoid constant digression to a discussion of the arguments already presented. 'Joint stiffness 'will refer to passive joint stiffness and grip strength will refer to the mean maximum indication of gripping force. Where differing measurement techniques do lead to a better understanding of the results obtained, then these will be highlighted.

Scott (1960) described morning stiffness as, 'varying from a scarcely perceptible stiffening of the fingers, sometimes in the earliest premonition of disease, to the torpid, turgid immobility which in advancing arthritis is the waking despair of the unhappy patient. '

The starting point for the experimentation of Scott was the observance that the hands of patients with rheumatoid arthritis sometimes appeared to be more swollen in the early morning than at other times, suggesting that tissue swelling was a cause of morning stiffness.

MCP joint stiffness was measured in the manner described in section 2.1.1. In addition measurements were made of hand volume, using a water displacement method, and grip strength, using a sphygmomanometer cuff. Five adult in-patients with chronic R.A. and four healthy subjects were measured each day at the time of first rising, around 6.00 a.m. and later in the day at approximately 6.00 p.m.. All subjects were studied for a period of at least ten consecutive days.

Results from the arthritic cases showed increases in hand volume and joint stiffness in the morning. Grip strength was lower in the morning than the evening. The results from the healthy subjects were the same in the case of hand volume and grip strength but no change was measured in joint stiffness from morning to evening.

The similar pattern of change in hand volume for arthritic and healthy subjects led to the conclusion that tissue swelling could not be the sole cause of the increase of joint stiffness in the morning present in arthritic subjects.

More recently, Kowanko et al (1982) have found that joint size was maximal and grip strength minimal in the morning. Measurements were made at home by the patients themselves. Interphalangeal joint circumference was measured using a plastic loop connected to a spring loaded pointer moving on a scale graduated in 1 mm steps. Grip strength was measured using an inflatable grip test bag inflated to 20 mm Hg. The highest reading of three attempts was recorded for each hand. Subjective assessments of pain and stiffness were also highest in the morning. A circadian variation in joint size would seem to indicate a variation in the swelling of the tissue surrounding the joint and thus local oedema does seem to be an important factor to consider. Unfortunately, no data was presented for healthy subjects and so the conclusions that can be made from these measurements are limited. It can be said that the results of Kowanko et al were in agreement with those of Scott and added weight to the argument that fluid retention during sleep may be a contributory factor in morning stiffness.

Wright and Plunkett (1966) undertook a number of experiments to investigate the variation of grip strength throughout the course of the day and night. It is unclear from the text but it appears that patients were measured at two hourly intervals, from the time of first waking at 6 am to some time later in the evening, perhaps 10.00 pm. Healthy subjects were measured over a full 24 hour period but the number of subjects involved is not stated.

It was found that healthy subjects exhibited a pronounced diurnal variation in grip strength, the minimal grip occuring at some time from 4 to 6 am. Immobilization of an arm by a plaster cast for six hours followed by immediate measurement demonstrated a similar reduction in grip force to that after overnight sleep. The grip strength rapidly recovered on removal of the cast. Futher experimentation was carried out to investigate the importance of immobilization. Two subjects were woken after three hours sleep, one was asked to perform a sedentary activity whilst the other undertook vigorous hand exercises. The results showed that for the former subject there was only a slight check in the diurnal grip pattern whereas for the latter there was an increase in grip which was sustained. These experiments suggest that immobilization during sleep may play a part in the diurnal variation of grip strength of healthy subjects but the subject numbers are too small for any firm conclusions to be made.

The references to the objective measurement of stiffness in a 24 hour period are small, even though other arthrographic results were presented for the MCP joint. However, the authors did infer that the waning of resistive torque at the joint with time (stress relaxation) was a possible explanation of the 'working off 'of stiffness observed in patients suffering from rheumatoid arthritis. This history dependence factor in joint stiffness was in agreement with Scott (sec. 2.1.1).

More evidence for the circadian variation of joint stiffness was provided by Backlund and Tiselius (1967). Objective measurements of joint stiffness and grip strength were made using an arthrograph and sphygmomanometer cuff respectively. Two hourly measurements from 7.00 a.m. to 8.00 p.m. were made in three patients suffering from R.A. and three healthy subjects. It was found that joint stiffness (no data was presented for elastic and dissipative resistance) decreased throughout the day in the arthritic subjects. Changes in torque were particularly noticeable towards the limits of joint range. The limits considered being 65 degrees and 5 degrees flexion. No change in joint stiffness was evident in the healthy subjects.

The grip results, when compared between healthy and arthritic subjects, followed a similar pattern to joint stiffness. An increasing grip strength as the day progressed was observed in arthritic subjects but no change was observed in healthy subjects.

The lack of circadian variation in grip strength in healthy subjects was surprising in view of the striking morning decrease demonstrated by Wright and Plunkett and by Scott.

From the results presented so far, although small in number, it can be seen that circadian variation in joint stiffness and grip strength have been measured separately. It has been suggested that the subjective feelings of morning stiffness may in fact be due to muscle weakness (sec. 1.2) but this may not be the case. It is interesting to speculate on the relationship between increased joint stiffness and decreased grip strength.

One possibility is that increases in joint stiffness may impede the establishment of grip and thus cause a decrease in it. Another possibility is that increases in joint stiffness may be accompanied by increases in pain which may limit the desire to exert a stronger grip. The findings of Backlund and Tiselius do not invalidate either of these possibilities. However, the circadian variation in grip strength in healthy subjects, observed by some workers, does present the further possibility that joint stiffness and grip strength may vary independently.

The perception of stiffness by arthritic subjects was investigated further by Backlund and Tiselius. Five subjects suffering from rheumatoid arthritis were asked to estimate their degree of stiffness several times by placing a mark on a scale graduated from 'not stiff 'to 'very stiff '. After each subjective recording objective measurements were then taken of MCP joint stiffness and grip strength using the methods previously described. For one subject it was found that subjective stiffness correlated strongly with objective stiffness but for two other subjects the strongest correlation was with decreased grip strength. From these results the dominant factors affecting the subjective feeling of stiffness are still unclear.

An investigation of the circadian variation of stiffness and strength in a group of 25 patients, all of whom were suffering from R.A., was undertaken by Inpen (1968). Objective measurements of grip strength and MCP joint stiffness were made by folded cuff and finger dropper (see sec. 2.1.3) respectively. The patients were measured six hourly for a period of 24 hours, starting at 6 a.m. All but one of the patients showed increased energy dissipation in the morning and sixteen showed a similar increase in the evening. Grip strengths also exhibited a diurnal variation but this was much less than the change in stiffness except for the immediate post-waking period.

Further experiments involving the measurement of joint energy dissipation and strength of grip before and after administration of a pure analgesic (physeptone/methadone) revealed that grip strength was markedly increased whereas energy dissipation was unchanged. The author's contention was therefore that decreases in grip strength were strongly correlated with increases in pain.

Significant improvement in morning grip strength was also shown by Myers et al (1981) following administration of an Indomethacin suppository to eleven hospital patients with classic R.A. More importantly, the apparatus used (see sec 2.3) also measured the mean time taken to establish the maximum grip pressure. The conclusion of the authors was that subjective impressions of morning stiffness were caused by a disturbance of motor function of the muscles involved in gripping. However, it must be pointed out that increases in resistance to motion at the finger joints, if present, would cause impairment of finger motion and thus an increase in the time taken to establish maximum grip pressure. There is no reason to suppose that administration of the indomethacin suppository could not have alleviated whatever mechanisms affect passive joint stiffness. Therefore, there is no reason to suppose that morning stiffness must be related to the muscles actively involved in gripping alone.

Certainly, the circadian variation of passive joint stiffness cannot simply be ignored. In studies of the knee joint, Thompson (1978) observed a general decrease in elastic stiffness and dissipated energy from morning to evening in a small number of arthritic subjects. However, because of high random variation and low subject numbers the author attached no significance to this result. Recently, more detailed circadian studies have been carried out by Yung et al (1984) and Helliwell et al (1987). Although both groups of workers have concentrated their attentions on the same joint and used arthrographic techniques, different planes of motion have been considered.

Yung et al (1984) used the MCP joint arthrograph introduced by Unsworth et al (1982). This machine was capable of performing small amplitude oscillations of 4 degrees at any point in the normal range in the flexion/extension plane. In a standard test, stiffness was measured every ten degrees from 4 degrees to 84 degrees flexion from the neutral position.

Eight healthy subjects were involved in the study and they were tested every two hours for a period of twenty four hours. This was the first time that objective measurements of stiffness had been made during normal sleeping hours but it was reported that the disruption to the subject's sleep pattern was negligible and that quality of sleep did not seem to be affected.

The results were presented in terms of the elastic torque resisting motion at 20 degrees flexion from the equilibrium position and the total energy dissipated for a whole test. The use of the equilibrium position of the joint as a datum rather than an absolute angular displacement is discussed in section 3.6. However, as the results of Helliwell et al were analysed in a similar manner it is worthy of a brief, if over simplified, explanantion here.

At the equilibrium position flexion and extension moments acting at the joint are in equilibrium. By using the point of zero nett torque as the datum it is possible to compare changes in elastic resistance for the same angular displacement.

Both elastic resistive torque and dissipated energy exhibited a circadian variation. Both parameters were increased in the early hours of the morning (0200-0400). Of the two, the elastic resistive torque showed the most dramatic peak for the majority of subjects, returning to an average value before the time of normal awakening. Increases in energy dissipation appeared to persist for several subsequent tests following the time of their maximum value.

These results are in direct contrast to those of Helliwell et al who found no significant circadian variation in elastic or dissipative stiffness parameters in any of the subjects they tested over a 24 hour period. However, there were two important differences in approach compared with Yung et al. Firstly, the subjects tested were all suffering from R.A. and secondly, the plane of measurement was abduction/adduction not flexion/extension.

A shift in equilibrium position was observed during the 24 hour period. In eight out of fourteen patients this position reached maximal ulnar deviation between 3.00 a.m. and 9.00 a.m.. It was suggested that increased ulnar deviation may cause a temporary deformity which, in combination with other factors, may lead to a patient's perception of morning stiffness.

To summarise the findings presented so far consider the following tables :

Table 2.1
Presence of circadian variation of stiffness in healthy subjects

Workers	Times	Joint	Plane	Method	Healthy No's	Circadian variation
Scott	6.00 - 18.00	MCP	Flex/ext	Constant torque	4	No
Backlund	7.00 - 20.00	MCP	Flex/ext	Arthrograph	3	No
Yung	24 hrs	MCP	Flex/ext	Arthrograph	8	Yes

Table 2.2
Presence of circadian variation of stiffness in diseased subjects

workers	Times	Joint	Plane	Method	R.A. No's	Circadian Variation
Scott	6.00 - 18.00	MCP	Flex/ext	Constant torque	5	Yes
Backlund	7.00 - 20.00	MCP	Flex/ext	Arthrograph	3	Yes
Ingpen	6.00 - 12.00	MCP	Flex/ext	Finger dropper	25	Yes
Thompson	8.00 - 20.00	Knee	Flex/ext	Arthrograph	4	Yes
Helliwell	24 hrs	MCP	add/abd	Arthrograph	14	No

Table 2.3
Presence of circadian variation of grip strength in healthy subjects

Workers	Time	Method	Healthy No's	Circadian Variation
Scott	6.00 - 18.00	Pressure	4	Yes
Wright	6.00 - 22.00	Pressure	?	Yes
Backlund	7.00 - 20.00	Pressure	3	No

Table 2.4
Presence of circadian variation of grip strength in diseased subjects

Workers	Time	Method	Diseased No's	Circadian Variation
Scott	6.00 - 18.00	Pressure	5	Yes
Wright	6.00 - 22.00	Pressure	?	Yes
Backlund	7.00 - 20.00	Pressure	3	Yes
Ingpen	6.00 - 24.00	Pressure	25	Yes
Myers	evening / morning	Pressure	11	Yes
Kowanko	8.00 - 20.00	Pressure	19	Yes
Harkness	8.00 - 23.00	Pressure	10	Yes

2.4.2 Discussion of circadian findings

Although all grip stength measurements have been made using a pressure method, the inherent drawbacks of which are known, there is clear evidence that the grip strength of of diseased subjects does exhibit a circadian variation. The conclusions to be drawn from the healthy subjects are less clear. The weight of evidence, although small, would suggest that in some healthy subjects grip strength does vary over a 24 hour period.

The data presented in tables 2.1 and 2.2 demonstrates that the issue of circadian variation of joint stiffness is confused. The most significant contributions to the study of diseased joints have been made by Ingpen and Helliwell et al. The results from these two groups of workers are derived from completely different measurement techniques, different planes of motion and are in direct contradiction.

As regards the circadian variation of healthy joints, only Yung et al (1984) have found any circadian variation of joint stiffness. The significance of the results of

Yung would suggest that a circadian variation is present but further evidence is required before firmer conclusions can be made.

If circadian variation of stiffness does exist in healthy joints but not in diseased ones, as suggested by the results of Helliwell et al, this raises some interesting questions. Firstly, why doesn't the stiffness of diseased joints vary, especially when other indicators of disease activity appear to do so ?. Secondly, is the phenomenon of 'morning stiffness 'actually unrelated to stiffness itself and more closely associated with pain or muscular deficiency ?

This latter question could be answered easily if the speculations about the patient's perception of stiffness, presented in section 2.3, are true. Namely, that arthritic joints are not really stiff at all and actually tend towards laxity, especially in the later stages of the disease.

2.5 Objectives

To date, an amount of interesting information about joint stiffness and grip strength, and their role as indicators of arthritic disease, has been collected.

Grip strength appears to be a reasonable measure of disease activity but cannot be relied upon solely if distinction is to be made between pain, stiffness, structural deformities and deficiencies in musculature. The accuracy with which absolute comparisons of grip strength can be made between results from different groups of workers is questionable, due to the problems of using pressurised bags as the grip transducer. One objective therefore is to attempt to devise a more reliable method of grip strength measurement that would be equally convenient as the sphygmomanometer cuff.

The role of joint stiffness as an indicator of disease activity is in doubt. However, clinical results are small in number both for the effects of therapy on joint stiffness and its circadian variation. There is a need therefore to conduct more research in these two areas. In so doing further light may be shed on the ongoing arguments regarding the perception of stiffness. Further clinical research on joint stiffness is therefore another objective of this study.

Measurement of joint stiffness is not a straightforward matter. Arthrographic measurement techniques have shown themselves to be extremely useful in distinguishing between different components of stiffness and it seems worthwhile to pursue this method. However, until very recently (Howe et al (1985)), arthrographic apparatus has been cumbersome and analysis of results lengthy and specialised. This has probably restricted arthrographic studies to small numbers of joints. New developments in microelectronics should make it possible to reduce the bulk of the apparatus and make data collection and analysis much easier than in the past. The development of an arthrographic measurement system, utilising these developments, will form a third objective.

However, before the latter objective can be accomplished, the rheological analysis methods used in arthrographic work must be reviewed. One reason for this is because various arthrographic workers have used different analysis techniques, but the chief reason is because the correct experimental procedure can only be devised if the rheology of human joints is understood. This review will be tackled directly in the next chapter.

CHAPTER THREE

THE USE AND ABUSE OF RHEOLOGY

3.1 The definition of rheology

The term rheology was coined by Professor E.C. Bingham and formally adopted at the meeting of the American Society of Rheology in 1929 as 'the science of the deformation and flow of matter.'

All materials deform or flow to some extent and hence the range of rheology is very wide. Biorheology is but one aspect of this wide range and is evidently the combined study of biology and rheology.

Scott-Blair in his introductory text on biorheology (Scott-Blair, 1974) states that :-

'Rheologists are perhaps of most practical use in studying materials whose composition and structure is exactly defined, so that the widest field of rheology has always been, and probably always will be, concerned with synthetic high polymers.'

Before detailing rheological invstigations of stiffness in human joints it is perhaps pertinent to discuss why a rheological approach has been adopted in the first instance.

3.2 Tissue, proteins and polymers

Much of the structural material of animal tissue is composed of various forms of proteins, e.g. Collagen, Elastin. These are examples of naturally occurring high polymers, that are long chain molecules of high molecular weight made up of repeating chemical units.

Synthetic rubbers and plastics are also high polymers and rheological investigation of their mechanical properties has revealed much about their molecular structure (Ferry, 1961). Wright and Johns (1960a) postulated that if connective tissue was studied in a similar way to synthetic polymers then structural differences in the tissue between normal and pathological situations might be revealed.

The authors performed experiments on the metacarpophalangeal joint of the index finger .They went on to develop a rather complex visco-elastic -plastic model of the joint (Wright and Johns, 1964).

Initial experimentation involved imposing sinusoidal motion on the joint whilst monitoring resistive torque as a function of rotational displacement, velocity and acceleration.

By varying the frequency and amplitude of the displacing waveform the stiffness of the joint was subdivided into the following categories : elastic stiffness, viscous stiffness, frictional stiffness and plastic stiffness.

It is useful to define clearly these different categories as they will be used extensively in the subsequent discussion.

3.3 Stiffness in general

All materials and structures deflect but the extent of that deflection varies considerably between materials when they are loaded. If a material is able to recover its shape completely after the deforming force has been removed then it is known as elastic. A certain number of solids do not recover completely but remain distorted, e.g. putty. This behaviour is known as plastic.

The deflection of a structure is affected both by its size, geometrical shape and also by the sort of material from which it is made. To overcome this problem the concepts of stress and strain have been introduced. If a test specimen of standard geometry is loaded and stress and strain are plotted a curve is generated which is to large extent characteristic of the material of the specimen.

The gradient of each curve in this linear region is a measure of the elastic stiffness of a given material (also known as the Youngs modulus). If the test specimen is of identical dimensions for each material then stiffnesses can be compared by substituting load for stress and deflection for strain. Similarly if the size and geometry of the human MCP joint can be assumed to be approximately equal between subjects then torque/displacement curves can be used for comparative purposes.

Actual materials show a great variety of behaviour. Several idealized materials have been invented which typify various aspects of material behaviour.

3.3.1 Elasticity

This is characterized by the change in resistive torque per unit displacement which is a function of displacement alone. All strains in an elastic material are completely recovered upon unloading. The characteristic equations for linear and non-linear elasticity are shown in fig.3.1 together with the simplest rheological element, the ideal spring.

3.3.2 Viscosity

A viscous material is one in which the stress is a function of the rate of strain. Viscous stiffness can be characterized by the torque required to produce a given rotational velocity. As in elasticity, viscosity can be linear or non- linear. The ideal rheological element of linear viscosity is the dashpot (fig.3.1). Progressive deformations are not recovered and no energy can be stored or regained. The work involved in shearing the fluid in the dashpot is completely dissipated as heat.

3.3.3 Friction, plasticity and yield

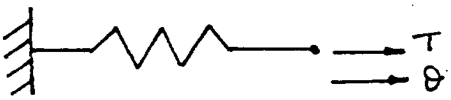
There appears to be a considerable amount of confusion in the literature when attempting to differentiate between friction and plasticity. Indeed, as remarked by Thompson(1978) there has also been some confusion in earlier papers between plasticity and visco-elasticity.

Flugge (1967) states that the phenomenon of plastic flow may be defined by the following statements (note:- torque and displacement have been substituted for stress and strain for the purposes of this study): (a) The material is elastic until it reaches the yield limit, that is, until a certain function of the torque components reaches a certain value. (b) Then additional displacement is possible without an increase in torque. (c) This additional displacement is permanent, that is, it remains when the torques are removed. (d) The time derivative of the displacement (the rate of displacement, $\dot{\theta}$) does not appear in the equations.

If statement (a) is included in a definition of plasticity then it is relatively simple to differentiate between plasticity and friction. Simple Coulomb friction arising from the sliding contact at the interface between two surfaces does not imply an initial elastic response. Hence resistive torque due to Coulomb friction would be independent of amplitude whereas those due to plasticity (at least in the elastic phase) would be amplitude dependent. This distinction is made by Goddard et al (1969). However, Thompson argues that the elastic response is not fundamental to plasticity and it is the stress/strain behaviour after yield point that is characteristic of a plastic material.

Figure 3.1 Simple rheological elements

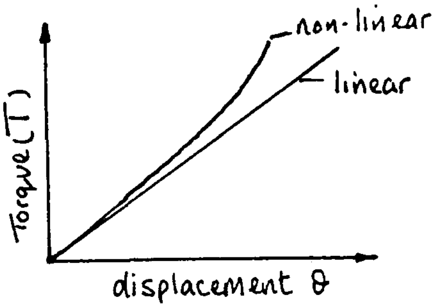
Ideal Elasticity (Spring)



Equations

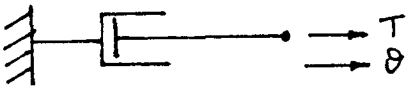
$T = K\theta$ linear

$dT = K(\theta)\, d\theta$ non-linear



Response

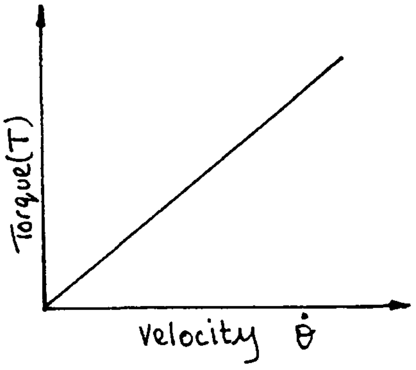
Ideal Viscosity (dashpot)



Equations

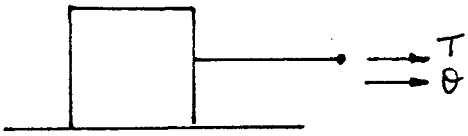
$T = \eta \dot{\theta}$ linear

$dT = \eta(\dot{\theta})\, d\dot{\theta}$ non-linear



Response

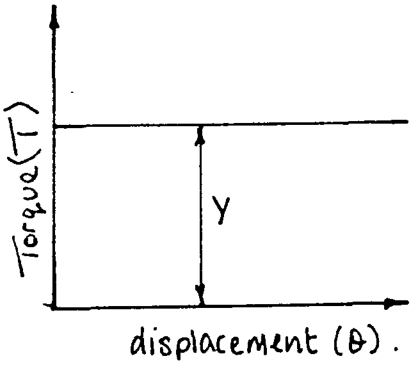
Plasticity



Equations

$\theta = 0$ for $T < Y$

$T = Y$ for $\theta > 0$



Response

Perhaps qualitatively a distinction can be made between friction arising from the interface between two materials or bodies, eg. between the articulating surfaces in the joint, and internal friction between slip planes or filaments in collagenous tissue. However, by the method of macroscopic experimentation on joints it is not possible to make this distinction quantitatively and thus there seems to be little point in undertaking any further argument to differentiate between the two.

The important point is that some time independent mechanism may be described whereby displacement is possible without an increase in torque after a threshold torque value has been reached, and, on removal of the torque, there will be a permanent deformation remaining. As regards terminology, plasticity will be used to describe this particular mechanism as it is consistent with some other workers and also implies a permanent deformation.

By omission of the initial elastic behaviour, which has already been catered for by the ideal spring, then plasticity can be represented in its simplest form by a block sliding on a surface (fig. 3.1). Thus there can be no stiffness due to this ideal plasticity alone only a superposition of constant torque on the torque/displacement curve. Strain hardening effects can be modelled by a number of plastic elements connected by loose strings so that each element comes into effect at a different displacement (Viidik, 1968).

Armed with these definitions the application and relevance of rheological work on human joints will now be discussed.

3.4 Rheological work on human joints

Wright and Johns (1960a) found that a sinusoidal oscillation of the MCP joint produced a torque displacement curve of the form shown in fig. 3.2.

As can be seen this curve is non-linear and exhibits hysteresis. For a sinusoidal waveform the angular velocity at zero displacement is a maximum. The authors infer that there can be no elastic torque and hence any torques occuring at zero displacent must be due to either viscosity or plasticity or a combination of both.

To be rather pedantic there may have been some elastic torque at the zero position. The centre point for the oscillation was chosen to be the mid-point of joint range. Therefore there can be no guarantee that at this position the elastic forces acting on the joint would have zero net resultant. This would only be true if the centre of oscillation was the equilibrium position.

Conversely, at maximum displacement the angular velocity is zero and hence the viscous torques are also zero. The torques at this position must be due to elasticity or plasticity or both.

The authors went on to investigate how the shape of the hyteresis loop changed with variation in amplitude and frequency of rotation. The maximum and minimum elastic stiffness during flexion and extension were measured as indicated in fig. 3.2. Elastic stiffness at full flexion and extension were measured by the slope of the line connecting the points of maximum amplitude with the origin.

Viscous stiffness in the sense of a torque/angular velocity curve was not explicitly evaluated. The torques at maximum velocity were taken to be representative of the viscous contribution to stiffness.

Stress relaxation experiments were also carried out. A step displacement of 30 degrees in to extension from the neutral position was imposed on the joint. The joint was maintained at this displacement and changes in torque were monitored with time.

Viscoelastic materials characteristically show a relaxation of torque with time. Usually this torque decays rapidly at first and then more gradually, either to zero or to a finite value. Wright and Johns found that the human MCP joint displayed prominent stress relaxation to a finite value of torque which was approximately half the initial value of torque immediately after the step (fig. 3.2). Clearly, such observations are to some extent subjective due to measurement problems (eg. length of measurement time and the resolution of the measuring device) but reasonable deductions can be made by comparing the relaxation time with the time of observation. Relaxation time taken as the time for the torque to decay to 1/e th (36 percent) of its initial value.

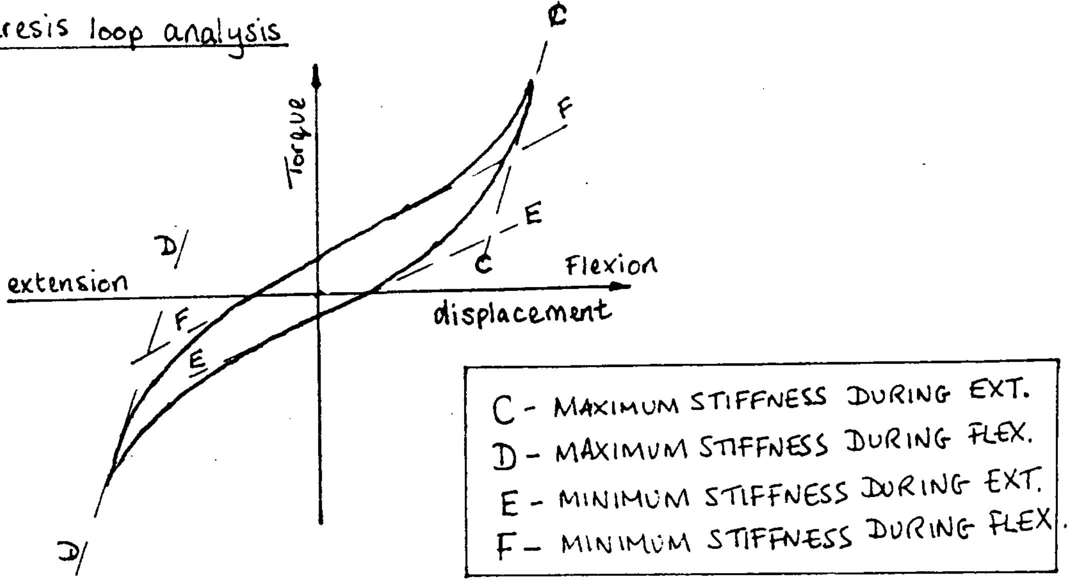
It is obvious from the terminology used to describe this experiment that plasticity was confused with viscoelasticity. This confusion led to the conclusion that the properties of the joint were dominated by elasticity and plasticity with viscosity playing a minor role. In fact what the experiments did reveal was that the properties of the joint were predominantly viscoelastic.

Terminology aside these original experiments are very important as they highlight some of the advantages of a rheological appproach to joint stiffness and also some of the difficulties that may be encountered when trying to compare experimental results from different groups of workers.

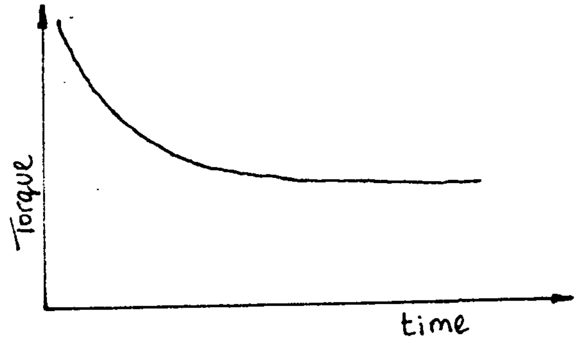
It is clear that if experiments are undertaken at different frequencies of rotation, or amplitude, or if the position of the centre of oscillation is varied within the range of motion then, in each case, a different torque/displacement curve will result. This latter point is perhaps why Wright and Johns (1964) went on to attempt to formulate a comprehensive rheological model of the joint. In this way the observed experimental responses could be unified and also further more enlightening experimentation could be undertaken.

Figure 3.2 Rheological results of Wright and Johns

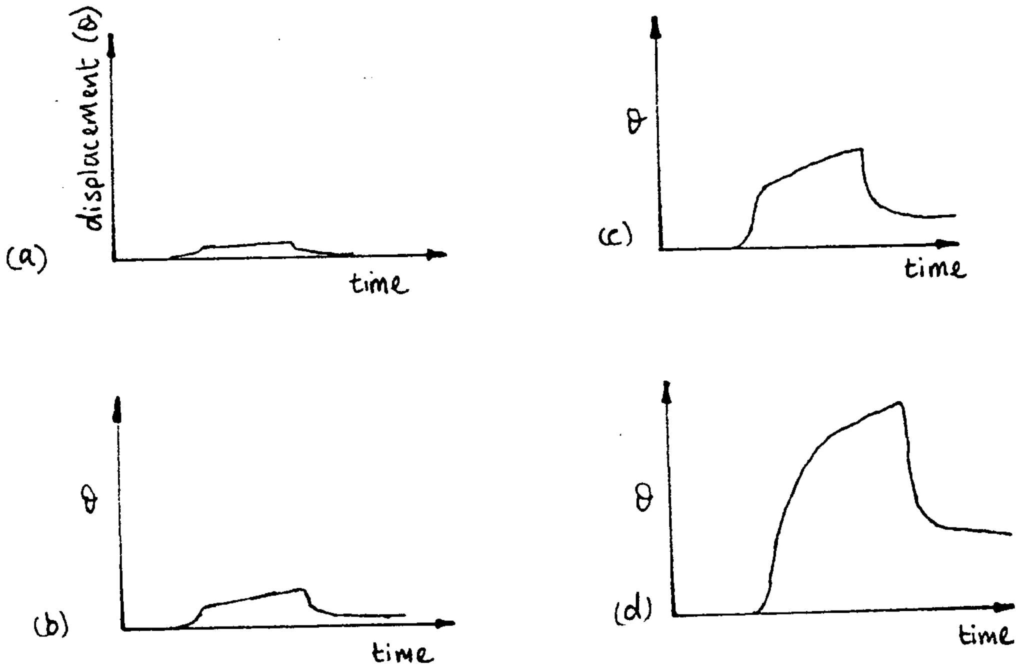
Hysteresis loop analysis



Stress relaxation



Creep experiments



Creep loads increasing (a) to (d)

The technique used to develop this rheological model was by use of networks of ideal springs, dashpots and sliders. The relevance and meaning of such models to the practical measurement of stiffness will now be discussed.

3.5 Spring-dashpot models

In the early development of linear viscoelasticity theory much use was made of the modelling of materials by networks made up of simple elastic and viscous elements such as the ideal spring and ideal dashpot that have already been mentioned. Simple networks either arranged in serial or parallel form or a combination of the two were devised to model ideal viscoelastic behaviour of both solids and fluids and were given names according to the workers that proposed them.

In the following descriptions stress and strain are reduced to torque and angular displacement and are denoted by T and θ respectively . Time will be denoted by t.

3.5.1 Maxwell element

A Maxwell element is simply a spring and dashpot connected in series (fig. 3.3). The spring has a modulus of elasticity denoted by K and the dashpot a viscosity denoted by η.

For the spring,

$$T_k = K\theta_k$$

For the dashpot,

$$T_\eta = \eta\dot{\theta}_\eta$$

Since both elements are connected in series the total displacement is :-

$$\theta = \theta_k + \theta_\eta$$

and

$$T = T_k = T_\eta$$

On differentiation with respect to time

$$\dot{\theta} = \dot{\theta}_k + \dot{\theta}_\eta$$

and

$$\dot{T}_k = K\dot{\theta}_k$$

Hence,

$$\dot{\theta} = \frac{\dot{T}}{K} + \frac{T}{\eta} \qquad (1)$$

To understand what this equation implies for a material consider a standard two stage test. In the first stage an initial torque, T_0 is applied at t=0 and the displacement is monitored with time (a standard creep test). In the second stage , after time t_1 the displacement is held constant and the torque is monitored with time (stress relaxation test).

Initially, when the torque T_0 is suddenly applied, the dashpot would be locked and the spring would immediately extend. This extension θ_0 is found simply from the equation for the ideal spring, i.e.

$$\theta_0 = \frac{T_0}{K}$$

After the sudden extension, due to the action of the spring alone, further extension, θ_a will take place as the dashpot relaxes.

As T is constant and equal to T_0 then $\dot{T} = 0$

Thus,

$$\dot{\theta}_a = \frac{T_0}{\eta}.$$

Integrating with respect to t,

$$\theta_a = \int \frac{T_0}{\eta}\, dt + C_1$$

$$\theta_a = \frac{T_0}{\eta} t + C_1$$

Now, at time t=0, $\theta_a = \theta_0$

Therefore, $C_1 = \theta_0$.

Hence, $\theta_a = \frac{T_0}{\eta} + \theta_0 = \frac{T_0}{\eta} t + \frac{T_0}{K}$

and $\theta_a = \frac{T_0}{\eta}(\frac{\eta}{K} + t)$.

Thus the whole displacement during the creep test can be described by:

θ = displacement after sudden application of torque, θ_a, plus displacement due to sudden application. i.e.

$$\theta = \frac{T_0}{\eta}(\frac{\eta}{K} + t) + \frac{T_0}{K}$$

That is, there is an instantaneous displacement at t=0 followed by a linear increase with time.

For the second stage (stress relaxation) T varies with time and θ is constant. Rewriting the equation (1) we have a first order differential equation.

$$\dot{T} + \frac{K}{\eta}T = 0$$

using the boundary conditions t = t_1 when T = T_0, then this can be solved as,

$$T = T_0 e^{-(t-t_1)\frac{K}{\eta}}$$

Thus in the second stage, at constant displacement, the torque in the material decreases exponentially to zero. The torque and displacement curves for both these stages are shown in fig. 3.4.

The Maxwell element is usually known as the Maxwell fluid because of its capability of unlimited displacement under a finite torque.

3.5.2 Kelvin element

A Kelvin element is simply a spring and dashpot connected in parallel (fig. 3.3). For two elements connected in parallel the displacement is the same for both elements and the torque is the sum of the torque in each.

$$\theta = \theta_k = \theta_\eta$$

$$T = T_k + T_\eta$$

hence,

$$T = K\theta + \eta\dot{\theta} \tag{2}$$

If consideration is again given to the standard two stage test, then for the first stage, when the torque is suddenly applied, the spring/dashpot combination is locked by the dashpot. Hence, there is no sudden displacement as was the case for the Maxwell element. After application of the torque, equation (2) can be rewritten as,

$$\dot{\theta} + \frac{k}{\eta}\theta = \frac{T_0}{\eta}$$

Using an integrating factor of $e^{\frac{k}{\eta}t}$ and integrating with respect to t,

$$\theta e^{\frac{k}{\eta}t} = \frac{T_0}{\eta}\frac{\eta}{K}e^{\frac{K}{\eta}t} + C_1$$

Now, at t = 0, θ = 0, therefore,

$$C_1 = -\frac{T_0}{K}$$

Thus, substituting this constant and simplifying we get,

$$\theta = \frac{T_0}{K}(1 - e^{-\frac{k}{\eta}t})$$

Which can be written as,

$$\theta = \frac{T_0}{K}(1 - e^{-\lambda t})$$

where

$$\lambda = \frac{K}{\eta}$$

That is the displacement increases exponentially and approaches the limit $\frac{T_0}{K}$. This is almost the behaviour of an elastic solid, the difference being that here the displacement does not at once approach the desired value, but approaches it gradually (delayed elasticity).

On fixing the displacement in the second stage, at time t_1, equation (2) becomes simply,

$$T = K\theta_t$$

and thus,

$$T = T_0(1 - e^{-\lambda t_1})$$

That is, the torque is immediately relaxed by a certain amount and then remains fixed forever at that value. Thus, the relaxation is incomplete. The torque and displacement curves for the two stage creep test of a Kelvin element are given in fig. 3.4.

By one serial and one parallel combination very simple models for a viscoelastic fluid and a viscoelastic solid have been generated. Adding more fundamental elements can lead to more complicated behaviour models.

3.5.3 Three parameter viscoelastic solid

A spring/dashpot model involving three fundamental elements is shown in fig. 3.3.

It can be shown in a similar manner to the two previous elements that the governing equation of this model is given by:-

$$T + \frac{\eta}{K_1 + K_2}\dot{T} = \frac{K_2\eta}{K_1 + K_2}\dot{\theta} + \frac{K_1K_2}{K_1 + K_2}\theta$$

For the first stage of the standard test the displacement is given by:-

$$\theta = T_0 \frac{K_1 + K_2}{K_1 K_2}\Big(1 - (1 - \frac{K_1}{K_1 + K_2})e^{-\frac{K_1}{\eta}t}\Big)$$

That is there is an instant elastic response followed by an exponential increase in displacement to a finite value.

During the relaxation phase the torque can be shown to be given by:-

$$T = \frac{K_1 K_2}{K_1 + K_2}\theta_1(1 - e^{-\frac{K_2+K_1}{\eta}\tau}) + T_0 e^{-\frac{K_1+K_2}{\eta}\tau}$$

where,

$$\tau = t - t_1$$

and, θ_1 = the displacement at time t_1

Thus, the torque relaxes exponentially to a finite value which is dependent on the series combination of the two springs.

The equations that have been derived from these spring dashpot models characterize simple forms of viscoelastic behaviour. By manipulation of the values of moduli (K or η) it is possible, in some cases, to reproduce experimental creep and relaxation curves from real materials. However when more complex forms of behaviour are considered, such as frequency response, these simple models usually prove inadequate. From the results of Ferry (1961) from experiments on PMMA rubber it is evident that none of the models discussed so far can model the material behaviour over the whole frequency range (see Lockett (1972)).

Real viscoelastic materials almost always require much more sophisticated mathematical models in order to describe their experimental responses completely. Thus, although these mechanical analogies provide a relatively simple qualitative picture of the manner in which viscoelastic materials behave, it should be noted that this is only feasible when the models contain only a few elements.

Now that some of the limitations and advantages of mechanical model making have been discussed some of the models relating to human joints will be presented.

Figure 3.3 Spring-dashpot models

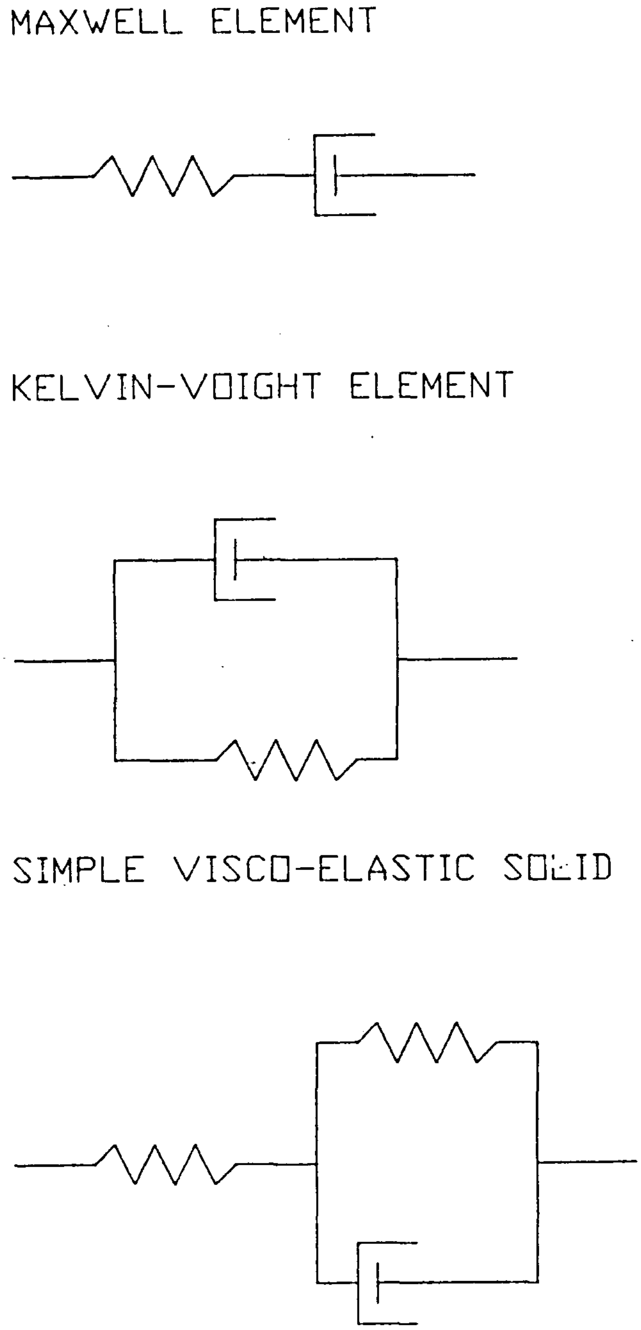
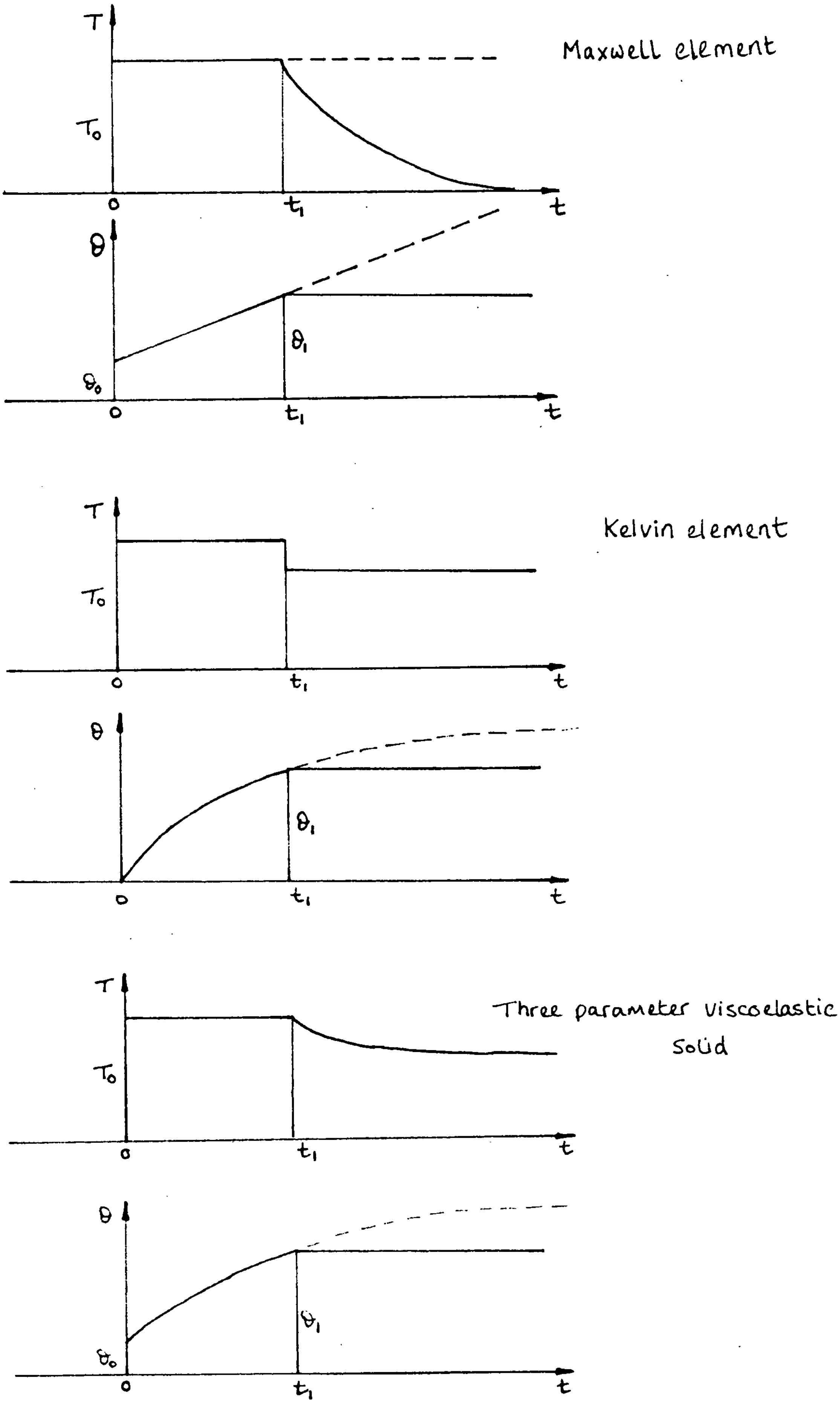


Figure 3.4 Creep/relaxation characteristics



3.6 Some joint stiffness models

3.6.1 Wright and Johns (1964)

The MCP joint model proposed by the authors is shown in fig. 3.5. It can be seen that the model is a three parameter viscoelastic solid connected in series to a Maxwell body via a strain hardening plastic element.

The model was derived from a series of creep and stress relaxation experiments . Displacement of the joint was monitored for a period of one minute following the sudden application of a fixed torque. Increasing the magnitude of the applied torque generated the experimental responses shown in fig. 3.2. There was an initial sharp jump in the displacement of the joint followed by a more gradual increase with time. On unloading, the joint recoiled quite abruptly but did not return to its original position, a permanent displacement remained. It is interesting to note that the higher the applied torque then the greater was the permanent displacement.

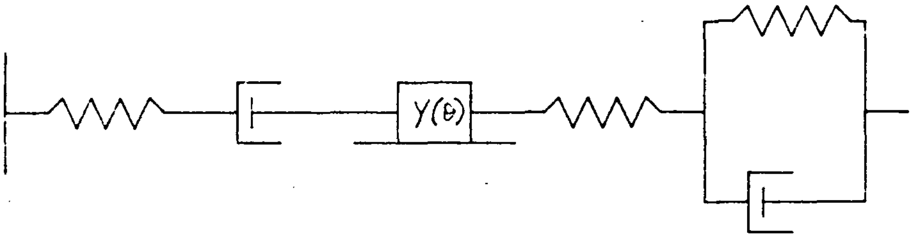
The creep response on loading is similar to the creep response of the three parameter viscoelastic solid as discussed in the previous section. On unloading, however, this model would show an initial sharp reduction in displacement and then gradually approach the original displacement from which the test began. The authors attributed the residual displacement on unloading to be due to plasticity and thus included a series plastic element. To account for the variation in residual displacement with increasing creep loads it was stated that the plasticity element was strain hardening.

The results from the stress relaxation experiments showed an exponential decrease in torque to a finite value. Following the discussion of section 3.5 and the stress relaxation response shown in fig. 3.4, then it can be seen that this response can be characterized by the three parameter viscoelastic solid. Inclusion of the strain hardening plastic element in series provides a band of torque upon which the viscoelastic response can be superimposed. Although no presentation of actual moduli was given it is reasonable to assume that the experimental responses have been characterized. Therefore, it is somewhat puzzling that a Maxwell element was included in series in such a fashion that it would only come into effect after the plastic element had yielded.

Figure 3.5 Joint stiffness models

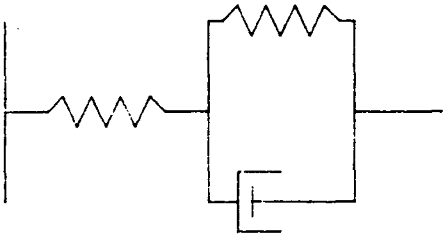
WRIGHT (1964)

Model of the human MCP joint



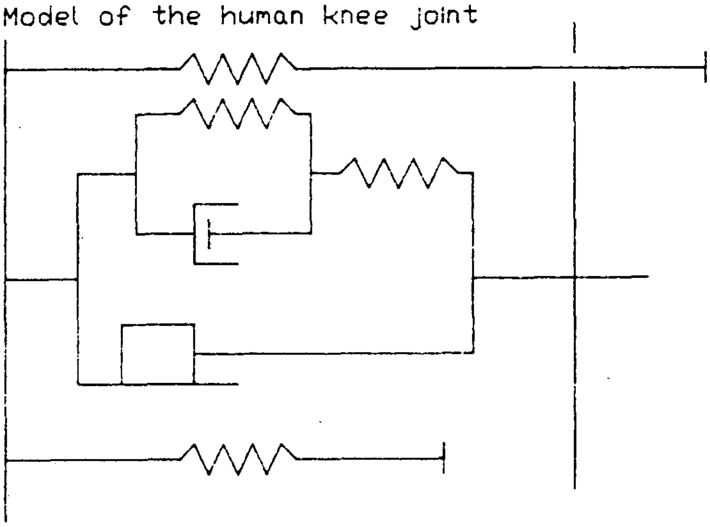
LONG ET AL (1964)

Model of the human MCP joint



THOMPSON (1978)

Model of the human knee joint



3.6.2 Long et al (1964)

In the course of work to investigate the factors in hand control, particularly active muscle action, the authors noted a discrepancy between predicted muscle action and measured muscle action. A major part of this discrepancy was attributed to passive forces in the muscolotendinous and connective tissue structures of the hand. Consequently they went on to investigate the nature of these passive forces.

Using a slightly modified arthrograph from that of Wright and Johns, resistive torque at the MCP joint was monitored with respect to displacement and velocity. The joint was oscillated with the wrist first in the neutral position and then when dorsiflexed. It was noted that the maximum torque in extension increased by approximately 50% when the wrist was dorsiflexed and that this change must be due to the increase of muscle length across the wrist, since no other factors had changed. When the wrist was flexed, the peak torques in extension decreased by approximately 30% and this was attributed to the release of the flexor muscle pull. Thus yet another variable had been shown to influence the results of this method of testing and obviously the position of the wrist must be held constant if experimental results are to be consistent.

Long et al introduced the concepts of phase lag and complex representations of torque as part of their standard analysis. The real components of the resistive torque were primarily elastic and in phase with the forcing displacement whilst the imaginary components were dissipative and 90 degrees out of phase with the forcing displacement. In view of future discussions concerning the effects of frequency on energy dissipation, the idea of a complex torque modulus will be discussed at this point. It will be shown that parameters such as energy dissipation and phase lag can be derived easily, for any linear viscoelastic model, by this method.

3.6.3 Complex analysis

For simple ideal elastic cases such as $T = K\theta$ the modulus of elasticity is independent of the frequency of the displacement waveform. However, in a totally general case, for a viscoelastic material, the modulus which determines the relationship between torque and displacement may be frequency dependent. i.e.

$$T = G(\omega)\theta$$

Where, T = applied torque, θ = displacement, G = viscoelastic modulus and ω = frequency.

Now, torque, displacement and modulus are all vector quantities (the modulus for a given material may vary from one plane to another) and may be expressed using the complex operator i.

For example, some vector r, with horizontal and vertical components r_1 and r_2 may be written as $r_1 + ir_2$, where $r_2 = r \sin\theta$, $r_1 = r\cos\theta$ and θ is the direction of the vector (see fig. 3.6).

Thus, the viscoelastic equation may be written in the totally general form,

$$T = G(i\omega)\theta$$

During a standard arthrographic test a harmonically varying displacement is imposed on the joint and the resistive torque varies harmonically. A harmonically varying quantity can be expressed in complex form by a rotating vector. For example, consider the general harmonic displacement shown in figure 3.6. The vector can be written in complex form as,

$$\theta\cos(\omega t + \phi) + i\theta\sin(\omega t + \phi)$$

expanded as,

$$\theta(\cos\omega t\cos\phi - \sin\omega t\sin\phi + i(\sin\omega t\cos\phi + cos\omega t\sin\phi))$$

$$\theta_1\cos\omega t - \theta_2\sin\omega t + i(\theta_2\sin\omega t + \theta_1\cos\omega t)$$

which gives,

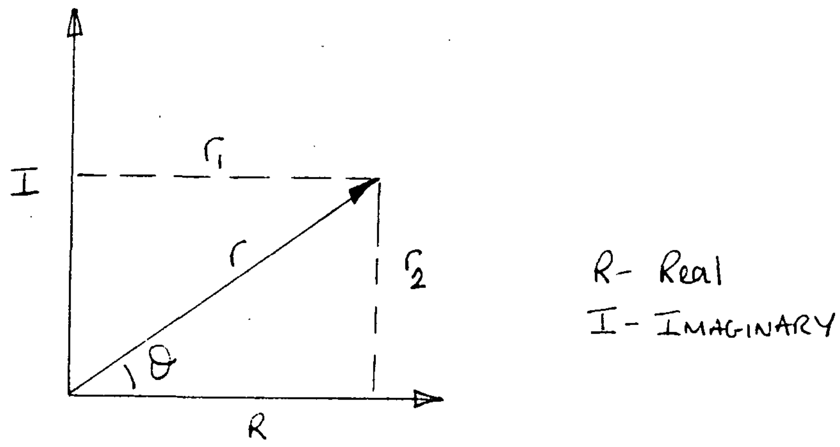
$$(\theta_1 + i\theta_2)(\cos\omega t + i\sin\omega t)$$

which can be rewritten as,

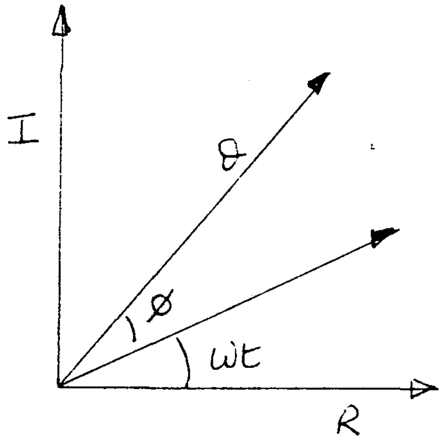
$$\theta_0 e^{i\omega t}$$

Figure 3.6 Complex vector diagrams

SIMPLE VECTOR REPRESENTATION IN COMPLEX FORM



ROTATING DISPLACEMENT VECTOR



Thus in general,

$$T = G(i\omega)\theta$$

where, $T = T_0 e^{i\omega t}$ and $\theta = \theta_0 e^{i\omega t}$.

That is,

$$(T_1 + iT_2)e^{i\omega t} = (G_1(\omega) + iG_2(\omega))(\theta_1 + i\theta_2)e^{i\omega t}$$

Equating real and imaginary this gives,

$$T_1 = \theta_1 G_1(\omega) - \theta_2 G_2(\omega)$$

and

$$T_2 = \theta_2 G_1(\omega) + \theta_1 G_2(\omega)$$

Now, for a standard arthrographic test the displacement waveform is given by $\theta = A \sin \omega t$. This implies that $\theta_1 = A$ and $\theta_2 = 0$. Thus, $T_1 = AG_1(\omega)$, $T_2 = AG_2(\omega)$ and

$$T = (G_1(\omega) + iG_2(\omega))Ae^{i\omega t}$$

Rearranging into real and imaginary this gives,

$$T = A((G_1(\omega)\cos \omega t - G_2(\omega)\sin \omega t) + i(G_2(\omega)\cos \omega t + G_1(\omega)\sin \omega t))$$

The plane of interest for the torque is the imaginary plane as this was the plane of the displacement. Therefore, in response to a forcing displacement $A \sin \omega t$,

$$T = G_1(\omega)A \sin \omega t + G_2(\omega)A \cos \omega t \tag{3}$$

which can be expressed as,

$$T = A|G| \sin(\omega t + \phi)$$

where,

$$|G| = (G_1(\omega)^2 + G_2(\omega)^2)^{\frac{1}{2}}$$

and,

$$\tan \phi = \frac{G_2(\omega)}{G_1(\omega)}$$

It can be seen, therefore, that the torque is composed of a controlling modulus $A|G|$, which is dependent on frequency, together with a harmonic which is out of phase with the forcing displacement by an angle ϕ. The phase angle ϕ represents the distribution of elastic and dissipative components of resistive torque.

Long et al stated that hysteresis is analogous to phase lag, but as pointed out by Thompson (1978), this is an oversimplification. To illustrate this point, the resistive torque response to a harmonic excitation of the form $A \sin \omega t$ will be derived for one of the viscoelastic models described earlier, the Maxwell body.

It has been shown that the Maxwell body has the differential equation

$$\dot{\theta} = \frac{\dot{T}}{K} + \frac{T}{\eta}$$

This can be written in complex form as

$$i\omega\theta = \frac{i\omega T}{K} + \frac{T}{\eta}$$

Separating real and imaginary parts this gives,

$$T = \frac{\frac{\omega^2}{K}}{\left(\frac{1}{\eta^2} + \frac{\omega^2}{K^2}\right)}\theta - i\frac{\frac{\omega}{\eta}}{\left(\frac{1}{\eta^2} + \frac{\omega^2}{K^2}\right)}\theta$$

Hence, the response to $A \sin \omega t$ is given by,

$$T = A\omega K\left(\omega^2 + \frac{K^2}{\eta^2}\right)^{-\frac{1}{2}} \sin(\omega t + \phi)$$

where,

$$\tan\phi = \frac{K}{\omega\eta}$$

The work done by any linear viscoelastic material can be evaluated in the following manner. In time δt the displacement will increase by $\dot{\theta}\delta t$. Hence, the work done on an element of the material is given by,

$$\delta W = T\dot{\theta}\delta t$$

Thus, the total work done during one cycle can be evaluated by the integral,

$$W = \int_0^{\frac{2\pi}{\omega}} dW = \int_0^{\frac{2\pi}{\omega}} T\dot{\theta}\, dt$$

Note: $\frac{2\pi}{\omega} = P$, the periodic time.

Considering the equation for resistive torque given in equation (3) then,

$$W = \int_0^{\frac{2\pi}{\omega}} G_1(\omega)A \sin \omega t A\omega \cos \omega t \, dt + \int_0^{\frac{2\pi}{\omega}} G_2(\omega)A \cos \omega t A\omega \cos \omega t \, dt$$

The first of the two integrals is zero, it represents the work done by the in phase, or elastic, components of the torque. The second integral represents the energy dissipated by the components of torque that are 90 degrees out of phase with the forcing displacement.

It can be shown that evaluation of the second integral leads to,

$$W = \pi A^2 G_2(\omega)$$

Now for the Maxwell body,

$$G_2(\omega) = \frac{\frac{\omega}{\eta}}{\left(\frac{1}{\eta^2} + \frac{\omega^2}{K^2}\right)}$$

hence the energy dissipated in one cycle is given by,

$$W = \frac{\pi A^2 \frac{\omega K^2}{\eta}}{\left(\frac{k^2}{\eta^2} + \omega^2\right)}$$

The dissipated energy is thus dependent on the amplitude and frequency of the displacement waveform and the spring and dashpot moduli. To assume that the amount of energy dissipated in a purely viscoelastic material is simply due to the effects of simple viscosity (i.e. frequency dependent only) is clearly erroneous.

Long et al also carried out stress relaxation tests on a number of subjects, relaxation time being used to characterize the results. From these two experimental techniques the authors proposed the joint model shown in fig. 3.5, which was simply the three parameter viscoelastic solid. The model is adequate to describe the results of the experiments but as these were not exhaustive it must be regarded as incomplete. The results of the creep experiments carried out by Wright and Johns are not explained by this model. Also tests at different frequencies may have suggested some further modifications.

3.6.4 Thompson (1978)

In a study of Knee joint stiffness Thompson developed a rheological model of the knee joint from a comprehensive series of experiments. The final model is shown in fig. 3.5. It can be seen that the rheological characteristics of the knee could not be described in purely viscoelastic terms. A plastic element was again included to explain stress relaxation results similar to those of Wright and Johns.

3.7 Torque datum and equilibrium position

Unsworth et al (1981) used a simplified arthrograph to investigate the stiffness of the MCP joint in a population of young adults. The arthrograph was not driven and so the joint was displaced incrementally and not oscillated as in other work. Initially the static equilibrium position was found (the natural angular position when the joint was at rest and the subject was completely relaxed). The torque was measured at positions 5 degrees either side of the static equilibrium position and then the joint was moved ten degrees towards extension. Torques were again measured at and either side of this displacement and the whole process was repeated at successive ten degree increments, moving to 20 degrees extension, then to 60 degrees flexion and finally returning to the equilibrium position.

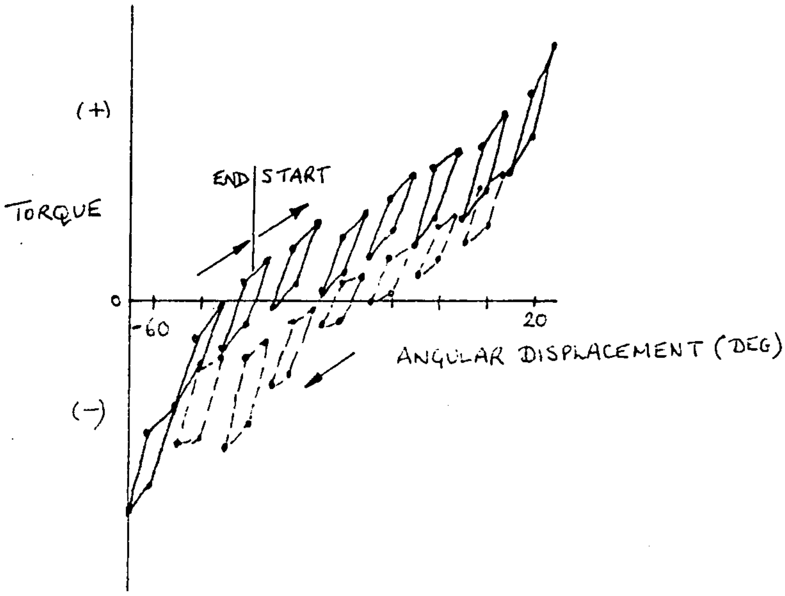
The results from this standard experiment and the method of analysis are reproduced in fig. 3.7. It should be noted that the lines joining the points are not plots of torque but merely constructions that connect the torques measured at either side of a particular displacement. A small number of subjects were tested in the reverse direction, ie. first into flexion and then into extension and finally equilibrium. It was found that changes in the order of testing did not lead to a significant change in the experimental results.

It can be seen that there are two angular positions of zero torque. One when moving into flexion, and the other when moving into extension. The authors suggested that stress relaxation of the flexor/tendon apparatus could account for this phenomenon. Which position to choose as the true equilibrium position of the joint is a matter of debate but if experimental procedures are consistent then this should not pose a problem.

The standard experiment was conducted on 23 males and 26 females. A considerable variation was found in the equilibrium position for this population. Values ranged from 16 degrees to 44 degrees. Consequently, Unsworth suggested that the equilibrium position should be used as the datum for each joint rather than comparing absolute angles of flexion. If the torque balance of the finger is taken into account in this manner, this means that joints that have identical stiffness characteristics but whose equilibrium positions do not coincide, will still give identical results. This would not be the case if an arbitrary reference angle was used as the datum. Consideration of the idealised torque/displacement characteristics shown in fig. 3.8 highlight this particular argu ment.

Figure 3.7 Experimental results of Unsworth et al (1981)

SAMPLE RESULTS



METHOD OF ANALYSIS

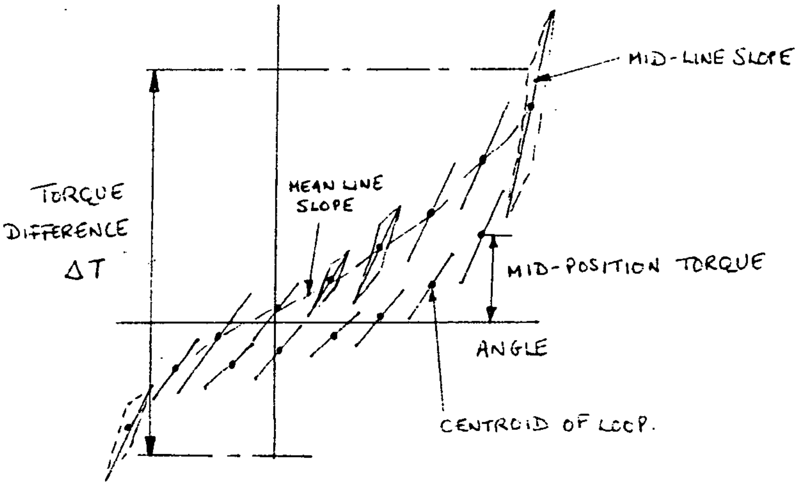
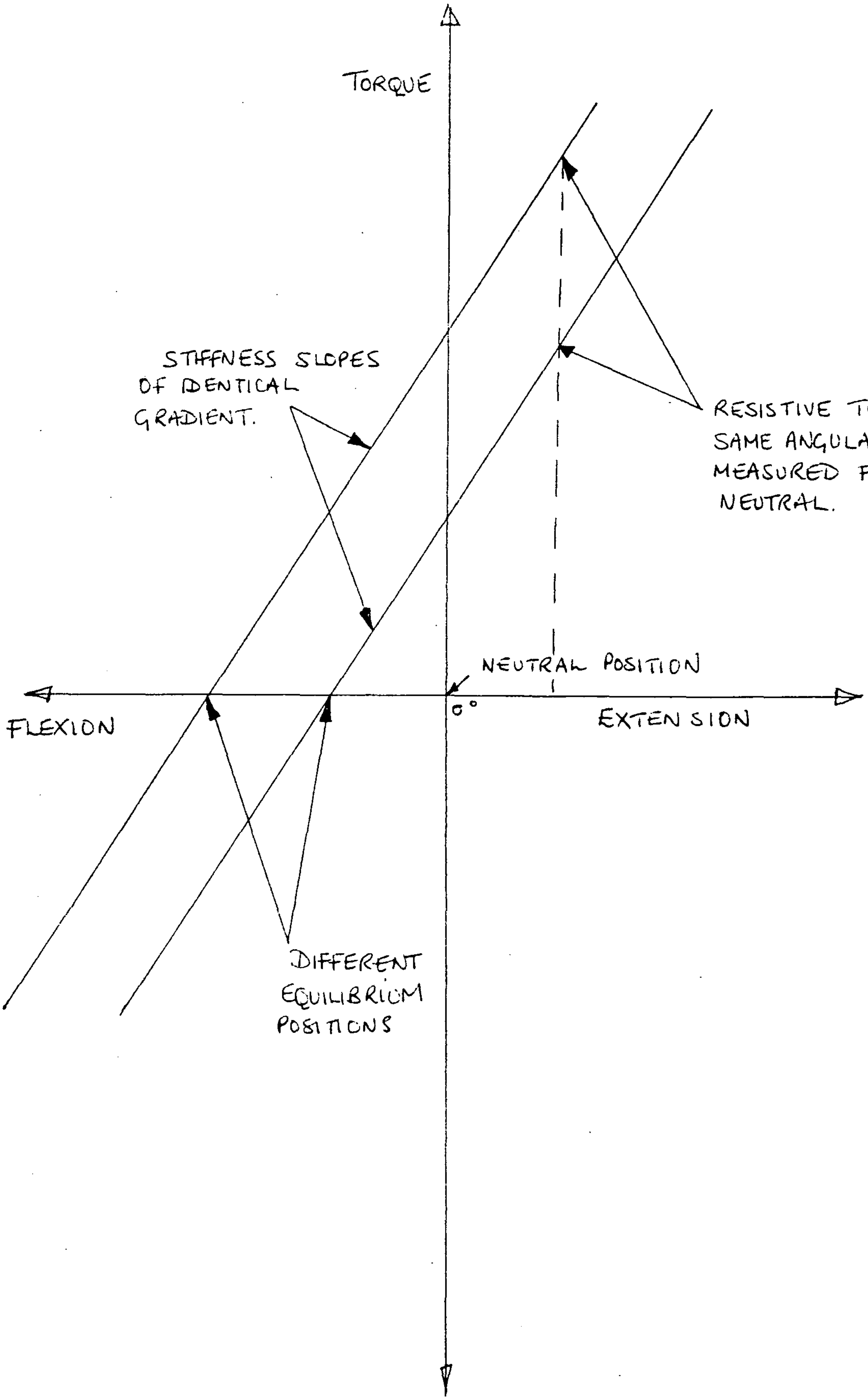


Figure 3.8 Idealised torque displacement characteristics



3.8 Limitations and advantages

In this type of work there is a temptation to relate particular properties such as viscosity to discrete structures within the joint. For example the viscous component of the torque/displacement curves does not necessarily arise form the shear of synovial fluid between the joint surfaces (suggested Wright, Dowson, Longfield, 1969). Indeed, in view of the body of work on skin, ligament and tendon and the complex mathematical models used to describe these structures (Danielson 1973, Gunner et al 1984, Woo 1981) it seems unlikely that this approach will yield any definitive information on the intimate nature of the tissues which comprise the joint.

To summarize what this method can reveal and what it cannot the following statements can be considered. Proteins are high polymers and may have complex moduli. Soft tissue is a composite material composed of proteins and other substances and its properties may be even more complex. Combinations of soft tissues and other materials and fluids are arranged in an elaborate mechanism to enable joint function. It also should be emphasised that during joint motion each element of the joint structure, such as capsule, tendons, ligaments and muscle, may not be actively involved, at any one time in producing any resistive torque. Some elements may only make a contribution at the limits of joint range or there may be a reorientation effect following successive oscillations of the joint. However, a knowledge of the relative contributions of different structures may help to shed some light in this respect and has been attempted by a number of workers.

3.8.1 Relative contributions of different structures

Wright and Johns (1962) performed large amplitude sinusoidal oscillation experiments, at five amplitudes of rotation within the range of motion, on the wrist joints of five cats. This joint was selected because of its similarities in size and function to the metacarpophalangeal joint in man. By progressively cutting away the structures that compose the joint and performing the experiment after each severance then it was possible to measure the contribution that each structure made to the torque/displacement curve. First the skin was cut and separated at the wrist. This was followed by transection of the extensor, then flexor, tendons above the wrist, removal of the tendons from the joint capsule and finally complete severance at the wrist. It was found that the joint capsule contributed 47%, muscles 41%, tendons 10% and the skin 2% to the total resistive torque in the midrange of motion. The restraining effect of the tendons became more important towards the extremes of joint motion.

Thompson performed a similar experiment on the knee with the joint from an amputated limb. The gastrocnemius was severed and the muscle bulk around the joint was removed, skin and fatty tissue were next followed by the capsule and patella and finally the collateral ligaments.

After noting the possible sources of error between 'in vivo and in vitro ', such as refrigeration, rigor mortis, and removal of most of the muscle groups prior to experiment, the author was able to make the following general conclusions. The muscle/fatty tissue contributed around 70 to 80 % of the elastic resistance and energy dissipation, the cruciate ligaments were a source of elastic resistance and the fatty tissue immediately around the joint a significant proportion of the energy loss.

The only other work that can be found to suggest the contribution of various structures to the overall stiffness are the experiments of Long et al (sec.3.6.2) and those of Barnett and Cobbold (1962). The techniques used in each case were non-invasive, 'in vivo ', measurements which utilized changes in contributions from different joint structures for different orientations of wrist and finger.

Barnett and Cobbold concentrated their attention on the 'Coefficient of resistance to motion 'of the distal interphalangeal joint. They equated the loss of potential energy in a decaying pendulum with the energy dissipated at the joint. Thus, this work is not a true measurement of stiffness but rather an evaluation of the dissipative components of the joint structure. Initial experiments were performed with the palm in a supinated position and the PIP joint fully flexed. The results from this experiment were then compared with those when the PIP was extended. In the first case their could be no action of the extensor or flexor tendons on the terminal phalanx and so it was possible to compare the effect of muscle on the energy dissipated at the joint. The authors concluded that the passive action of the muscles contibuted about half of the total energy dissipated at the joint.

From these observations it is possible that some general deductions can be made. Although the results presented are from different joints, in all cases the contribution from the passive pull of the muscles to the elastic stiffness and the energy dissipation appears to be highly significant. In the case of the MCP joint the contibution of the joint capsule also appears to be significant. Therefore it seems likely that any gross changes in the character of the hysteresis loop must be due to changes in the passive properties of the tissue comprising the joint capsule or the muscles or a combination of both. However, it should be remembered that during joint motion any impairment of the mechanism by which some structures act will affect their contribution even though there have been no changes in the properties of the structure itself. For example, restriction of movement of the tendons by ligamentous arrangements such as occurs in the phenomenon of 'trigger finger 'will affect the contribution from the muscles although the rheological properties of the muscles themselves are unchanged.

3.9 In summary

It is suggested that macroscopic rheological investigation of this kind is not very useful in its own right in isolating the source of any pathological changes in the structures of the joint. However, if an accurate rheological model is found for a joint and if the coefficients of its governing equation are found to be reasonably constant in a normal functional situation then gross changes of these coefficients will suggest that the function of the joint is impaired. Moreover, if a diseased joint exhibits a changed coefficient or coefficients then a modification of these to the normal value by some known method, would give corroborative evidence to the effectiveness of the aforementioned method, in modifying joint stiffness at least.

The other important aspect is that the very process of rheological investigation, the experiments and arguments to determine a model, provide vital information as to what factors are important in a standard experiment to measure joint stiffness and in the analysis of results. It has been shown in this chapter that frequency, amplitude of oscillation, position of oscillation, wrist position, displacement history and torque datum must be consistent if accurate conclusions are to be drawn from large scale experiments on joint stiffness.

CHAPTER 4

EQUIPMENT DESIGN AND CALIBRATION

In the interests of clarity the contents of this chapter are divided into two separate sections. Each section will include the design criteria for each piece of equipment, the factors considered in the evolution of the final design and calibration and testing of the completed device.

Section one descibes the development of a system to measure the passive stiffness of the human metacarpophalangeal joint, namely the horizontal MCP joint arthrograph (Unsworth et al, 1982). The overall requirement was for a system which would ; be reliable and easy to use, automate the test procedure, process the results at the time of testing and be capable of storing the processed results and other relevant information in easily retrievable format. This development would facilitate larger scale clinical studies than had previously been undertaken.

Section two describes the design and development of a dedicated microprocessor system for grip strength measurement. In this case the proposal was to produce a portable unit which would provide graphical and numerical data of the force contributions of individual fingers and the maximum total grip in a power grasp of standard duration. In this way it was hoped that the development of the grip could be observed and problems associated with the function of a particular finger could be isolated.

SECTION 1

4.1 Outline of the horizontal MCP joint arthrograph

This machine was designed to measure the passive stiffness of the metacarpophalangeal joint of the index finger. The basic principle of operation was to measure resistive torque at the joint throughout a predetermined flexion-extension cycle, movement occuring in the horizontal plane.

Before beginning a technical description of the machine it is worthwhile, and hopefully less confusing, to review the descriptive terminology which will be used consistently throughout this section.

4.2 Moment Conventions

The following definitions can be more readily understood by reference to fig. 4.1.

Neutral position :- The angular position where the proximal phalanx and the metacarpal bones are in alignment. This is arbitrarily defined to be zero degrees.

Extension :- The angle through which the proximal phalanx may be moved dorsally from the neutral position. Angular positions in extension are defined as negative.

Flexion :- The angle through which the proximal phalanx may be moved towards the palmar aspect of the hand from the neutral position. Angular positions in flexion are defined as positive.

Extension moment :- The sum of the moments acting on the joint in a sense which attempts to move the joint into extension. In fig. 4.1 these moments would be clockwise.

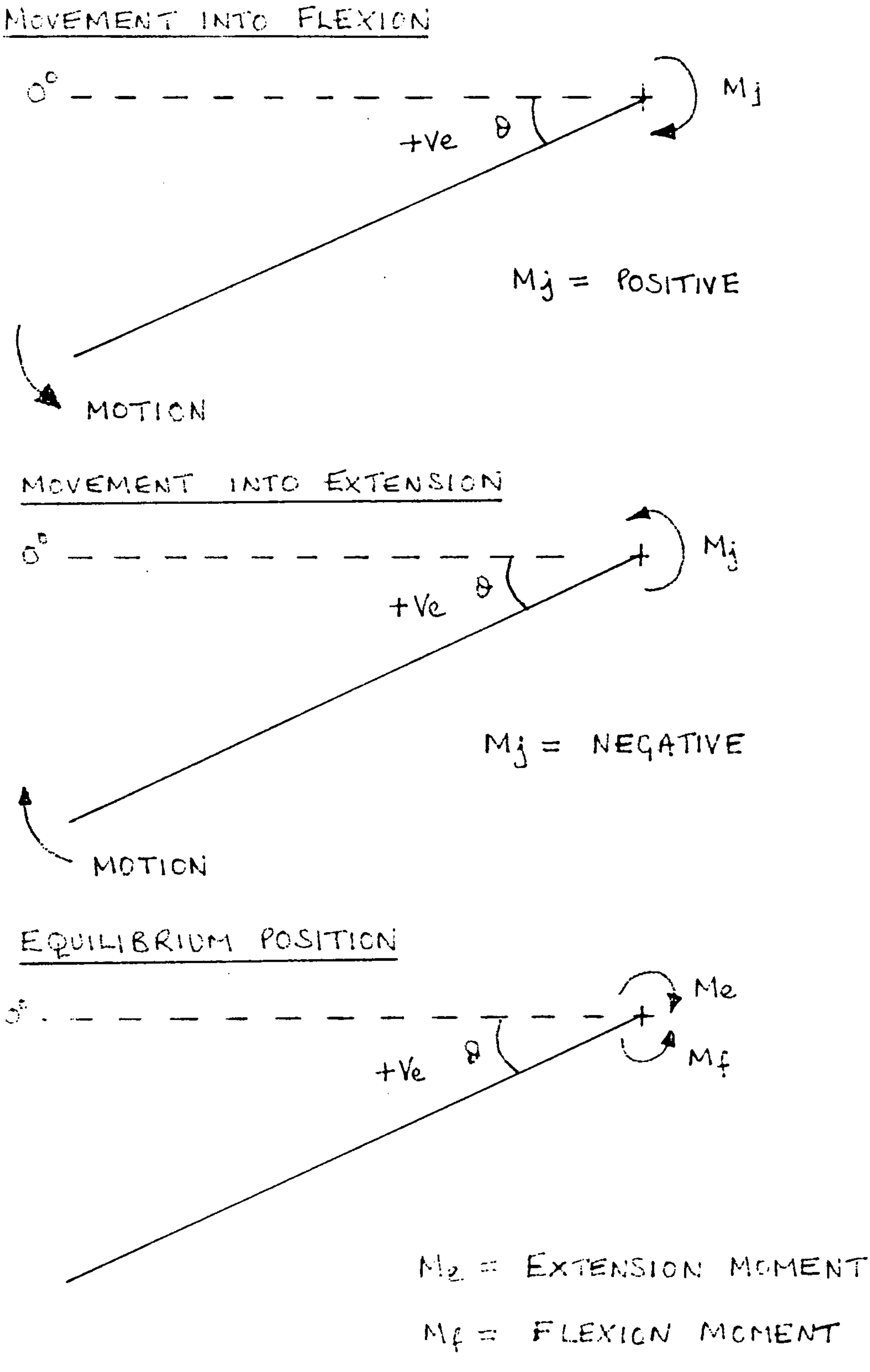
Flexion moment :- The sum of the moments acting on the joint in a sense which attempts to move the joint into flexion. In fig. 4.1 these moments would be anticlockwise.

Equilibrium position :- In the absence of gravitational or muscular forces the position when the flexion/extension moments about the joint are in equilibrium, i.e. there is zero nett torque at the joint.

Torque :- Resistive torque is taken as positive when resisting flexion. Units are Nm.

Fig 4.1 Moment Conventions

Mj = RESISTIVE TORQUE AT THE JOINT



AT EQUILIBRIUM POSITION $M_e = M_f$

4.3 Technical description.

A review of the literature reveals that the design criteria for any arthrograph-type machine can be divided into three broad elements.

The arthrograph should be :-adjustable to accommodate different sizes of limb, driven by a smooth, silent and versatile drive mechanism, sensitive, accurate and repeatable in its' measurement of resistive torque and angular position of the joint.

A basic machine had already been designed which fulfilled these criteria (Unsworth et al 1982). This machine will be described briefly to help understand the extensive development work carried out to meet the requirements previously stated in the introduction to this chapter. How each of the design criteria were satisfied will now be discussed in turn.

4.4 Positioning of the joint

Plate I shows how the hand was orientated in relation to the body of the arthrograph and the plan view in plate II reveals the positioning of the joint with reference to the axis of rotation of the drive arm and the torque transducer.

The hand was placed in position on the adjustable arm rest. The index finger was inserted in the torque transducer and retained by an elastic sling whilst the rest of the fingers curved easily around the smooth, cylindrical wooden grip. The thumb was suspended in a small sling clear of the plane of movement of the finger. "Plastizote" sheets of various thicknesses placed on the arm rest allowed cushioning and height adjustment of the hand in relation to the torque transducer. Six ball bearings allowed movement of the arm rest in the horizontal plane thus enabling the centre of rotation of the joint to be aligned with the centre of rotation of the arthrograph drive. Once the joint was located, locking nuts secured the arm rest in position.

4.5 The drive mechanism

Simple harmonic motion of the joint was achieved by a synchronous motor driving a Scotch Yoke mechanism. The Scotch Yoke was attached to a pulley and belt arrangement which effected motion of the drive arm. Mounting of the Scotch Yoke mechanism on a carriage, which was threaded on to a long lead screw and crank handle, allowed the mean position of oscillation to be varied throughout the whole joint range. Two large bolts, one at either end of the limit of travel of the carriage, could be adjusted to prevent the joint from being displaced beyond a comfortable range of motion.

The side view in plate III of the arthrograph, with side panels removed, allows the interior mechanism of the machine to be observed.

By changing the radius of the eccentric on the Scotch Yoke and by varying the motor speed, various combinations of amplitude and frequency of oscillation were possible. However, larger values of amplitude and frequency can give rise to significant inertial torques from the finger and consequently care needed to be exercised, when choosing particular combinations, so that the resolution of the measured torque was not compromised. The calculation for acceptable frequency-amplitude combinations and a plot of values are shown in appendix one. For the standard test it was decided to oscillate the joint at a frequency of 0.1 Hz and an amplitude of 20 degrees.

Plate I Side View of the arthrograph with the hand in position

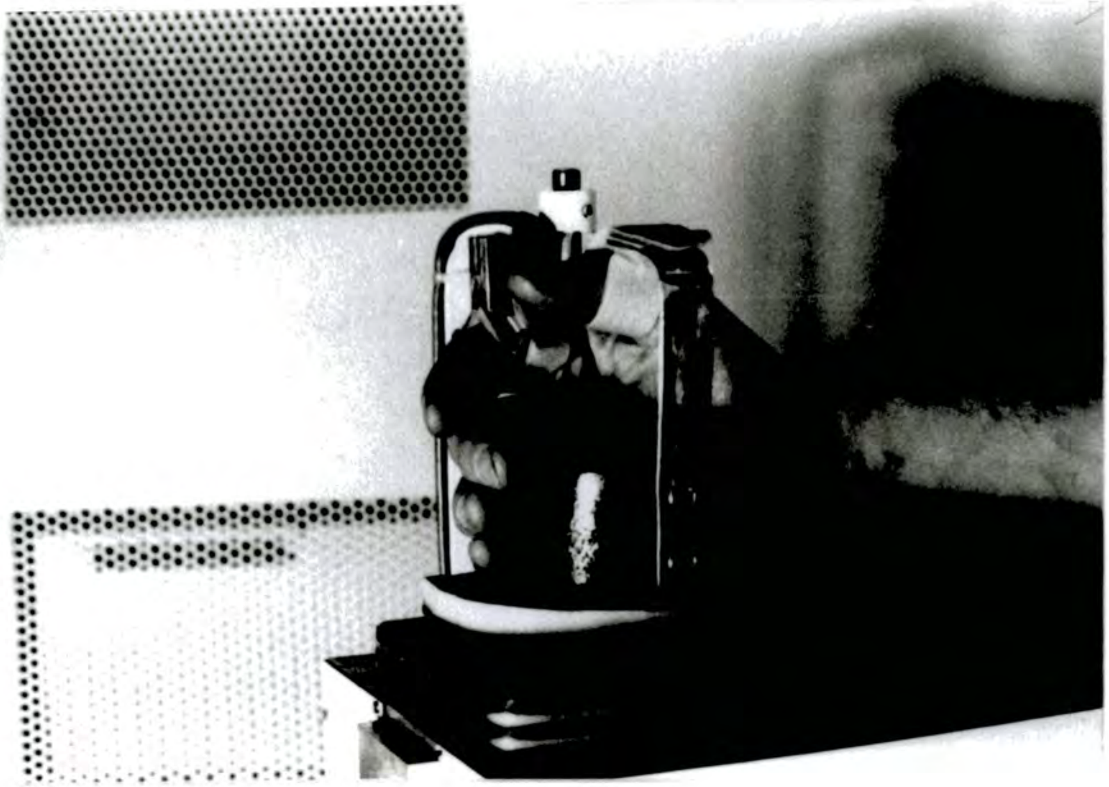


Plate II Plan View of the arthrograph

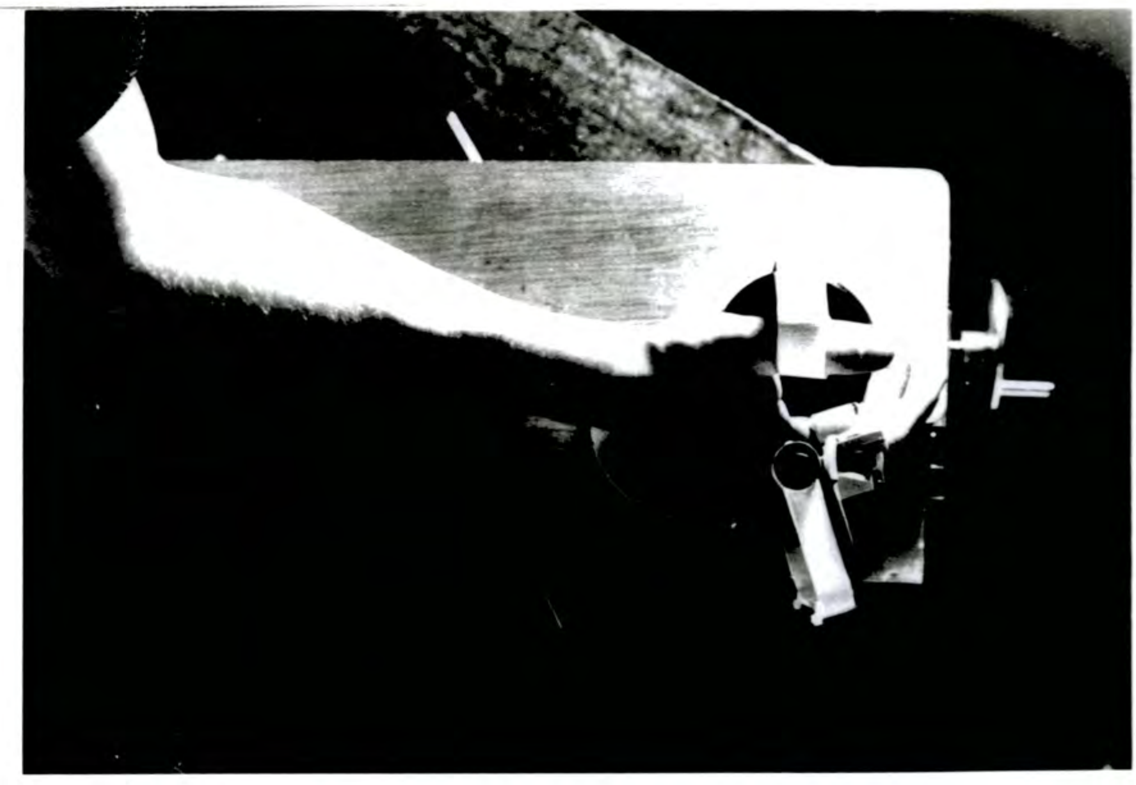


Plate III Side View of the Arthrograph with panels removed

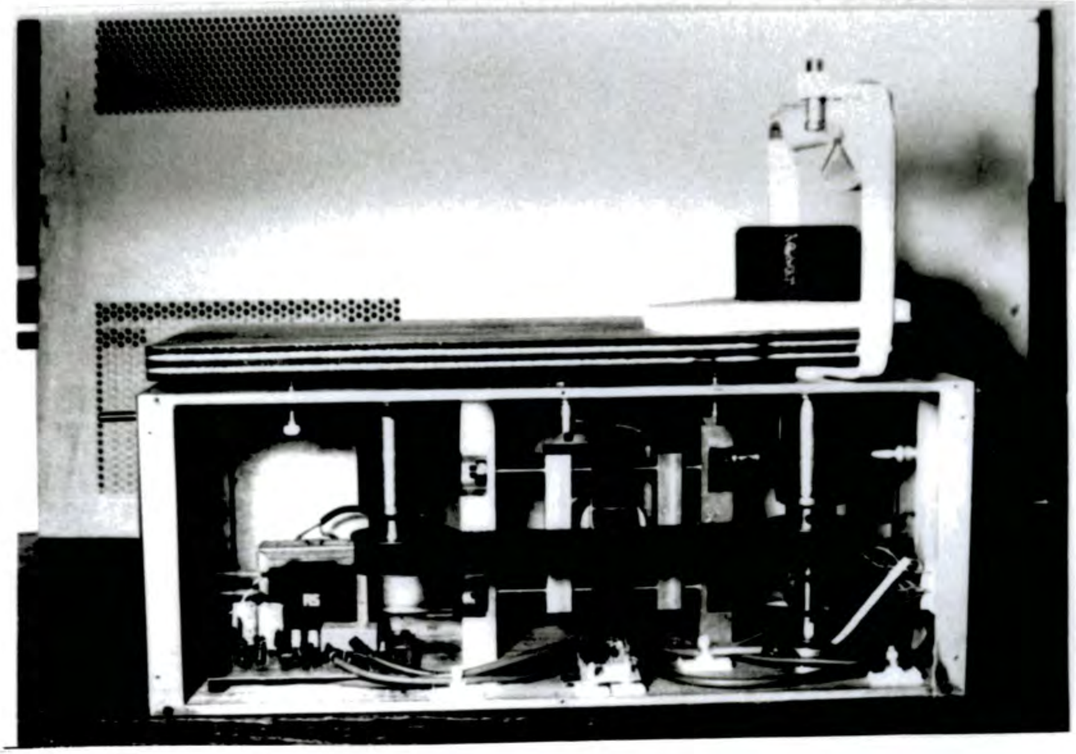


Plate IV The complete system

4.6 Torque and angle transducers

4.6.1 Angular displacement transducer

A 10Kohm potentiometer, mounted directly on the shaft of one of the main drive pulleys and used as a simple voltage divider, provided the electrical analogue of the angular position of the drive arm.

4.6.2 Torque transducer

The V-block finger holder was attached to the drive arm by a thin steel cantilever. Any resistive torque at the joint was converted to a proportional strain in the cantilever. Four strain gauges were bonded to the cantilever, two on each side, and connected in Wheatstone Bridge configuration with four active limbs. When arranged in this fashion the output from the gauges were additive and the maximum sensitivity was therefore achieved.

However, there is one theoretical problem that should be borne in mind before calibration of this type of transducer. For the signal to be exactly repeatable for joint torques of the same magnitude then theoretically the point of application of reactive loading by the finger on the transducer should occur at the same point within the finger holder. This can be seen by consideration of the bending moment diagrams in fig. 4.2 and by the following calculations which refer to the figure.

In case 1 the position of reaction of the finger on the holder occurs on the end of the holder which is farthest from the base of the cantilever (the distance L1 in the figure).

M_j = the resistive torque at the joint.

M_g = the bending moment at the plane of the gauges.

In case 1 for moment equilibrium about the root of the cantilever.

$$F_1 L1 = M_j$$

and

$$M_{g1} = F_1(L1 - a)$$

$$M_{g1} = M_j - F_1 a$$

In case 2 the reaction force occurs on the opposite end of the holder, a distance L2 from the base of the cantilever.

For case 2,

$$F_2 L_2 = M_j$$

and

$$M_{g2} = F_2(L2 - a)$$

$$M_{g2} = M_j - F_2 a$$

now,

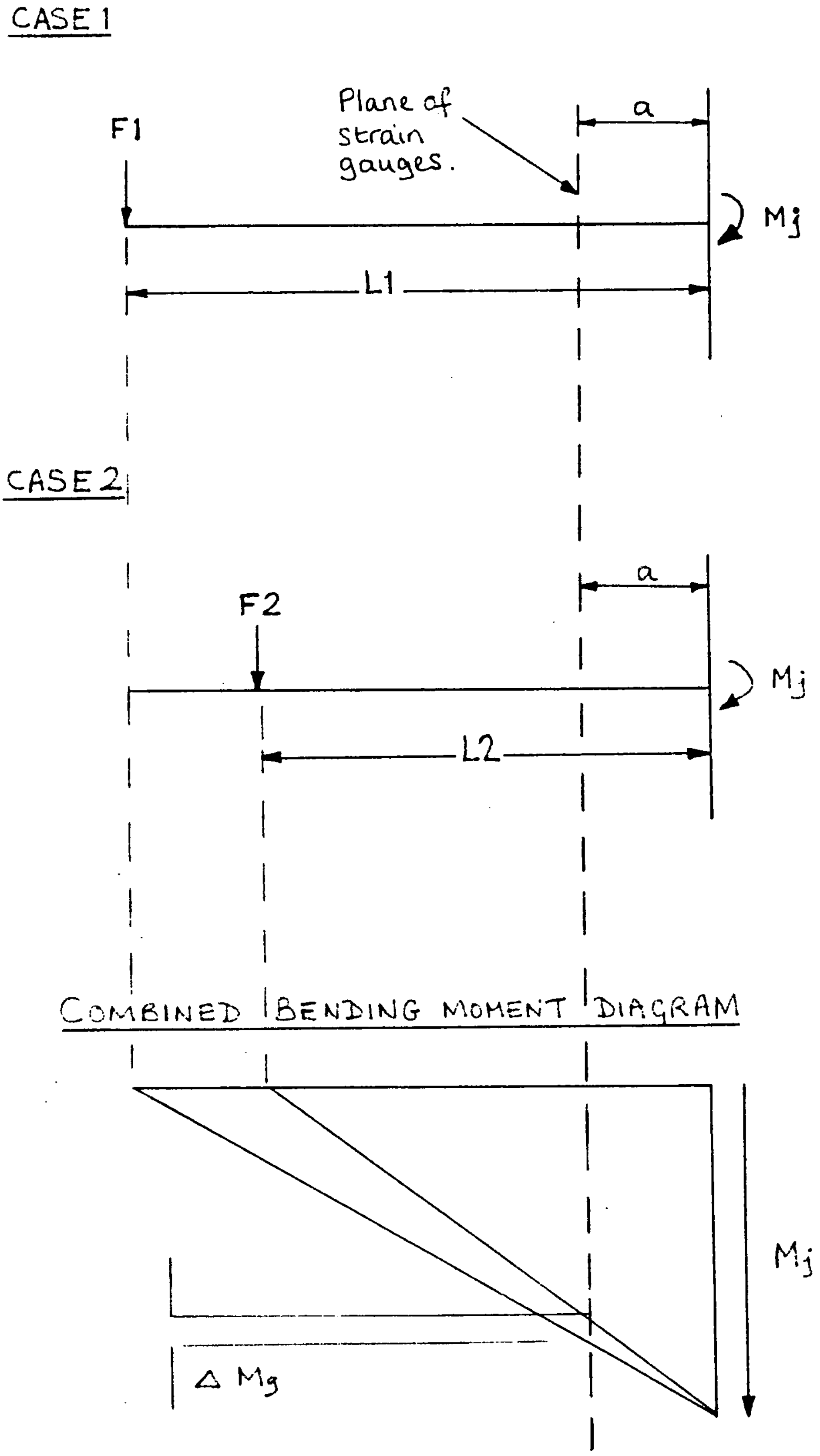
$$L1 \neq L2 \quad F_1 \neq F_2 \quad and \quad hence \quad M_{g1} \neq M_{g2}$$

For a different point of application of reactive load within the finger holder of the transducer a different bending moment would be measured for the same torque at the joint.

The obvious solution would seem to be to locate the finger between two knife edges but this was not easily achievable when comfort was also considered. Redesign of the transducer either to measure the difference between two strains or the shear strain, would eliminate the effects of the variation in the point of loading if force was the quantity to be measured. The figures and accompanying calculations in Appendix One demonstrate why these solutions would be unsuitable in this case. Yet another suggestion was to use a torque-tube transducer . As this measures torque directly, the loading problem would of no consequence. However, in view of the small magnitude of the torques to be measured, this alternative, although theoretically possible, is extremely difficult to apply in practice.

It was decided therefore to investigate the significance of this theoretical error during the calibration of the transducer.

Fig. 4.2 Effect of point of loading on the measured torque



4.7 System requirements

The basic elements of the arthrograph have now been described. At this point it is appropriate to review the design requirements of the complete measurement system.

The system was to be used to collect large quantities of data by repetition of a standard test procedure. In the course of the experimental work it would also have to be moved from one location to another and be flexible enough to function effectively in a busy clinical environment.

These two factors suggested that development should proceed in two areas. Firstly, the hardware for signal processing and interfacing should be reduced in size, as far as possible, so that the system would be reasonably portable but without compromising its function. Secondly, data collection, processing, and storage should be handled automatically so that experimental work could be performed with a minimum of effort.

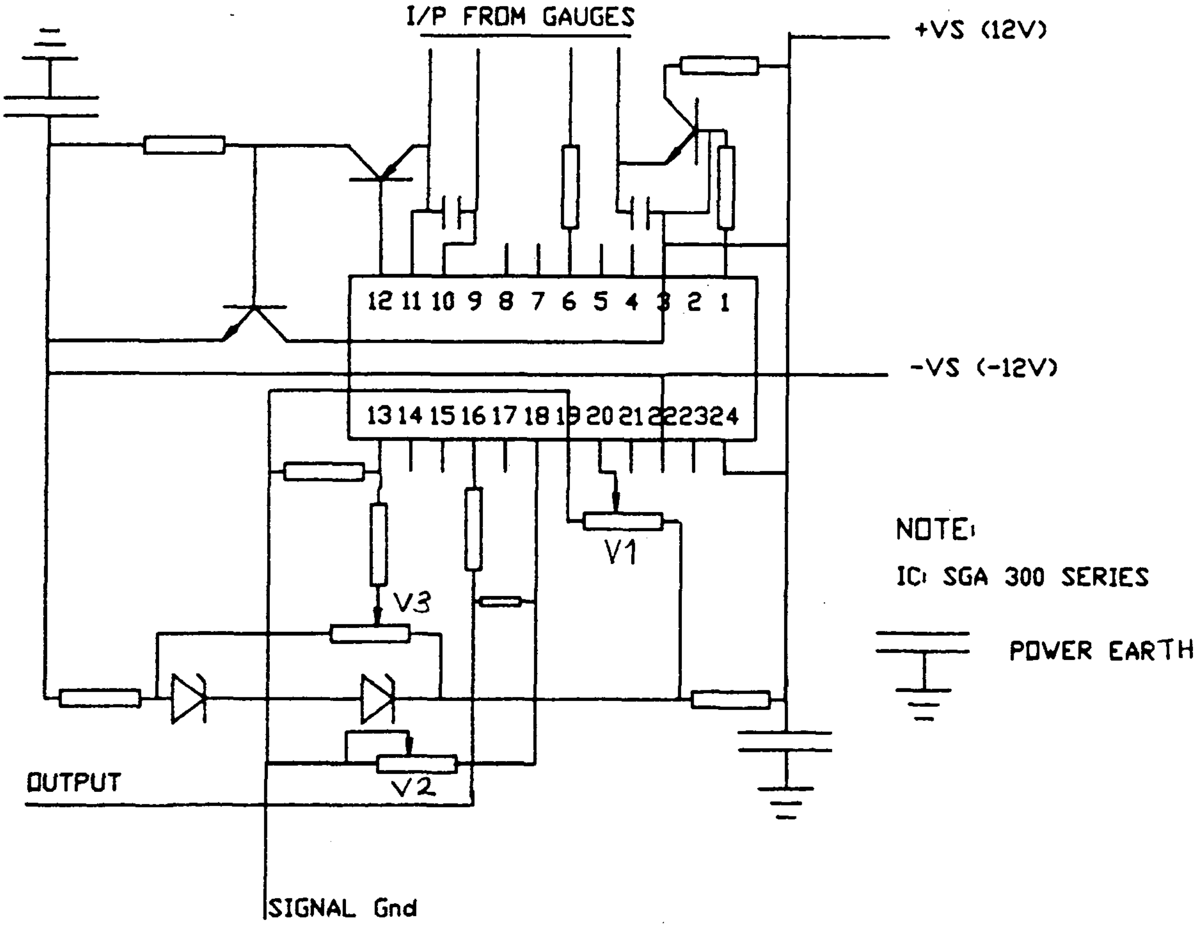
4.8 Signal processing

4.8.1 Strain gauge amplification

Voltages caused by changes in strain can be less than 1mV but may be superimposed on a much larger common mode voltage. This common mode voltage can be generated in certain circumstances by magnetic fields associated with currents flowing through disturbing wires which are in close proximity to the strain gauge lead wires or by fields due to motors or switchgear. If the voltage becomes significant relative to the strain gauge signal then separation of the true signal from the noise signal can become quite difficult. In view of this problem the strain gauge amplifier had to be capable of achieving very good common mode rejection.

The output signal from the torque transducer was amplified by a custom built , miniature strain gauge amplifier circuit based around a low noise, low drift, linear D.C. amplifier housed in a 24 pin D.I.L. package (fig. 4.3). The advantage of such a design over a conventional amplifier made from discrete components is the exceptional common mode rejection that can be obtained combined with its relatively small size. The amplifier overcame the problem of common mode rejection by removing the common mode voltages. This was achieved by controlling the negative bridge supply voltage in such a manner that the voltage at the negative input terminal was always zero. Consequently, for the symmetrical bridge that was used in this transducer application, a negative bridge supply was generated which was equal and opposite to the positive bridge supply, hence zero common mode voltage.

Fig. 4.3 Strain gauge amplification circuit



Potentiometers V1,V2 and V3 allowed adustment of gain, range and zero offset respectively. The only real disadvantage of using this amplifier IC was that a warm up time of approximately five minutes was necessary before the output signal was free from drift. The amplifier circuit was mounted within the arthrograph body as close as possible to the transducer so that the length of the input lines, and hence the level of effect of external noise and signal distortion, was reduced.

4.8.2 Angular signal amplification

In order to achieve the maximum possible angular resolution it was necessary to amplify the signal from the angle potentiometer. A simple non-inverting amplifier circuit was designed based on a 741 operational amplifier.

4.9 Microcomputer Interfacing

An Apple II plus microcomputer and a DIO9 digital interface card were readily available in the laboratory and so it was decided to utilize them for the processing and interface requirements respectively. The use of a digital interface as opposed to a analogue to digital interface did initially present some difficulties as the analogue to digital conversion had to be handled by external, custom designed circuitry. However, for the purposes of prototyping, this did not present a problem but it was recognised that some redesign might be necessary at a later date to make the system more robust and reliable.

As a result an ADC (Analogue to digital conversion) circuit was designed based on two 427E ICs(fig. 4.4) and this was mounted on the rear plate of the arthrograph. Timing signals to initiate conversion were generated by the DIO9 and the parallel data from the ADC board was latched when the appropriate end of conversion acknowledgment signal was obtained.

After overcoming some initial timing difficulties this method of interfacing was found to function reliably and was retained for a considerable time. Ultimately, however, maintenance of the multiway parallel connectors proved to be very time consuming and consequently the DIO9 and ADC board were replaced by a proprietory eight bit, 8 channel ADC/MUX (Multiplexer) board. In the final version therefore the two analogue signals representing torque and angular displacement were amplified within the body of the arthrograph and then fed, via screened cabling, to the ADC/MUX board which resided in the microcomputer. A schematic diagram of the complete system is shown in fig. 4.5.

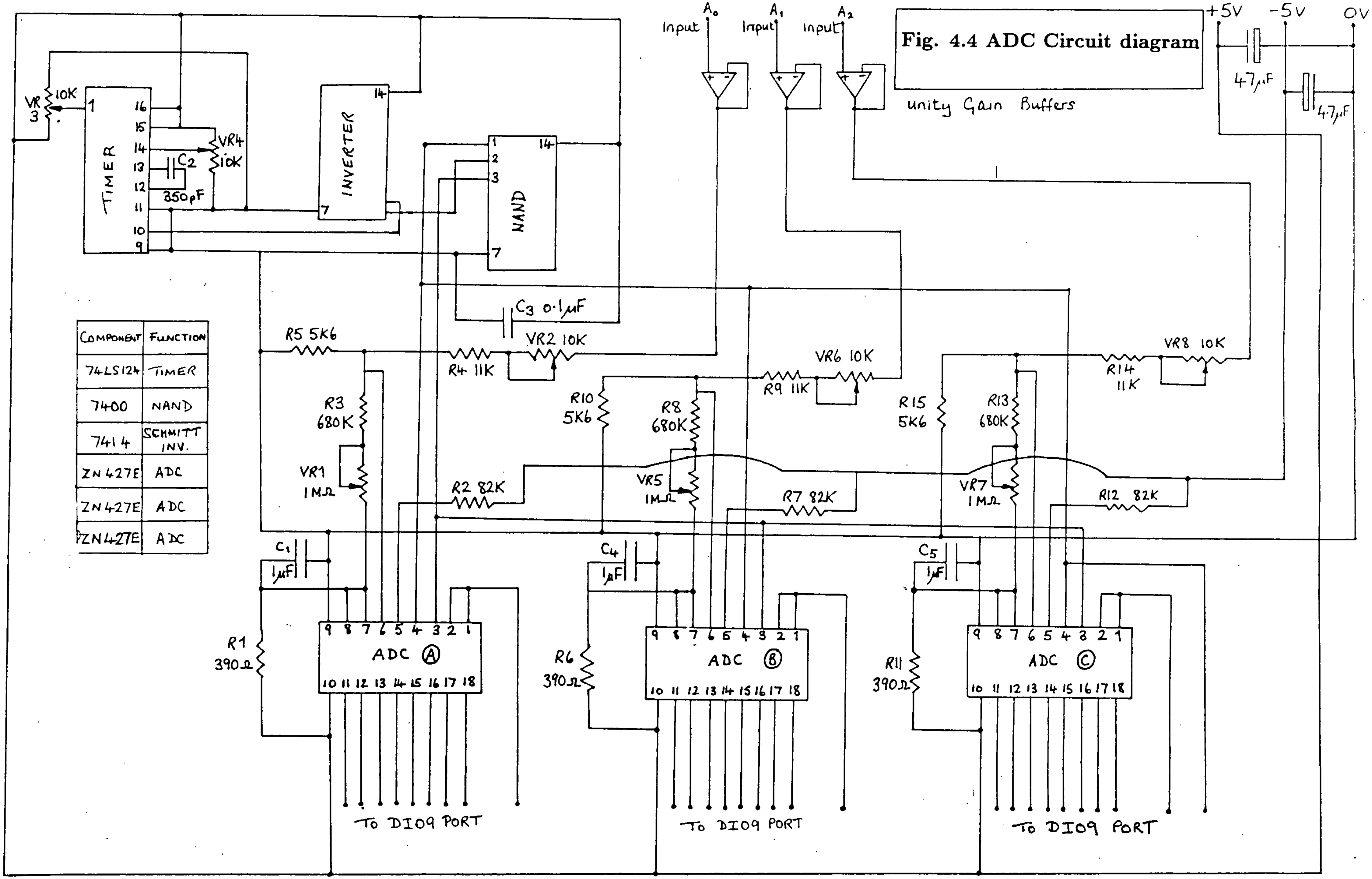
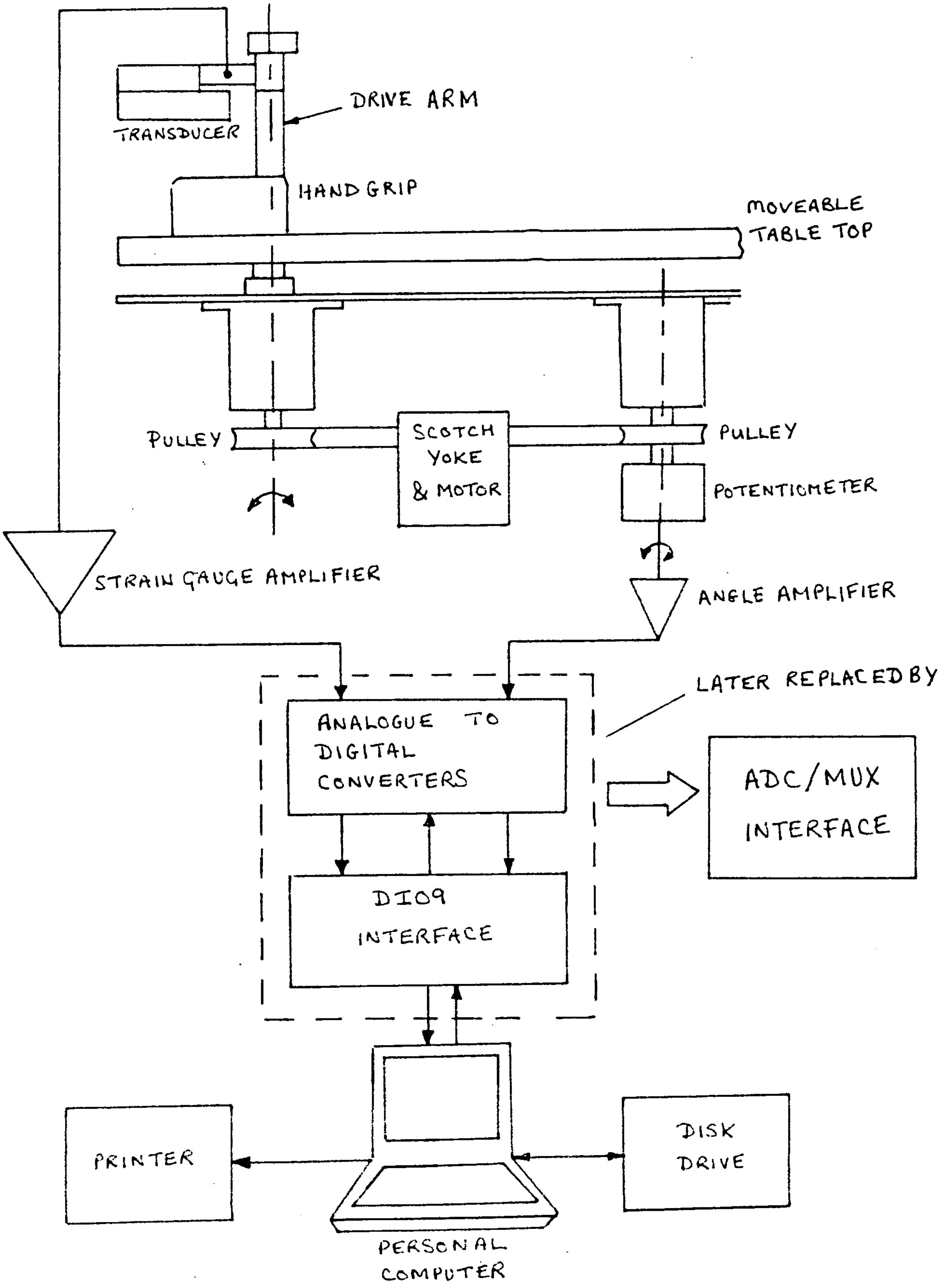


Fig. 4.4 ADC Circuit diagram

COMPONENT	FUNCTION
74LS124	TIMER
7400	NAND
7414	SCHMITT INV.
ZN427E	ADC
ZN427E	ADC
ZN427E	ADC

Fig. 4.5 Schematic diagram of the arthrograph



4.10 Calibration

The ADC/MUX was set up for unipolar operation with a maximum input signal level of 10V per channel. For an eight bit converter the best possible resolution was therefore 0.039V. A small test program was written so that the digital values of the two active channels could be monitored on the microcomputer screen. By inputting voltages of known values to these channels the accuracy and linearity of the converter was checked and adjusted as necessary.

4.10.1 Angle calibration

The range of motion for which an angular displacement reading would be required was from twenty degrees extension to seventy degrees flexion. Although the joint could be moved beyond these values it was felt that this choice of range was a reasonable compromise between flexibility and angular resolution. For maximum angular resolution to be obtained this choice would imply that 70 degrees would correspond to a digital reading of 255 and -20 degrees would correspond to a zero reading. Thus the angular resolution was limited to just over a third of a degree (0.35).

The arm rest was removed and a series of reference lines were marked on the top plate of the arthrograph. Each line corresponded to the angular position that the mid-point of the drive arm would assume at -20 degrees, zero degrees and 45 degrees.

The motor was switched on and the maximum and minimum readings of the drive arm were monitored on the screen. As the amplitude of oscillation had already been selected to be 20 degrees it was therefore known that the difference between the two values was equivalent to an angular displacement of 40 degrees. Hence by adjusting the gain of the angle amplifier the digital readings could be changed until the difference between them was 114 (equivalent to 40 degrees). Once the gain had been set then the motor was stopped when the drive arm was at its position of maximum extension for the particular oscillation. The drive arm was then moved , via the crank handle, until its mid position was in alignment with the reference line corresponding to -20 degrees. At this point the zero offset was adjusted until the reading was zero. Further checks were carried out by rotating the drive arm to the other reference lines and monitoring the readings. A summary of the reference angles and the calibrated reading is given in table 4.1.

Table 4.1 Summary of reference angles

Angle (deg.)	Calibrated digital reading (bits)
-20	0
0	57
45	184
70	255

4.10.2 Torque transducer calibration

It was vital for accurate calibration of the transducer that all possible loading modes were thoroughly investigated. From the schematic diagram of the transducer shown in fig. 4.6 it can be seen that reactive load due to a given resistive torque at the joint could possibly occur at any point along the length of the finger holder. The reactive load would be eccentric to the axis of the cantilever and hence would cause an axial bending moment as well as the desired longitudinal bending moment. In order to investigate any possible errors due to variation in transducer response because of the variety of loading positions, calibration was conducted for three modes of loading.

Before this could proceed it was necessary to consider what range of values and what resolution would be required. From other arthrographic work, particularly the work of Unsworth et al and Yung et al with the horizontal arthrograph, it appeared that an appropriate resolution to aim for would be 0.001 NM., with a range of + 0.15 NM. to - 0.15 NM.. It was hoped that this choice would give a sufficiently large range of response to cater for very stiff joints and stil be able to resolve all important detail during the measurement of joints that were very lax.

Initially it was ensured that the transducer was mounted in the correct position on the arthrograph, perpendicular to the drive arm. With the arthrograph standing on a level surface and the transducer free from load the range and zero offset potentiometers were adjusted until the digital reading was 120, an approximate mid range value. The drive arm was then rotated to the zero angular position and the arthrograph turned on its side. When in this position weights could be freely suspended from the transducer and their line of action was perpendicular to the longitudinal axis.

The first selected calibration position was the centre of the strap locating nut which was furthest from the axis of rotation, shown as position A in fig. 4.6 . Weights were supended form the transducer by a light, strong cord. The transducer was progressively loaded and unloaded and the digital readings were recorded at each increment. In this way and by adjusting the gain of the strain gauge amplifier the ideal calibration curve for this position was obtained which was within the desired range of response. A similar procedure was then carried out at position B, which was the centre of the strap locating nut at the opposite end of the finger holder, with unaltered amplifier gain settings. The two calibration curves are shown for comparison in fig. 4.7. In this figure the vertical axis is the equivalent torque at the axis of rotation of the joint which would cause the imposed loadings at positions A and B (also allowing for the constant torque due to the weight of the transducer itself).

Clearly the difference in gradients of the calibration curves would lead to the same resistive torque at the joint having two distinct values depending on which calibration curve was selected. However, this result was not altogether surprising following the discussion in section 4.6.2. The error between the two gradients was approximately 5% and as this was the maximum that could be achieved it was not considered that in a standard test situation the real error would be of sufficient magnitude to preclude the use of this type of transducer.

The next stage in the calibration was to repeat the calibration procedure described above for the other side of the transducer. In this way it was ensured that the response would be symmetrical and that the amplifier signal would not saturate at some point within the limits of the desired range. Happily, the response proved to be a mirror image of the previous side.

Following this check the arthrograph was then returned to its upright position and weights were hung from positions C and D, from which it was possible to generate the maximum possible axial moments about the transducer. The transducer proved to be insensitive to axial moments in the range that was of interest.

Finally the arthrograph was turned on its side once more and the final calibration was carried out with weights suspended from the mid-point of the finger holder. The final calibration curve, the gradient of which was used in all subsequent calculations, is shown in fig. 4.8. The mid-point was chosen so that the errors due to point of loading could be minimized. The transducer was then loaded to the maximum value of its range and left for a while whilst the digital readings were continuously recorded by the computer. Subsequent analysis of these readings revealed that the signal from the transducer was extremely stable and that no drift had occured.

In a similar way to the measured angle the resolution of the torque transducer was determined by the resolution of the analogue to digital converter. From the given calibration curve 1 bit change was equivalent to 0.0012 NM. Hence the desired resolution was nearly achieved.

Fig. 4.6 Schematic diagram of the Torque transducer

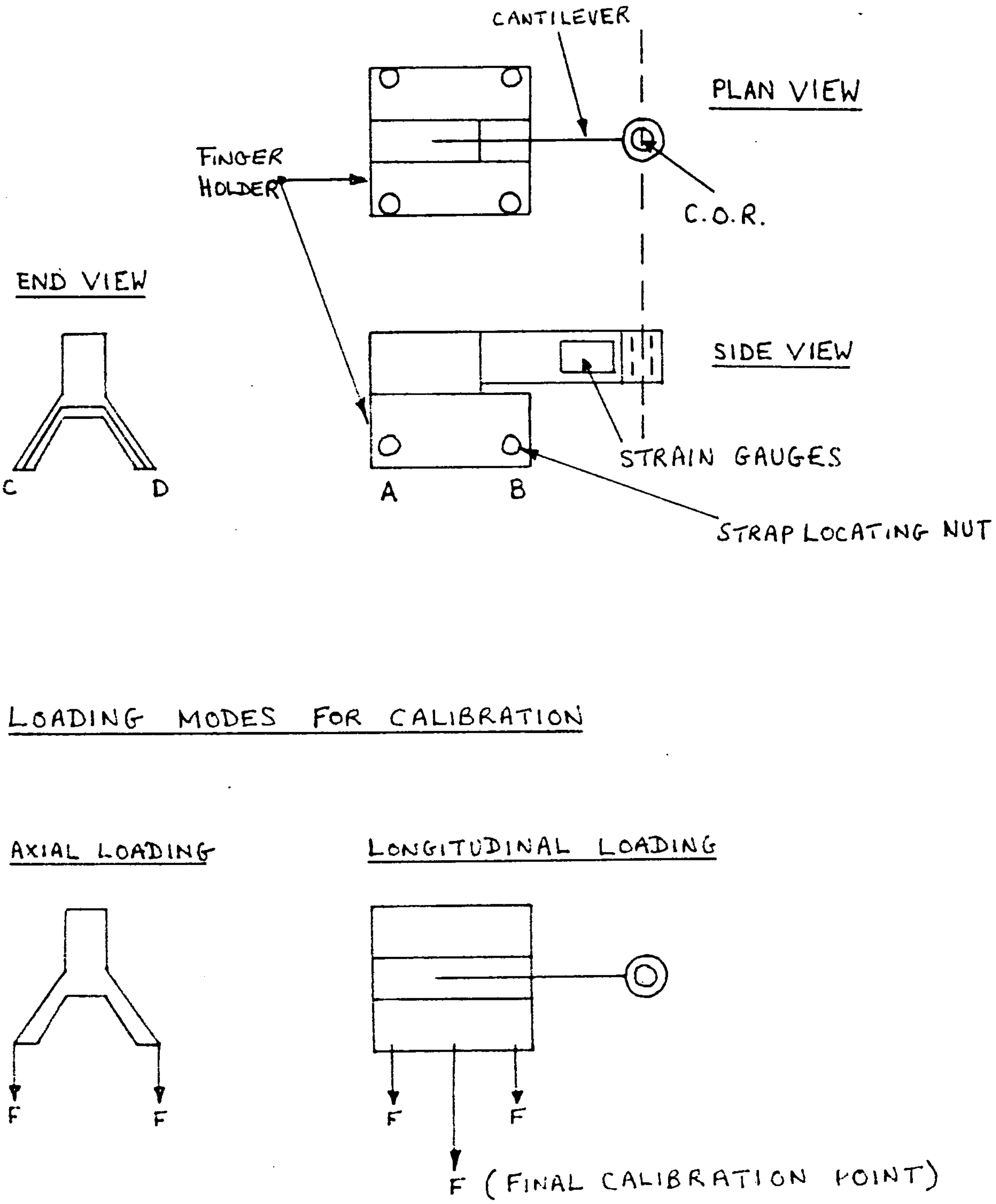


Fig. 4.7 Responses of the torque transducer loaded at A and B

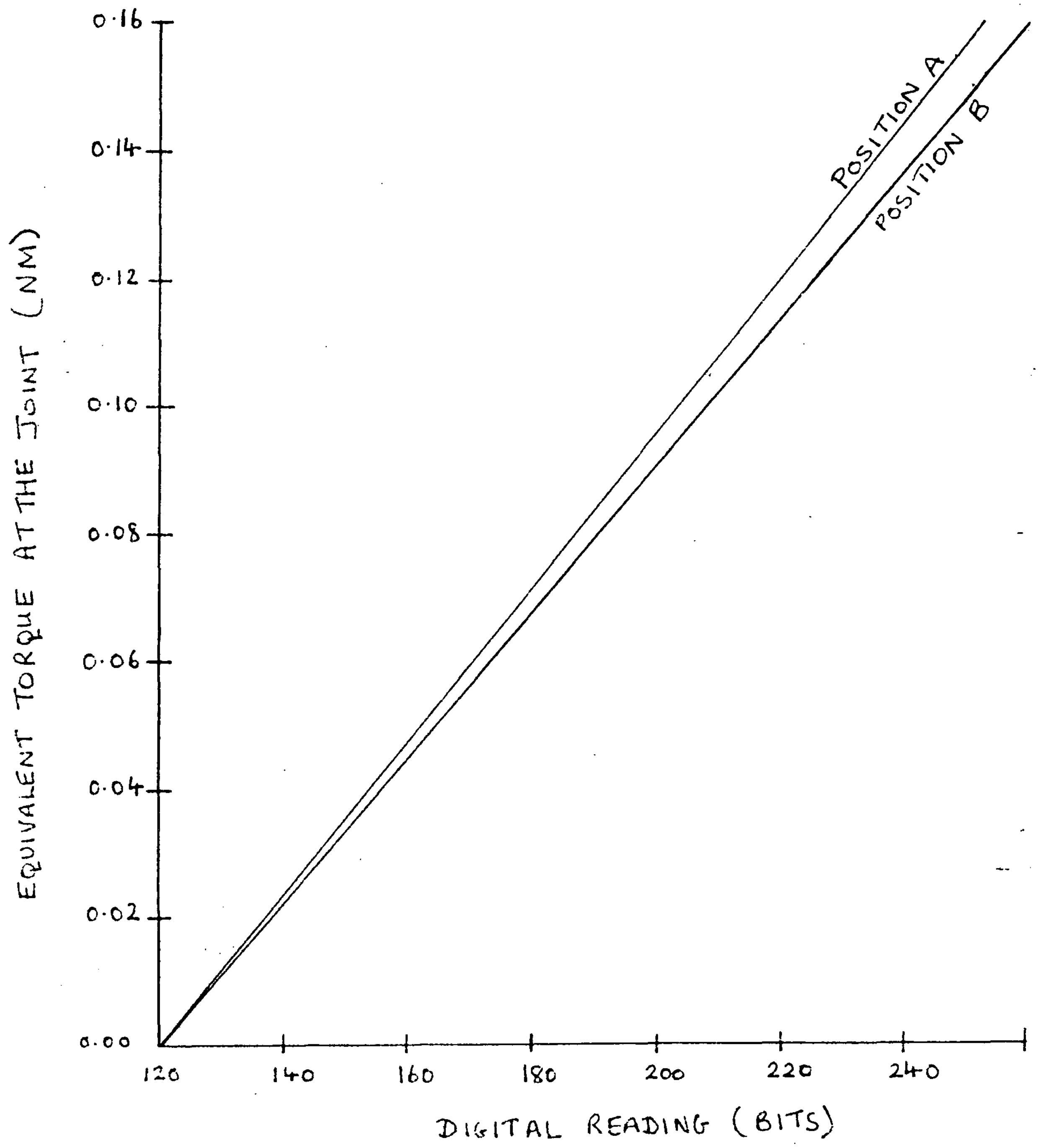
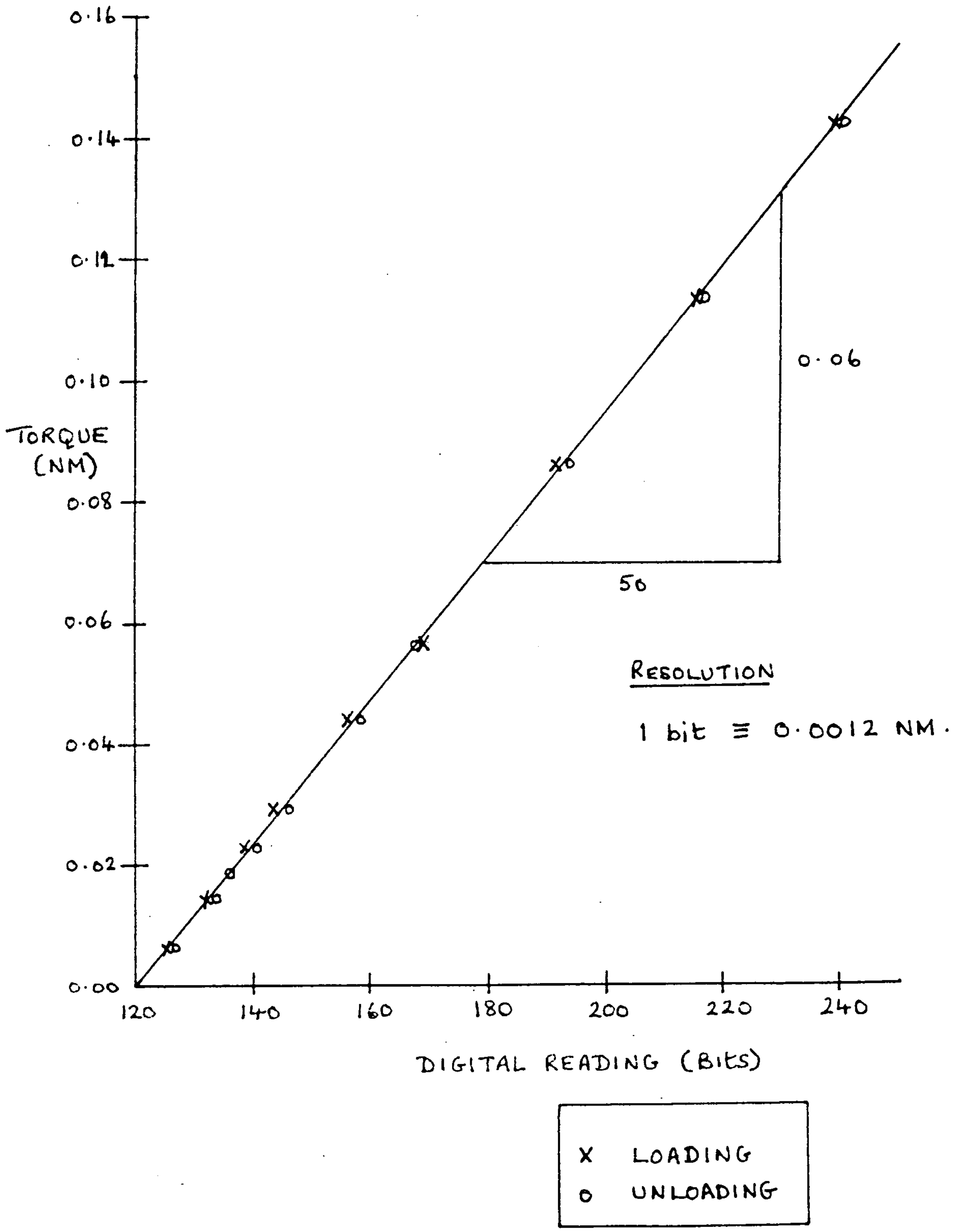


Fig. 4.8 Final Calibration curve for the torque transducer



4.11 Software development

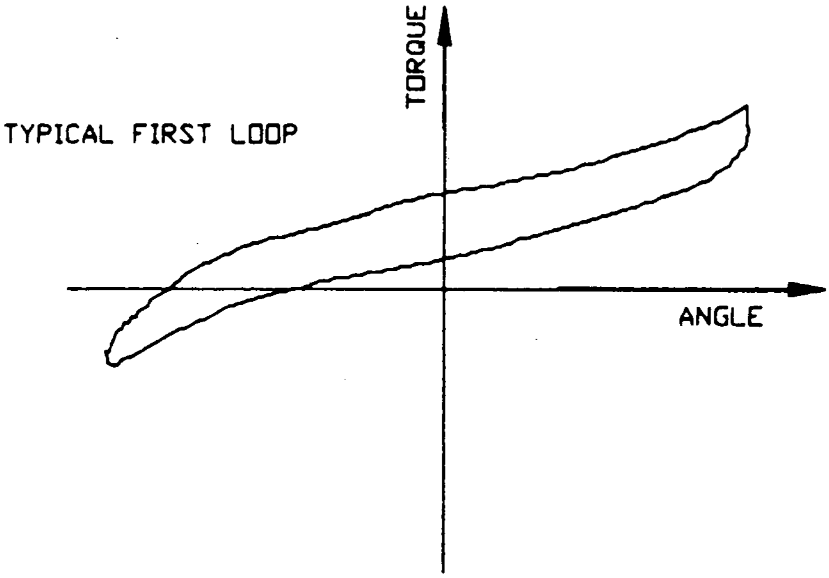
All of the initial work was concerned with the design of an appropriate control program for a standard test. The various forms of testing have already been discussed in chapter three. It was decided that for speed and ease of testing to adopt the method that involved displacing the joint through one large amplitude measurement cycle. However the thorny problem of what position, in the range of motion, to centre the cycle still remained. When this method had been used previously the datum position for each oscillation had been some arbitrary reference point such as the mid-position of range of motion or the neutral position but in view of the previous arguments presented in chapter two a procedure was sought which would centre the cycle on the equilibrium position of the joint.

Essentially the standard test procedure consisted of an initial measurement cycle centred about a position that was estimated to be close to the equilibrium position of the joint. Analysis of the hysteresis loop that resulted from this cycle gave an indication of the true equilibrium position of the joint and the cycle centre was then moved to this position and a second measurement cycle was executed. Typical primary and secondary hysteresis loops resulting from this procedure are shown in fig. 4.9. The experimentation that led to this procedure will be discussed in more detail in the next chapter.

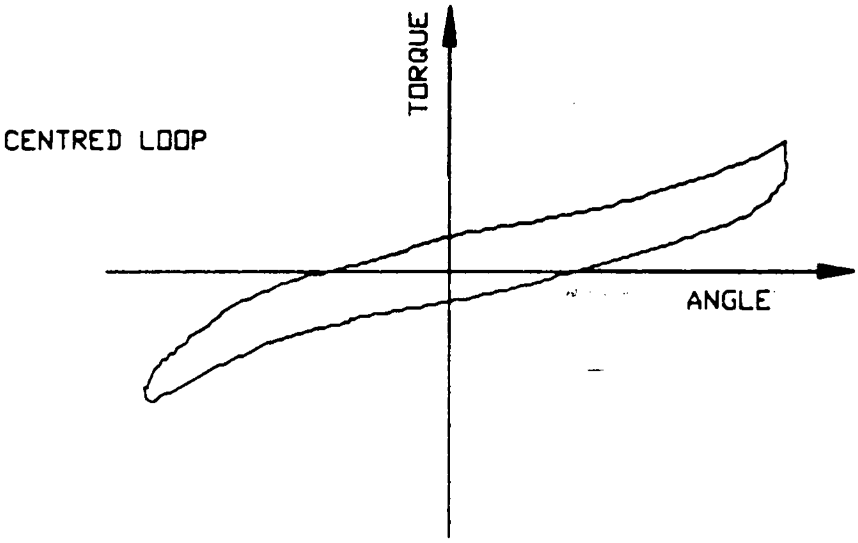
4.11.1 Arthrograph control software

It can be seen from the flow diagram in fig 4.10 that the arthrograph control software had to fulfill two main functions. The first function was to perform an iterative procedure until the hysteresis loop was thought to be acceptable. The loop from the first measurement cycle was displayed on the microcomputer screen and was judged to be acceptable for further processing if the trace was smooth and well centred. Irregularities in the loop such as sudden peaks or regions of excessive undulation were taken to be an indication of muscular activity and hence they were rejected. Once the iteration was complete the second function of the program was to calculate all the relevant parameters and record them on disc and paper. Each of these functions will now be described in more detail.

Fig. 4.9 Sample hysteresis loops during centring

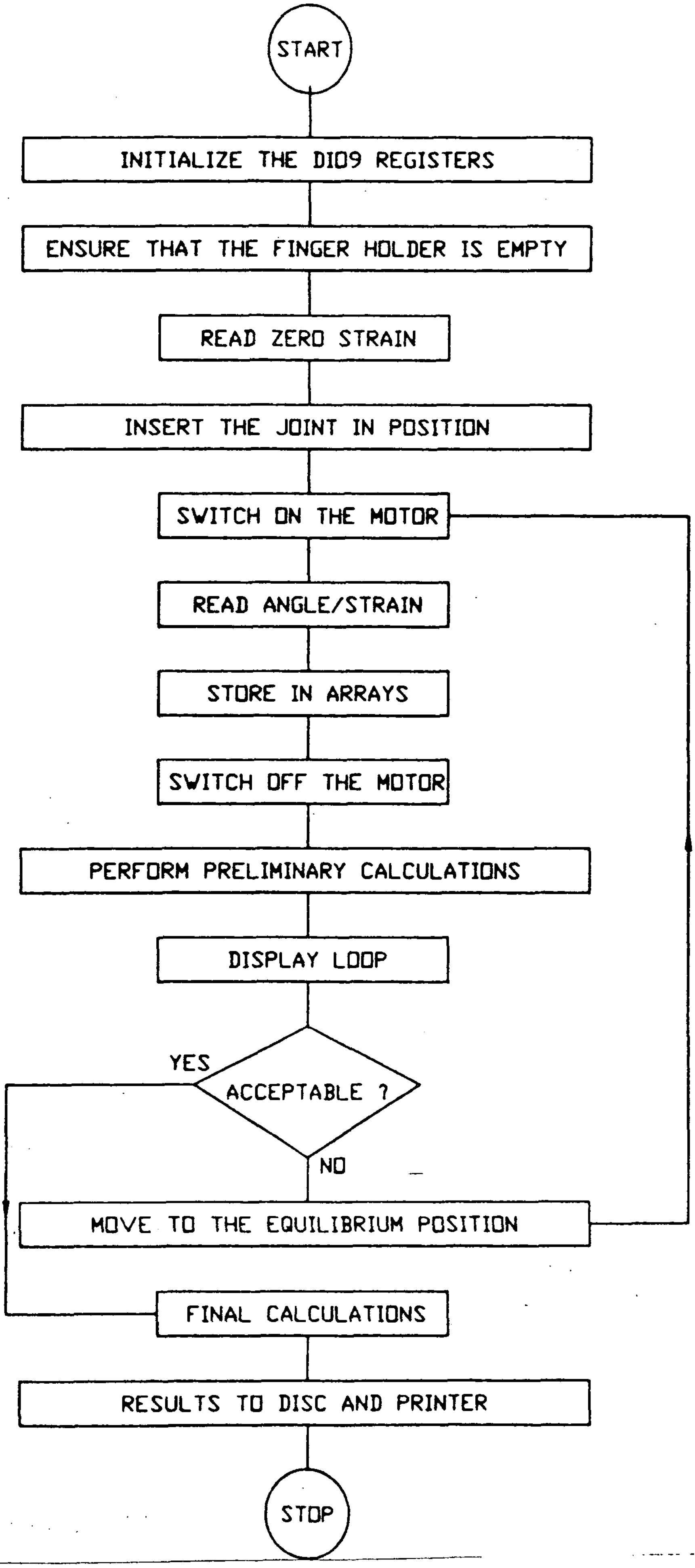


1st CENTRE OF OSCILLATION



2nd CENTRE OF OSCILLATION

Fig. 4.10 Flow diagram for arthrograph control software



4.11.2 Sampling the signals

A read of either of the transducer signals was achieved by simply reading the appropriate memory location in the microcomputer. Memory updates were only allowed to occur when the loaction was not being read and hence it was impossible to read a value that was midway through conversion.

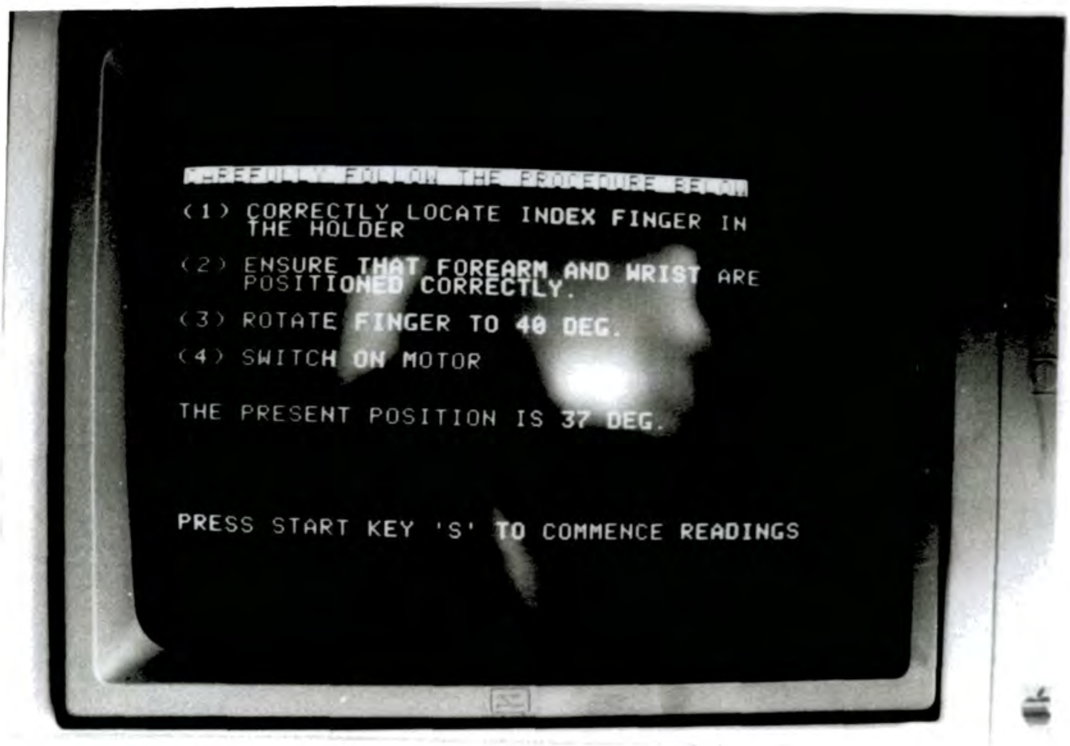
For simplicity of operation a menu screen of instructions was generated for each stage of the test procedure. Advancing from one menu screen to the next was accomplished in all cases by a single key press. Inadvertent operations were largely eliminated by 'freezing' the keyboard apart from the relevant function keys.

Before the first measurement cycle was commenced a torque reading was taken from the unloaded transducer. This reading was stored and used as a reference value for all subsequent calculations.

The first search cycle was initiated by depression of the start key 's', when the finger had been placed in the transducer and was moving into flexion. Readings of torque and angle were taken alternately in the manner that has already been described Although this meant that each group of two torque/angle readings was not a true pair the time difference between them was so small (approx. 50 microsecs) that it could be ignored. A short delay routine was inserted between each pair so that the sampling rate was not so high that the data could not be processed with ease. As the standard test cycle was 0.1 Hz this meant that samples had to be taken for at least ten seconds. In order that no data would be lost the sampling time was set just over the ten second period and subsequently the data set was truncated to remove the excess. The results were stored in a pair of matched arrays.

A routine was then called which calculated the equilibrium position. The result of this calculation was displayed on the screen together with information of how to move the drive arm from its present position to such a place that the next measurement cycle would be centred on the equilibrium position. A continuous display of angular position was generated at this point to aid the procedure. Plate V shows the actual menu screens that were displayed during the test.

Plate V The Menu Screens



CAREFULLY FOLLOW THE PROCEDURE BELOW

(1) CORRECTLY LOCATE INDEX FINGER IN THE HOLDER

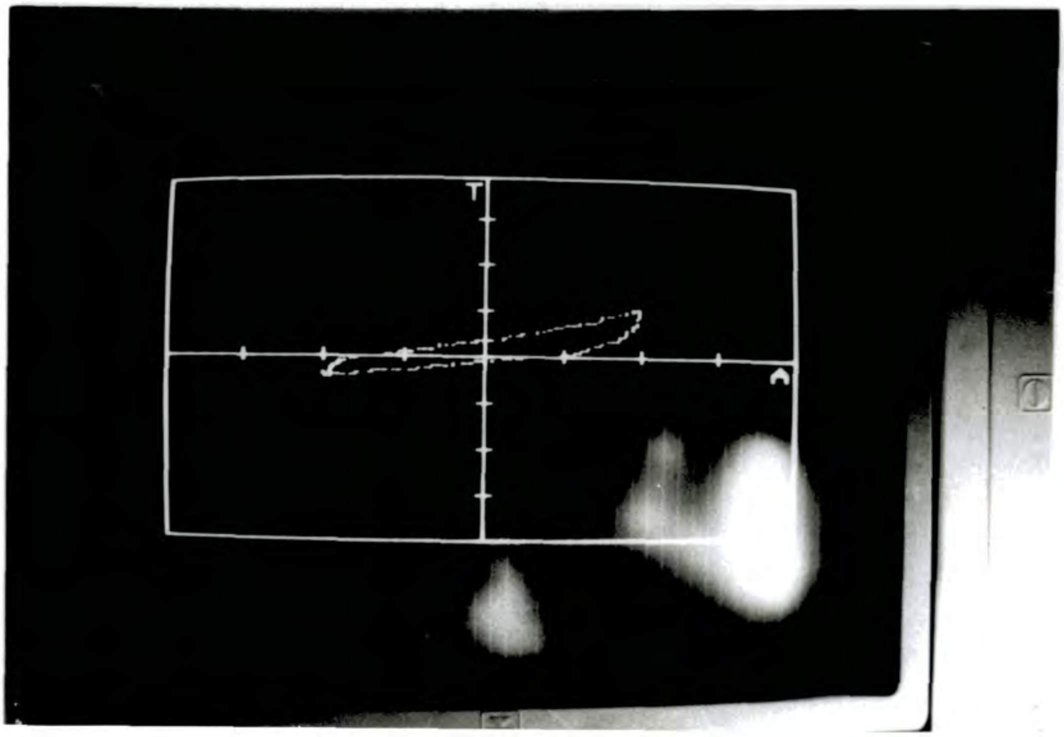
(2) ENSURE THAT FOREARM AND WRIST ARE POSITIONED CORRECTLY.

(3) ROTATE FINGER TO 40 DEG.

(4) SWITCH ON MOTOR

THE PRESENT POSITION IS 37 DEG.

PRESS START KEY 'S' TO COMMENCE READINGS



4.11.3 Data processing and storage

The hysteresis loop was analysed to determine six characteristic variables. These were :- cycle centre position, peak to peak torque range, flexion, extension and mid-position slopes and energy dissipation.

The torque range was calculated by a simple data sorting routine and subsequent subtraction of the maximum and minimum torque values.

Before the slopes could be calculated the loop had to be divided into three regions. The data points that lay within 10 degrees of the centre position were grouped together as were those which fell in the last ten degrees at either end of the displacement. Linear regression was then used to determine the gradient of the line of best fit through each of the three groups.

Energy dissipation was represented by the area of the loop and this was calculated by using the trapezium rule.

A printout of the results was automatically generated on a small, silent thermal printer. Fig. 4.11 shows the format of a typical set of results. The operator was then given the choice of whether or not to save the results on the appropriate file within the database.

4.11.4 Database details

A database program was written so that all subject details could be recorded as well as the results from the tests. The database acted as a shell within which the control program could be accessed. In this way it was ensured that the test results were always recorded on the correct subject record. Following consultation with clinical colleagues it was decided that the most useful items of information would be :- Name, date of birth, hospital code no. , sex, dominant hand and diagnosis. In addition to this general data other details were recorded before the start of each test such as:- date of test, time of test, procedure etc. Fig. 4.12 shows the basic sequence of operation of the database program.

Fig. 4.11 Typical results format

```
    RESULTS

NUMBER OF POINTS TAKEN = 301 MEAN EQ. POSITION = -5.0 DEG.

CENTRE OF CYCLE = -1.0 DEG.

TORQUE RANGE (PEAK TO PEAK) = .0924 NM.

ENERGY DISSIPATION = .01631764 JOULES

 SLOPES-UNITS NM./DEG.

FLEXION = 3.361E-03

EXTENSION = 2.175E-03

MID. POSITION = 1.259E-03

HYSTERESIS LOOP

HORIZONTAL SCALE:- 1 DIVISION= 10 DEG.
VERTICAL SCALE  :-1 DIVISION=0.05 NM.
```

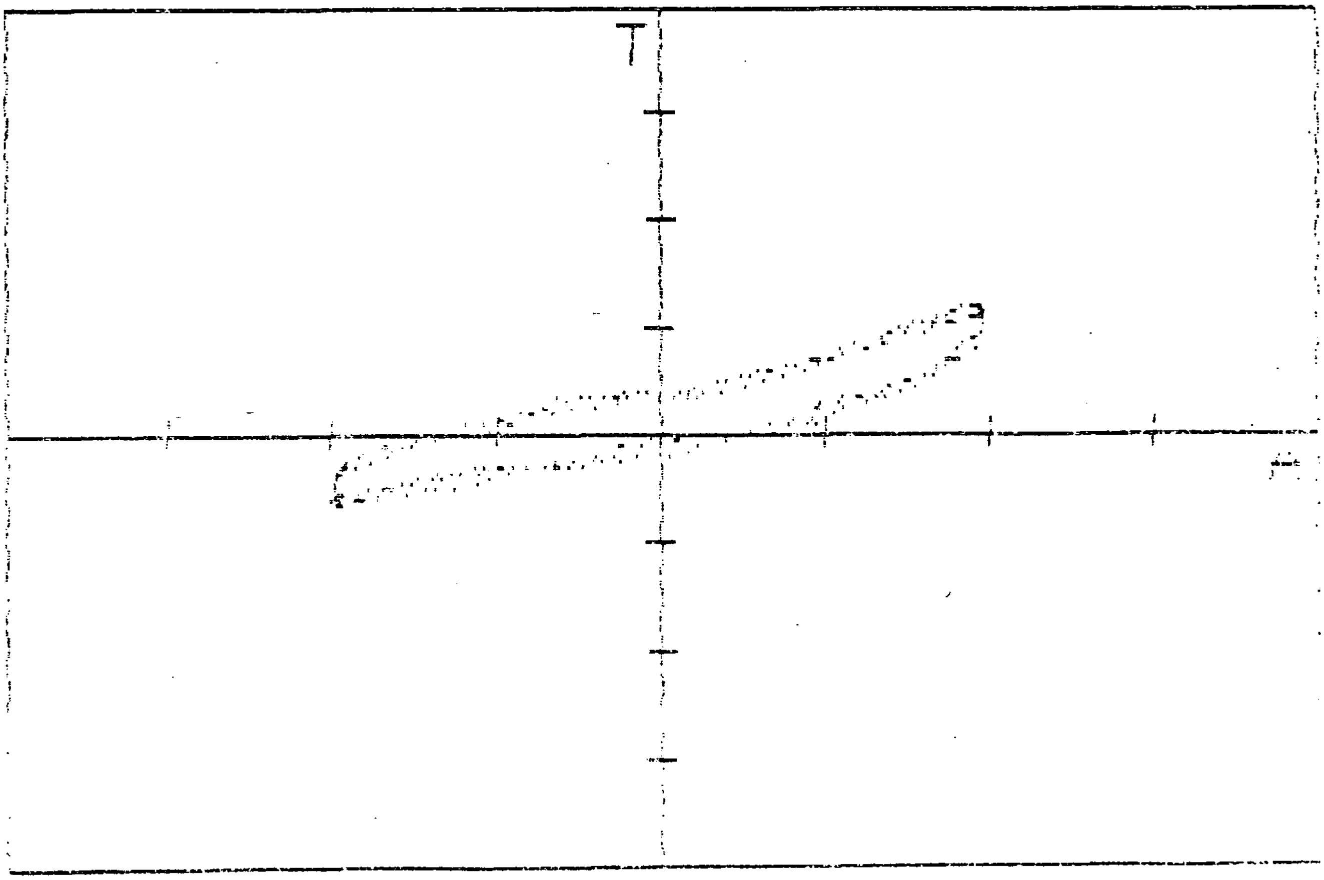
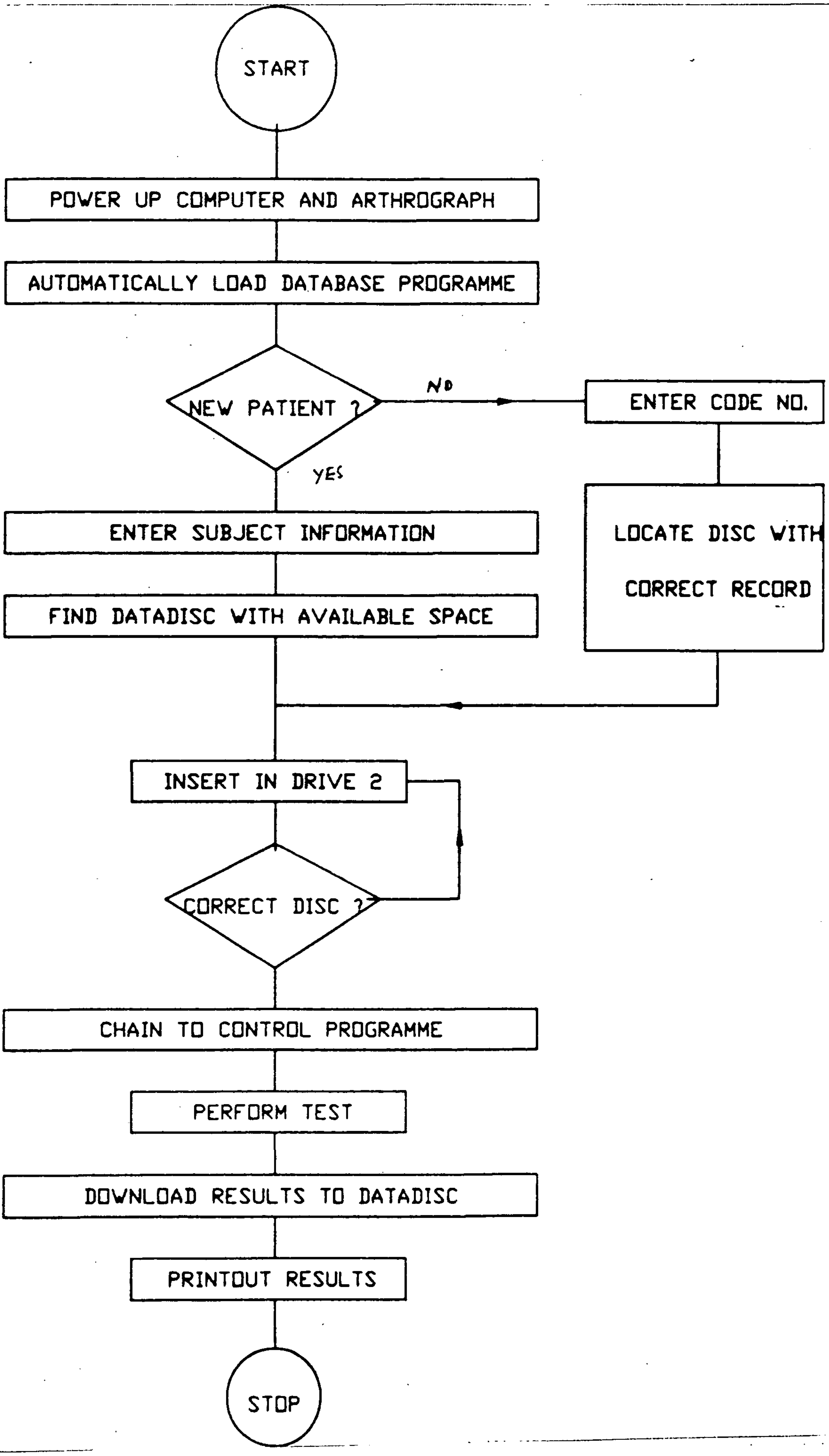


Fig. 4.12 Sequence of operation involving the database



SECTION 2

4.12 Overall design requirements of the gripstrength machine.

The aim was to produce a unit to measure isometric gripstrength which would satisfy the following criteria:- It should measure the gripstrength and the level of contribution of each digit to the total grip force. It should produce a permanent record of all the measured parameters and derived results in a clear, easily understandable form. It should be portable and self contained so that the unit would be easy for clinicians to carry around a ward or take 'on call'. In addition it should be rugged, simple to use and totally safe in operation.

These criteria suggested that the final design must incorporate a transducer to generate electrical signals which are proportional to the forces being measured. A unit for manipulating and processing these electrical signals as well as a device to present the output would also be required.

Before design could proceed a decision had to be made regarding the adoption of a digital or analogue system. The main advantage of an analogue system is that the design, manufacturing and fault finding procedures of a prototype system can generally be much shorter than in a similar digital system. Numerous fully tested analogue circuit designs, to accomplish a variety of tasks, are readily available. However, when final system configuration is uncertain and when reasonably complex data manipulations are involved, a digital approach must be considered.

The ability to store,process and manipulate data gives a digital system great flexibility. System versatility is limited only by the ingenuity of the control program. For example once the prototype system has been designed, input and output devices could be redesigned and replaced with relative ease if desired. In view of this and because of the fairly large quantities of data to be obtained and the subsequent processing of this data, a digital solution was favoured in spite of its greater system complexity.

4.13 Final proposal

It was decided to base the design on the grip transducer developed and tested by A.R. Jones(Jones et al 1985) in the course of his work on hand assessment. Data conditioning and manipulation would be handled by a dedicated microprocessor and the results presented on a miniature printer. A schematic diagram of the proposed design is shown in fig. 4.13.

Operation of the device would be such that the user could initiate the system by pressing a 'start' button once the test subject was ready to grip the transducer. When the device sensed a value of one Newton or greater from any of the subjects fingers then collection of readings of force from each of the fingers would commence. The proposed sequence of operation is shown in fig. 4.14.

Description of the system elements.

4.14 Grip Transducer.

The transducer consisted of an aluminium housing, smoothly shaped to fit into the palm of the hand. The fingers fitted naturally around the transducer each resting on the a contoured pad which was free to align itself for comfort. In this way subjects, even those with a degree of deformity, could adjust their hand until a position could be found which enabled them to exert their maximum grip. Forces exerted by each of the four fingers were transmitted, via the pads and a push rod assembly, to four mild steel cantilevers rigidly clamped within the housing (fig. 4.15).

Strain gauges bonded to each cantilever measured the strain produced by the applied force. The gauges were connected in "full bridge" configuration to achieve maximum sensitivity and temperature compensation.

It can be seen that the transducer produces four separate electrical signals , each of which is an analogue of the force exerted by the particular finger during a 'power grip'. To avoid interference between the four signals and to reduce the effects of external noise the wires leading from each strain gauge bridge were fully screened. The cable leading from the transducer was securely clamped within the housing to provide strain relief for the electrical connections.

4.15 Electronic configuration

Before the system could be designed in detail it had to be decided how to approach the problem of preprocessing the analogue signals from the grip transducer. Three possible configurations were considered, the position of the multiplexing stage being the main factor.

Fig. 4.13 Schematic diagram of the proposed design

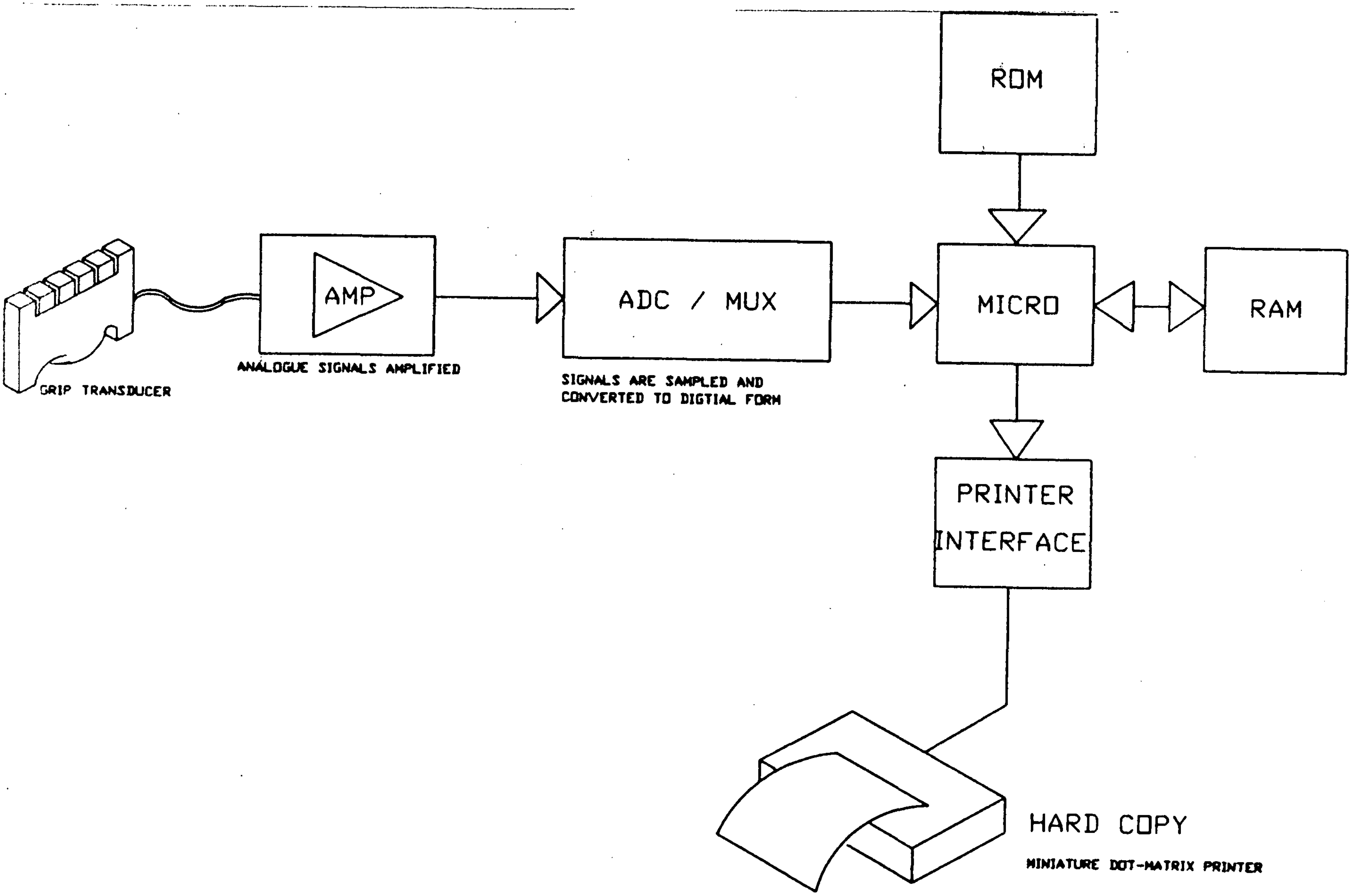


Fig. 4.14 The proposed sequence of operation

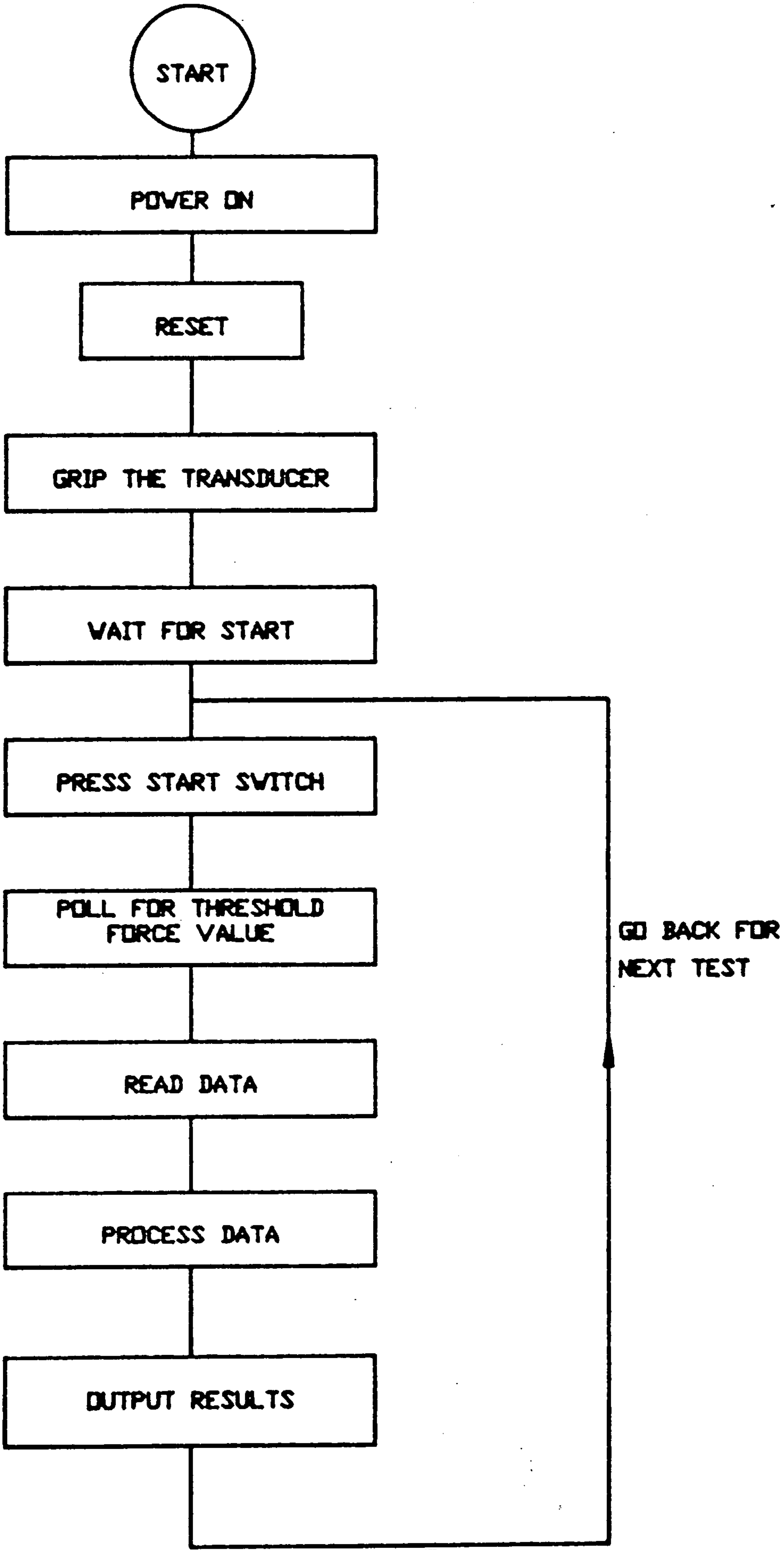
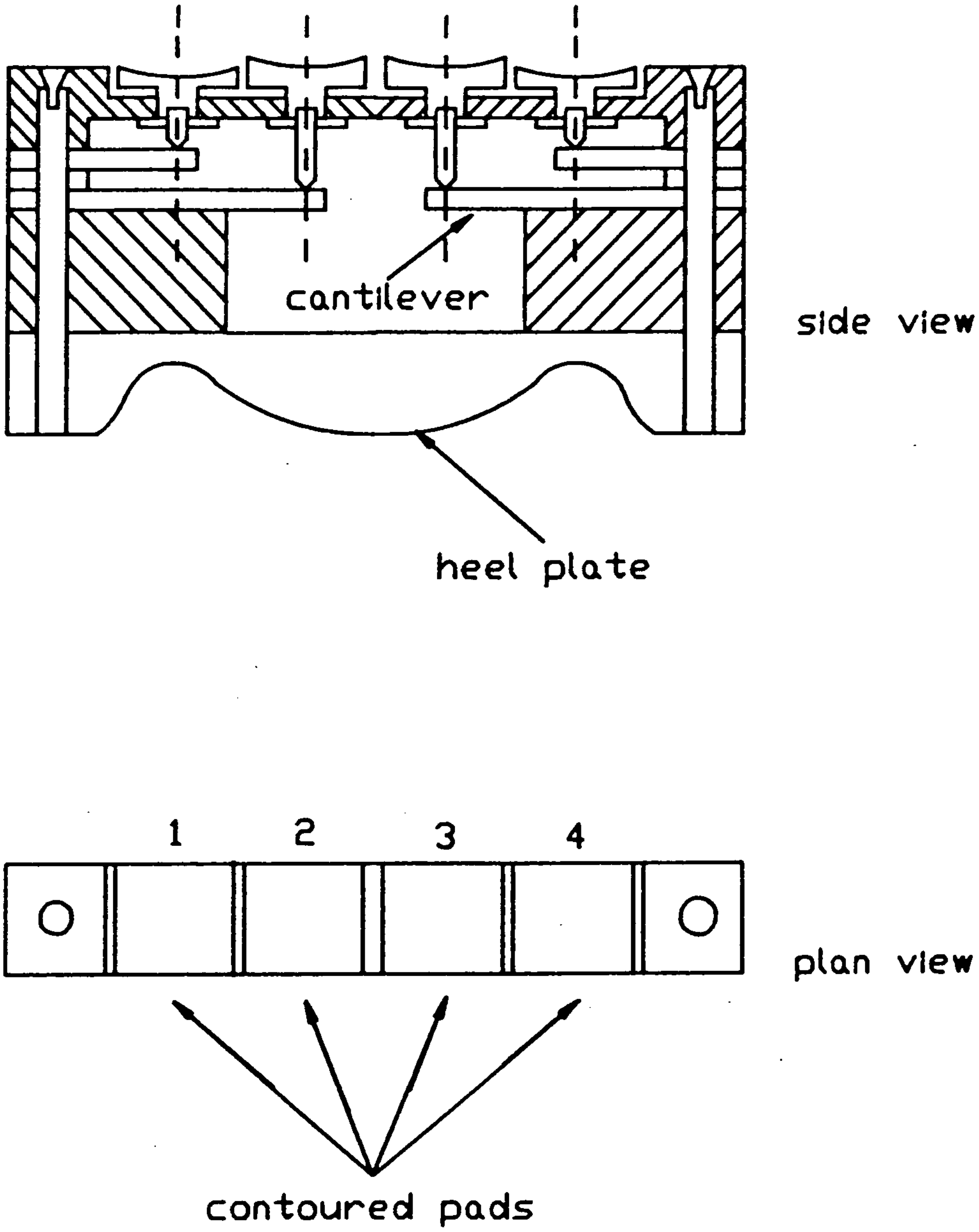


Fig. 4.15 The grip transducer



If the multiplexer was placed immediately after the strain gauges then only one signal, at any one time, would have to be amplified and converted to digital form. This configuration would have meant that only one amplifier and converter would be necessary.

Although this configuration was possible it may have proved complicated to implement. The processor would not only have had to control the data sampling frequency but also send out timing pulses to synchronize the multiplexer and converter and wait for the appropriate acknowledgement signals when these devices had finished their respective tasks. From a control point of view it was decided that this approach was unnecessarily complex.

Carrying out the multiplexing after the amplification stage would have had the disadvantage of requiring four amplification circuits and the timing problems described in the previous configuration would still be present.

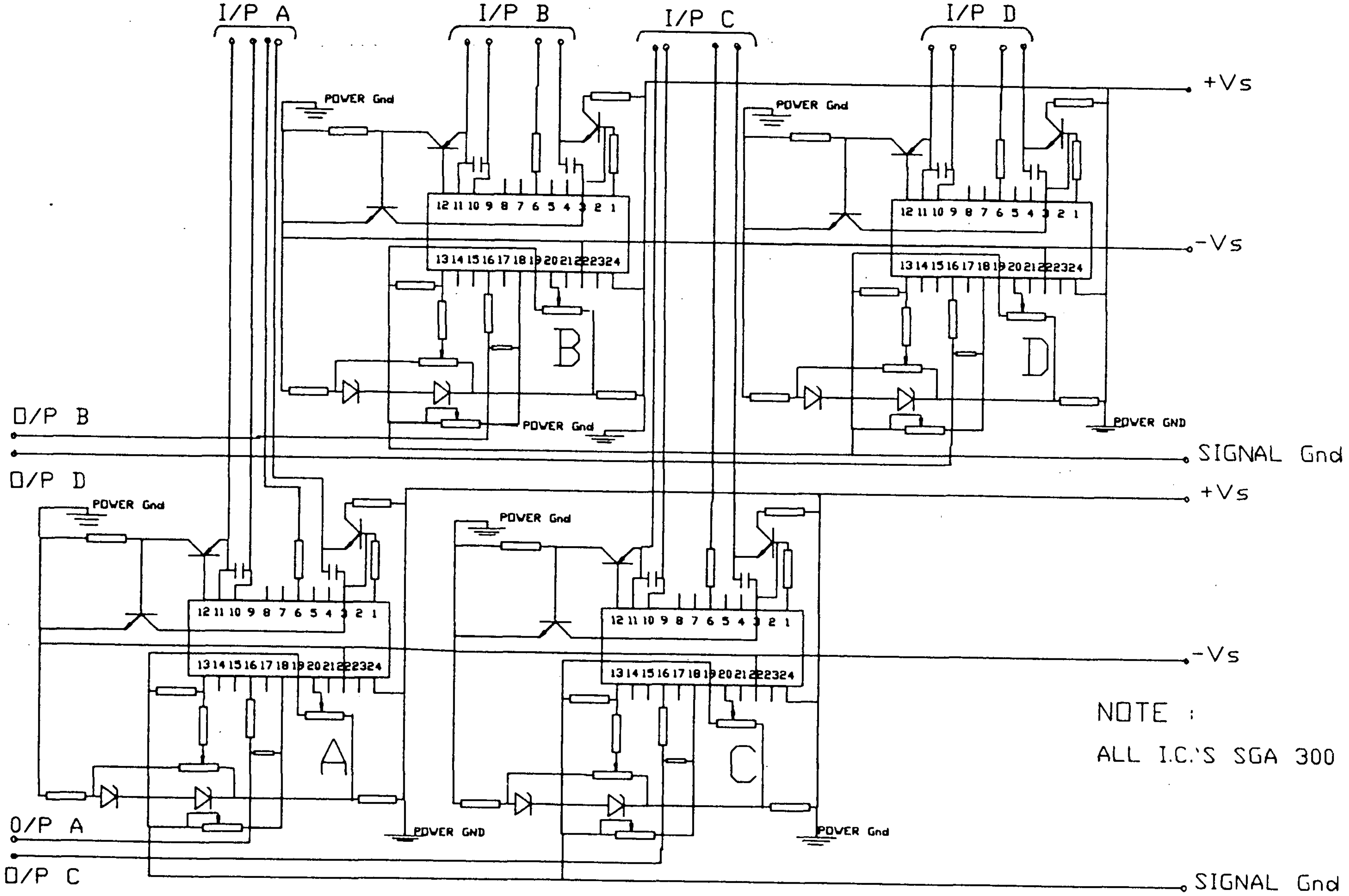
Multiplexing after the conversion stage would have required four amplifiers and four converters, although timing problems would have been considerably reduced.

The optimum solution was found by utilizing the 7581 combined multiplexer and analogue to digital converter. Effectively this meant that the second suggested configuration was adopted. However, all timing problems were dealt with by the on chip logic of the 7581 which will be described in more detail in section 4.17.

4.16 Strain gauge amplification.

To ensure compatibility of signal level with the rest of the system an amplification stage was necessary. A large number of proprietory strain gauge amplification and conditioning units were available but because of their size they would have added considerable bulk to the device and hence detracted from its portability.

A circuit design based on the SGA 300 series IC seemed the obvious choice as it had already been used successfully, for a similar task, in the arthrograph. Four amplification circuits (fig. 4.16), one for each signal, were manufactured on a single printed circuit board. The use of four amplifiers may seem rather inelegant and wasteful, however the necessity for this has already been discussed in the previous section. Another important advantage of four distinct amplification stages is an independence in the setting of gain, range and zero offset for each signal during calibration of the transducer.



NOTE :
ALL I.C.'S SGA 300 SERIES

Fig.4·16 Strain gauge amplification : circuit diagram for grip box

4.17 Analogue to digital conversion (ADC) and multiplexing (MUX)

The analogue signals needed to be sampled at a frequency which was fast enough to ensure that no significant data was lost but not so fast that the converter would not have time to finish conversion of the previous signal. Once conversion was finished the microprocessor would read the value and store it in memory. The time taken for this read/store process was also important as some values could be missed altogether if this was too slow or rerecorded if too fast.

The use of the 7581 combined MUX and ADC eliminated most of these synchronization problems. This IC was capable of accepting eight analogue inputs. Each input was converted into an eight bit word using the successive approximation technique. Results from the conversions were stored in the internal 8x8 dual port RAM. Memory updates only occured when the microprocessor was not addressing the converter memory. Each of the transducer signals was therefore "seen" by the microprocessor by addressing a particular memory location in which the data was continually updated. A complete scan through all eight channels took 640 microseconds and this fixed the maximum possible sampling rate at 1562 samples per second. It was not envisaged that a sampling rate anywhere near this maximum value would be required.

A high sampling rate in isolation is no guarantee of accurate signal reproduction. Accuracy also depends on the resolution of the ADC. The 7581 had an eight bit converter and hence the ability to reconstuct the analogue signal was limited to 1 part in 256 of the full range of the converter. The full range was 10 V and hence the best resolution possible was 0.039 V.

4.18 The microprocessor and support IC's

In this application exceptional speed or large address capability was not important so a 6800 series microprocessor, manufactured by Motorola, was used. The 6800 series had advantages in that it was well supported by a large variety of compatible IC's and prototype development aids.

The actual version used was a 6802 which was very similar to the 6800 but had the added features of on board clock logic and 127 bytes of scratchpad RAM. A 2732 (4k) EPROM and a 2128 (1k) RAM were used to store the control program and data respectively. It was decided to use a PIA (6821) to output the serial data to the printer interface rather than an ACIA. The original reason for this decision was to give the system greater flexibility if other peripheral devices, such as LCD's or signal lamps, were to be added at a later date. In retrospect this choice should not be applauded as control of parity, transmission rate and number of stop bits had to be handled by the system software. A large burden was therefore placed on the software and also troubleshooting of system faults was made much more difficult.

A full circuit diagram of the microprocessor board is shown in fig. 4.17. The peripheral devices were correctly assigned in accordance with the system memory map (fig. 4.18) by the use of a 74514 decoder and several logic gates. By placing the ROM in the highest portion of the memory map reset and interrupt vectors could be included. RAM was placed in the lowest memory portion so that the faster direct addressing mode could be used by the processor.

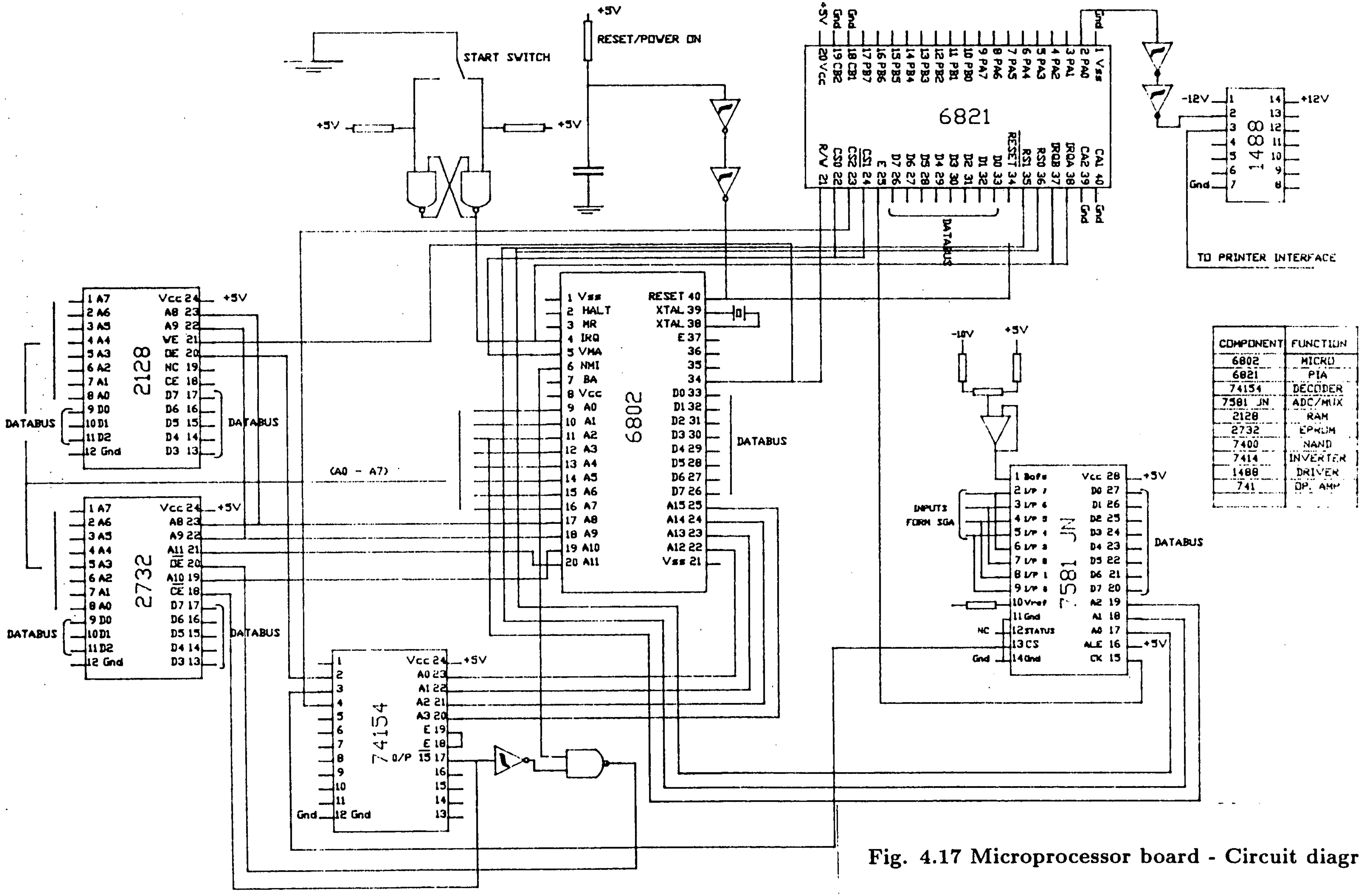
For simplicity of operation it was arranged for the system to reset when the power was switched on. When reset occurred the starting address of the monitor program was forced into the programme counter. The processor was then instructed to wait for an interrupt request to be supplied by depression of the start button. When this had occurred the start address of the main programme was loaded into the programme counter and the test could be commenced.

4.19 The printer

Low power cosumption and small size were the major constraints in the choice of a suitable printer. The printer chosen was a PU1100 twenty column- miniature dot-matrix printer manufactured by Datac. It could receive serial data at either 110 or 1200 baud in standard RS232/ASCII code or 20 mA current loop input. The interface board incorporated a twenty character line buffer and required a delay of at least 750 ms between each line of twenty characters.

4.20 Power supply

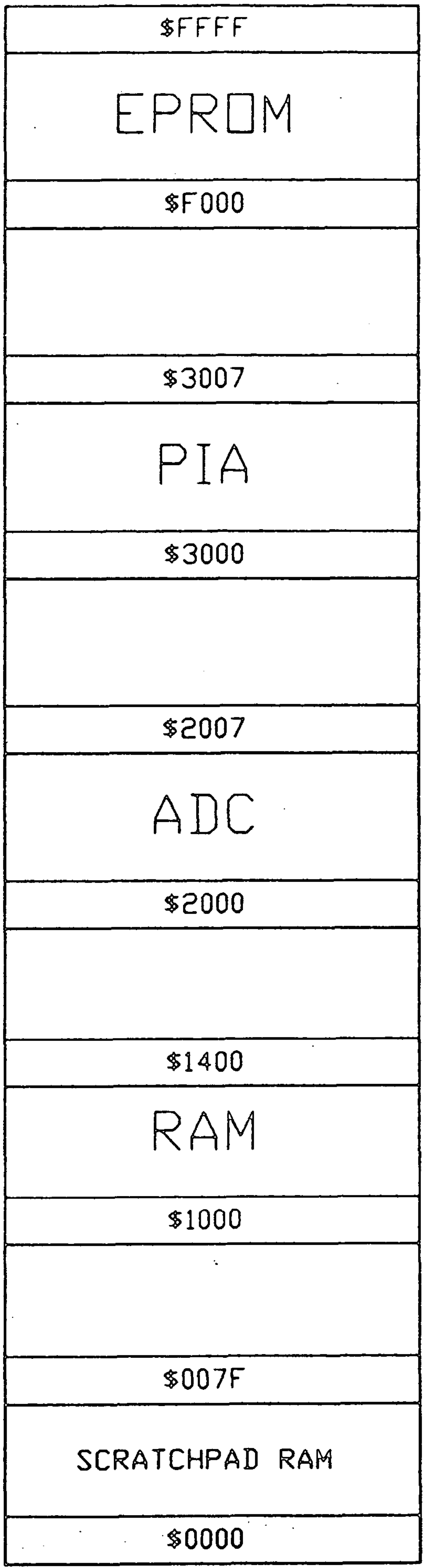
As far as device portability was concerned it would have been advantageous to power the unit from a DC battery supply. However, in view of the peak currents demanded by the printer and the strain gauge amplifier circuit , use of the mains supply seemed a better solution. It was felt that the inconvenience of finding a power point was preferable to a very short battery life.



COMPONENT	FUNCTION
6802	MICRO
6821	PIA
74154	DECODER
7581 JN	ADC/MUX
2128	RAM
2732	EPROM
7400	NAND
7414	INVERTER
1488	DRIVER
741	OP. AMP

Fig. 4.17 Microprocessor board - Circuit diagram

Fig. 4.18 System Memory Map



4.21 Software development

It is not the intention to discuss in this thesis the software details of programming in 6800 assembler. Only a brief outline will be given of the method of development of the main control programme so that the features of the device can be understood more fully.

After conversation with clinical colleagues it was decided that the most useful parameters to be calculated would be the maximum total grip and the maximum force contributions from each finger in a standard power grasp of six seconds duration. In addition to these numerical results a graph of force v time was to be plotted which would yield information as regards the establishment of maximum grip force and its duration as well as allowing possible dysfunction of any of the fingers to be observed.

During the initial design stages it was not so important that the optimum scale was chosen because this could easily be changed by editing the control programme. However, it seemed desirable that two possible scales should be available in the final version so that very weak grips and also reasonably strong ones could be accommodated without an unacceptable loss of resolution in the graphical output.

The printer interface and printer were connected to a standard 6800 development system which was itself interfaced with a Cifer microcomputer. By entering dummy data from the keyboard to simulate the output form the ADC/MUX it was possible to develop and debug the assembler program without having the problem of fault finding the system hardware at the same time.

The algorithms for reading the data, outputting the graph, calculating the parameters and printing are given in Appendix two in the full assembler listing.

Following the start up procedure the program polled each of the transducer inputs until a value equivalent to a force of 1N was detected at which time collection of the data commenced.The sampling frequency was selected to be one reading from each of the inputs every 0.12 seconds. Therefore at the end of the sampling period fifty samples of data had been collected from each input and the data was then processed.

After all of the information had been printed the program looped back to the position where it would wait for an interrupt request from the start button.

4.22 Final assembly and miscellaneous design features

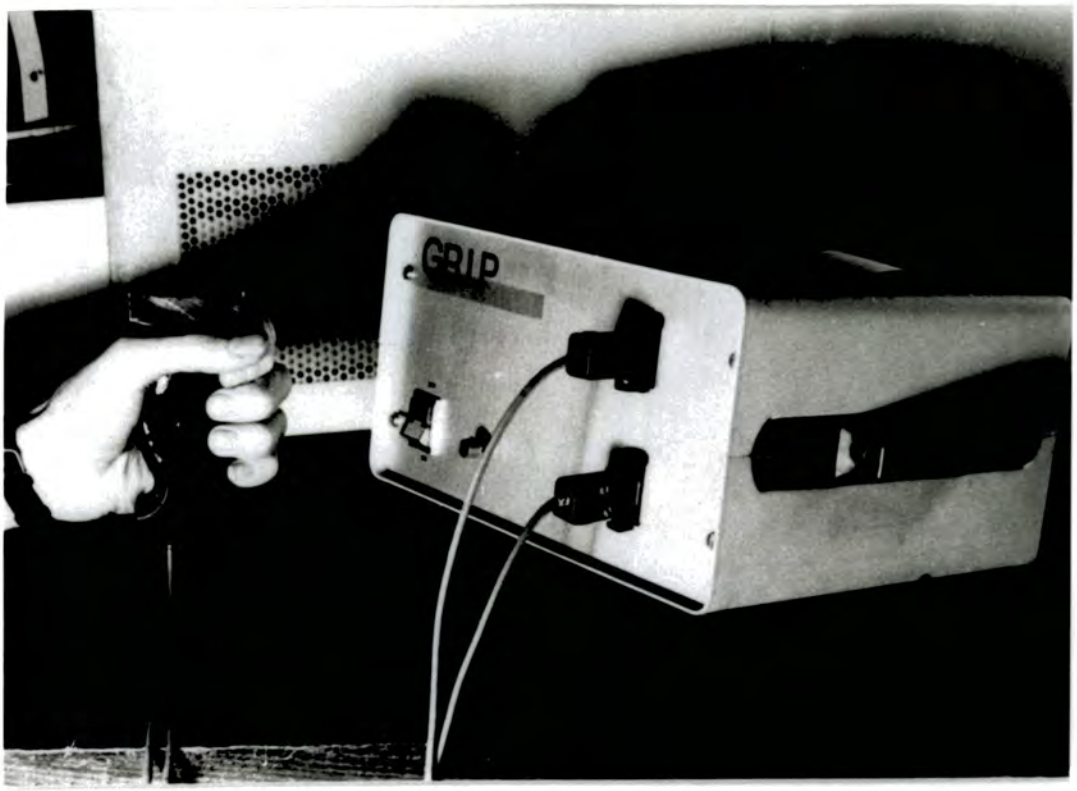
Each element of the system was checked individually, as far as was possible, and then all of the elements were connected together. Waveforms, logic levels and baud rates etc. were observed and modified in the normal manner until the system was functioning in accordance with its design specification.

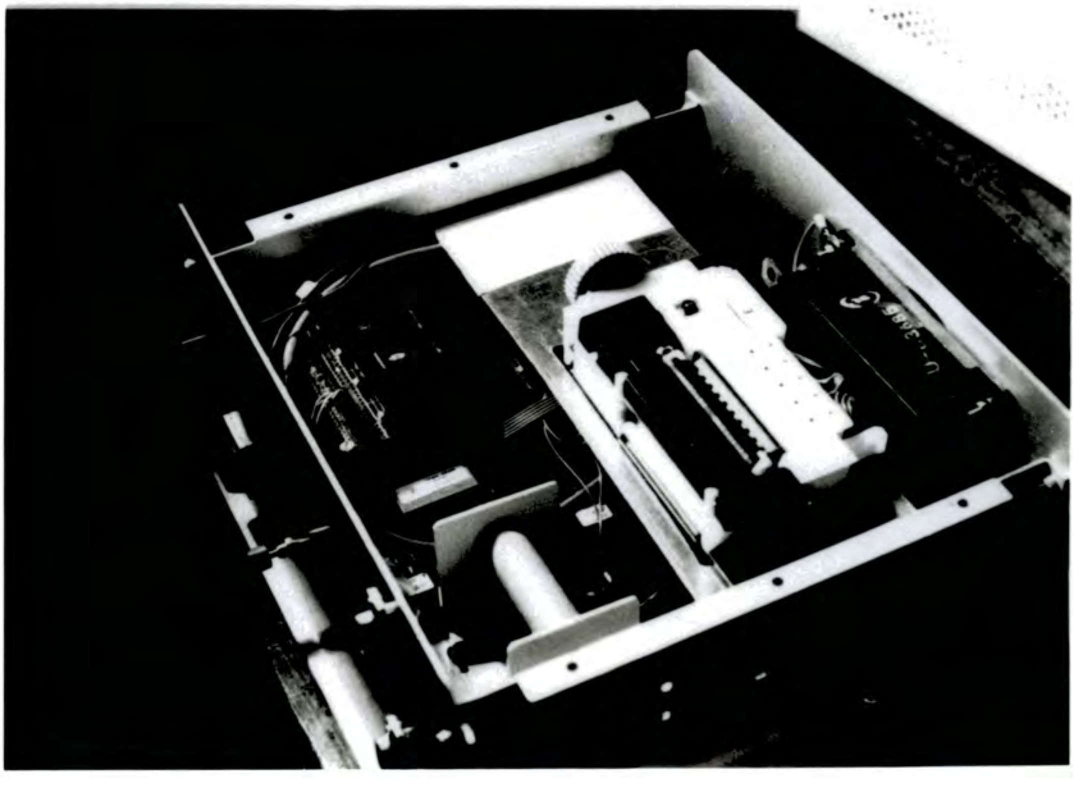
The completed system was then assembled in a suitably sized instrumentation box together with the power supply. Plates VI and VII show views of the completed device. It was ensured that access to the potentiometers for adjusting the gain and range of the amplifiers was unimpeded and that all circuit boards, printer and power supply were well secured. As can be seen in plate VI, a small fan was fitted in the box to provide cooling for the circuit boards, power supply and printer.

All circuit boards were protected individually from unusual supply surges or faults by overvoltage breakdown Zener diodes and the whole system was protected by a 1 amp fuse in the mains supply circuit.

The transducer was connected to the main unit by flexible, shrouded cables and removable terminal connectors.

Plate VI and VII Views of the competed device





4.23 Calibration

With the microprocessor board temporarily disconnected from the rest of the system the ADC/MUX was calibrated for unipolar operation with a full range of 10 V. By inputting voltages of a known value the accuracy and linearity of response of the ADC was checked, ie 5 V input gave a reading of 128 bits , 10 V input flickered between 254 and 255 bits and so forth.

The microprocessor board was reconnected and an oscilloscope was used to monitor the voltage outputs from the strain gauge amplifiers. The grip transducer was mounted horizontally on a level surface but in such a manner that weights could be suspended beneath each finger pad by a light, strong nylon cord.

From the earlier work of Jones it appeared highly improbable that the contribution of any one finger would exceed 250 N (for normals this was generally true and for patients certainly true) so for convenience an ideal calibration curve of 1N to 1 bit was decided upon. This meant that the maximum measurable force from each finger was 255N and that the resolution of the device was fixed at one Newton. Gain, range and zero offset were altered progressively until the ideal curve was achieved. After this procedure the transducer was unloaded and the readings once again were monitored to check for unacceptable hysteresis. The transducer was then reloaded and the whole system was left switched on for a time to see if there was any appreciable drift from the ideal calibration curve.

It was seen that hysteresis was negligible and that the response of the transducer in the given range was predictably linear.

CHAPTER 5

PILOT STUDIES AND GENERAL METHOD

5.1 Introduction

Pilot studies were carried out to determine the range of values and the repeatability of each device. In this way the calibration ranges and the test method were evaluated to ensure that the experimental error in the results was within acceptable limits before larger scale studies were undertaken.

5.2 Standard setting up procedure for the arthrograph

Experience during previous arthrographic work had shown that the test environment should be quiet and free from other distractions to aid subject relaxation during the test. Suitable environments were selected where possible and when the nature of the experimentation allowed it (it will be explained later that during the circadian variation experiments this was not possible). The arthrograph was placed on a low level table with computer and printer nearby. The screen of the computer was so positioned that the test subject would not be able to view the screen during the test as it was felt that the screen would be a distraction which would hinder subject relaxation.

The computer and arthrograph were switched on and the control programme was automatically loaded and set running. If the subject had not been tested previously then the general information was entered at this juncture and a new data file was generated. For those subjects that had been tested previously then the correct data disc was located and inserted in the appropriate drive.

The subject was seated in a comfortable upright posture close to the side of the arthrograph. The subject's right arm was rested on the arm rest with the fingers positioned around the cylindrical grip. The thumb was placed in the support sling. It was ensured that the wrist was in the neutral position and that the index finger would be able to move freely in the flexion/extension plane without impedance from the grip, thumb or the adjacent finger. A range of 'Plastizote 'packings were used to adjust the height of the joint to position the torque transducer.

The next step was to align the centre of rotation of the MCP joint with the centre of rotation of the arthrograph, which was marked by a hole through the central shaft of the torque transducer. By looking through this hole it was possible to position the centre of rotation of the joint using a template. The geometry of the template was such that a dot on its top surface gave the average position of the centre of rotation based on the work of Unsworth and Alexander (1979). The three clamps securing the arm rest were released and the armrest was moved until the centres of rotation coincided and then the clamps were secured again. Once the joint had been accurately centred the proximal phalanx was retained firmly but comfortably in the torque transducer by elastic straps.

If the motor was then switched on until the joint was at the maximum flexion, then by subtracting 20 degrees (the amplitude of rotation) from the angle given on the scrolling display, the centre of oscillation could be determined. By rotating the crank handle and simultaneously monitoring the angle display, the centre of oscillation could be positioned anywhere in the normal range of motion.

Following the work of Unsworth et al (1981) it was decided to attempt to centre the oscillation on the equilibrium position of the joint. It is clear from the arguments presented in chapter Three(sec 3.7) that two positions of zero torque exist, one when moving into flexion and the other when moving into extension. Furthermore these two positions change according to the previous displacement history. For example, if the joint is oscillated about a position of 40 degrees flexion and the positions of zero torque are found, then these positions will not be quite the same for an oscillation centred around 30 degrees flexion and so forth. In order that the standard procedure would be reasonably consistent for each joint tested, then a first oscillation would have to be performed about a predetermined angular position. It was thought that the results from this oscillation could then be used to predict the equilibrium position of the joint. However, as the indicated equilibrium position would shift from one test to another then it was necessary to investigate the nature of this shift. In this way, the positional error bounds, within which the variation of the parameters of the hysteresis loop would be acceptable, could be determined.

5.3 Variation of equilibrium position

The joint was oscillated at series of positions, in the normal range of motion, at an amplitude of 20 degrees and a frequency of 0.1 Hz. The test was repeated three times at 40 degrees, 25 degrees and 15 degrees to check for variation in any of the characteristic parameters. Previously, Unsworth et al (1981) have shown that the direction of approach to equilibrium position is important. If the joint is moved from extension to flexion then the two positions of zero torque will be different from those obtained when moving in the reverse direction. Thus in this series of experiments it was decided to adopt a standard procedure of always moving the centre of oscillation from flexion towards extension. The experimental results from two subjects are shown in tables 5.1 and 5.2 but before they are discussed the parameters derived from the hysteresis loops, briefly mentioned in section 4.11.3, will be described in more detail. Reference to figure 5.1 will perhaps, illustrate the definitions with greater clarity.

Torque range (TR) is defined as the peak to peak difference in resistive torque (extension to flexion). Thus this parameter includes both elastic and dissipative components of torque and is frequency and amplitude dependent. Units are Nm.

The mid-position slope parameter (Mid. sl) is defined as the elastic stiffness response in the central region of the oscillation. The slope was calculated by fitting a regression line through the data points at 10 degrees either side of the centre of oscillation. The units of the mid position slope are Nm per degree.

Flexion and extension slopes (Fl. sl. and Ex. sl.) are characteristic of the elastic stiffness at the limits of the particular displacement. They were calculated by fitting a regression line through the data points 10 degrees from the limits of displacement. Units are Nm per degree.

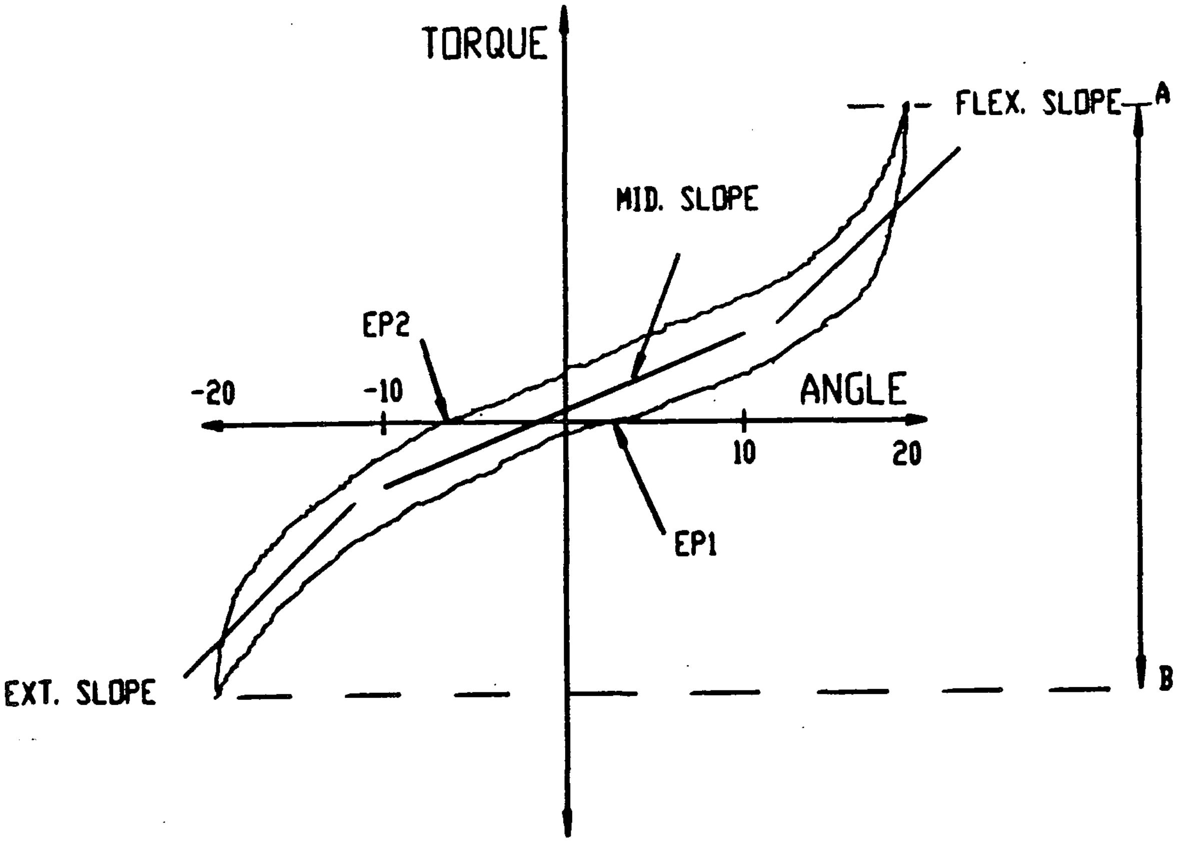
Energy dissipation (Energy dissip.) is defined as the energy lost during one period of oscillation and represented by the area of the hysteresis loop. The area was calculated by the trapezium method. The units of the energy dissipation are Joules and the parameter is frequency and amplitude dependent.

Mean equilibrium position:- Defined as the mean of the two zero torque positions when moving into flexion and when moving into extension. The units are degrees. For the standard test procedure followed here the mean equilibrium position was always approached from positions further in flexion.

5.4 Observations

Reference to tables 5.1 and 5.2 reveals, rather unsuprisingly, that as the centre of oscillation was moved further into extension then the flexion slopes decreased

Figure 5.1 Definition of parameters



DEFINITIONS

Torque : positive when resisting flexion

Angle : Shown positive in flexion with reference to the cycle centre.

Energy dissipation : The area of the hysteresis loop

Mean equilibrium position : The mean of EP1 and EP2

Torque range : The peak to peak difference in torque, A to B

Flexion slope : Best straight line through the last ten degrees flexion.

Extension slope : Best straight line through the last ten degrees exten:

Mid slope : Best straight line through the central 20 degrees.

Table 5.1 Repeatability at different cycle centres

Subject 1 : Centre of oscillation at 40 degrees flexion

Test No.	Mean EQ. (degrees)	Torque range (Nm)	Mid. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$	Fl. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Ex. sl. ($\frac{NM}{deg} \times 10^{-3}$)
1	27.2	0.145	2.86	17.4	8.42	1.58
2	26.8	0.134	2.43	14.2	7.36	1.48
3	25.8	0.141	2.58	15.8	7.89	1.52
Mean	26.6	0.139	2.62	15.8	7.89	1.52
S.D.	0.665	0.005	0.22	1.60	0.53	0.05
C. of Var	2.5%	4.0%	8.3%	10.0%	6.7%	3.3%

Subject 1 : Centre of oscillation at 25 degrees flexion

Test No.	Mean EQ. (degrees)	Torque range (Nm)	Mid. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Fl. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Ex. sl. ($\frac{Nm}{deg} \times 10^{-3}$)
1	18.1	0.099	1.68	12.9	4.99	1.67
2	17.2	0.088	1.59	12.4	3.83	1.43
3	17.7	0.089	1.56	11.2	4.42	1.25
Mean	17.6	0.092	1.61	12.2	4.41	1.45
S.D.	0.45	0.006	0.06	0.90	0.58	0.21
C. of Var	2.6%	6.5%	3.80%	7.30%	13.0%	14.0%

Subject 1 : Centre of oscillation at 15 degrees flexion

Test No.	Mean EQ. (degrees)	Torque range (Nm)	Mid. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Fl. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Ex. sl. ($\frac{Nm}{deg} \times 10^{-3}$)
1	17.7	0.079	1.32	10.5	2.79	2.46
2	18.8	0.079	1.31	10.3	3.33	1.70
3	18.2	0.078	1.32	10.4	3.10	2.51
Mean	18.2	0.078	1.31	10.4	3.07	2.22
S.D.	0.55	$5.7x10^{-5}$	$5.7x10^{-5}$	0.08	0.27	0.45
C. of Var	3.0%	0.07%	0.4%	0.8%	8.8%	20.0%

Table 5.2 Repeatability at different cycle centres

Subject 2 : Centre of oscillation at 40 degress flexion

Test No.	Mean EQ. (degrees)	Torque range (Nm)	Mid. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Fl. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Ex. sl. ($\frac{Nm}{deg} \times 10^{-3}$)
1	29.0	0.128	2.19	15.4	7.85	1.39
2	26.4	0.132	2.18	16.9	7.65	1.26
3	27.2	0.131	2.08	15.9	7.87	1.30
Mean	27.5	0.131	2.15	16.1	7.79	1.31
S.D.	1.33	0.002	0.06	0.79	0.12	0.07
C. of Var	4.8%	1.6%	2.8%	4.9%	1.5%	5.0%

Subject 2 : Centre of oscillation at 25 degrees flexion

Test No.	Mean EQ. (degrees)	Torque range (Nm)	Mid. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Fl. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Ex. sl. ($\frac{Nm}{deg} \times 10^{-3}$)
1	25.6	0.080	1.08	11.9	4.13	1.44
2	20.3	0.084	1.23	12.6	4.50	1.43
3	19.7	0.085	1.15	12.4	4.21	1.41
Mean	21.8	0.083	1.15	12.3	4.30	1.42
S.D.	3.24	0.003	0.08	0.36	0.18	0.02
C. of Var	14.9%	3.4%	6.5%	2.9%	4.1%	1.1%

Subject 2 : Centre of oscillation at 15 degress flexion

Test No.	Mean EQ. (degrees)	Torque range (Nm)	Mid. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Fl. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Ex. sl. ($\frac{Nm}{deg} \times 10^{-3}$)
1	19.9	0.072	0.87	11.9	2.78	2.21
2	18.3	0.072	0.97	10.6	2.97	1.59
3	18.1	0.076	1.00	10.1	3.28	1.70
Mean	18.7	0.073	0.95	10.9	3.01	1.83
S.D.	0.98	0.0024	0.068	0.97	0.25	0.33
C. of Var	5.2%	3.3%	7.2%	8.9%	8.3%	18.0%

and the extension slopes increased. There was also a general decrease in the torque range, mid. position slopes and energy dissipation parameters as the joint was oscillated at positions further into flexion. This emphasizes the dependence of these parameters on position of oscillation as well as frequency.

There was a stabilization of the mean equilibrium position from 25 to 15 degrees and the mean equilibrium position for the latter centre of oscillation can be seen to be further into flexion than the cycle centre itself, thus indicating that the position of equilibrium has been overshot. Comparison of the difference between the parameters as equilibrium is approached shows that there is an angular region within which the variation is quite small. The percentage variations of the parameters between the different cycle centre positions are shown below.

From the mean values of subjects one:

Between	Mean eq.	torque range	mid pos.	energy dissip
40 and 25 deg	28%	29%	34%	18%
25 and 15 deg	2%	11%	14%	11%

From the mean values of subject two:

Between	mean eq.	torque range	mid. pos.	energy dissip.
40 and 25 deg.	16%	32%	42%	19%
25 and 15 deg.	11%	9%	13%	8%

It therefore seemed reasonable to assume that a positional accuracy error bound during the centreing procedure of plus or minus five degrees coincidence, between the centre of the cycle and the mean equilibrium position, would not produce results which would differ greatly.

5.5 Standard test procedure

The centre of oscillation was positioned at 30 degrees flexion as this was felt to be a value that would be in close proximity to the natural equilibrium position of the joint. The joint was oscillated sinusoidally at 20 degrees amplitude and a frequency of 0.1 Hz. After this preliminary test was completed the mean equilibrium position was found and displayed on the screen together with the information as to how far and in what direction to move the joint to centre the oscillation on this position. The joint was moved via the crank handle until the new position was attained and then a second test was carried out. At the end of the second test, if the coincidence of the centre of oscillation and the mean equlibrium position were not within the error bounds then the joint was moved again in the appropriate direction and a third test was executed. This iterative procedure continued until the two positions were within the error bounds and was usually achieved in two loops and certainly after three. The data from the test was then processed to determine the parameters and the results were stored on the appropriate datafile and printed out.

Bird et al (1981) and Long et al (1964) have shown that the effects of any reflex or voluntary muscular activity that occur during this type of test are of such a magnitude compared with the level of torques being measured, that they can be easily detected as sharp irregularities in the shape of the hysteresis loop. If any such irregularities occurred at any time in the procedure then the test was repeated.

A number of workers have noted that numerous successive oscillations of the joint can lead to a general reduction in stiffness parameters. Scott described this to be a similar phenomenon to the 'working off of stiffness 'amongst arthritic patients. From a rheological viewpoint a reduction in viscosity caused by the duration of the shearing time is known as thixotropic and as tissue is a viscoelastic material it could be that this effect is occuring in measurements of joint stiffness that involve repeated oscillation of the joint.

As the iterative procedure involved in the standard test may have led to a change in the stiffness parameters because of this phenomenon, and to ascertain the variability of results for future work, repeatability experiments of the standard test were undertaken.

5.6 Repeatability experiments

The standard test was performed consecutively five times on five subjects. For three of the subjects the joint was removed from the arthrograph between tests and all the controls were reset. The other two subjects were tested with the joint in place in the apparatus for the whole duration of the tests. Results from these experiments are shown in tables 5.3, 5.4, 5.5, 5.6 and 5.7.

5.7 Observations

When the joint was removed between tests it was found that the coefficient of variation of the parameters torque range, mid. slope and energy dissipation were either at or considerably below the 12% value . This was considered to be a reasonable value of repeatability for experiments of a biological nature. However, the flexion and extension slopes exhibited a considerably higher variation. A

Table 5.3 Repeatability results: Subject 1

(joint removed between each test)

Test No.	Torque range (Nm)	Mid. slope ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Flex. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Exten. sl ($\frac{Nm}{deg} \times 10^{-3}$)
1	0.092	1.19	11.0	5.32	1.89
2	0.080	1.22	10.8	3.80	1.54
3	0.076	1.19	14.2	3.09	2.27
4	0.072	1.23	10.9	3.24	1.48
5	0.076	1.21	11.3	3.75	2.05
Mean	0.079	1.21	11.67	3.84	1.84
S.D.	0.008	0.02	1.43	0.88	0.33
C.of Var.	10.0 %	1.7%	12.2%	22.9%	17.9%

Table 5.4 Repeatability results: Subject 2

(joint removed between each test)

Test No.	Torque range (Nm)	Mid. slope ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Flex. sl ($\frac{NM}{deg} \times 10^{-3}$)	Exten. sl ($\frac{Nm}{deg} \times 10^{-3}$)
1	0.059	0.99	9.1	2.11	1.45
2	0.059	0.85	10.6	1.46	2.32
3	0.052	0.86	9.5	1.69	1.70
4	0.048	0.93	9.2	1.45	1.41
5	0.050	0.74	8.9	1.45	1.57
Mean	0.053	0.87	9.48	1.63	1.69
S.D.	5.25	0.09	0.07	0.29	0.37
C.of Var.	9.76%	10.90%	7.32%	17.54%	21.88%

Table 5.5 Repeatability results: Subject 3

(joint removed between each test)

Test No.	Torque range (Nm)	Mid. slope ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Flex. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Exten. sl ($\frac{Nm}{deg} \times 10^{-3}$)
1	0.080	1.16	10.8	3.35	2.11
2	0.073	1.00	10.9	3.09	2.11
3	0.070	1.05	9.9	2.75	2.44
4	0.081	1.09	9.8	2.63	2.57
5	0.077	1.17	10.0	2.89	2.09
Mean	0.076	1.09	10.32	2.94	2.26
S.D.	4.61	0.07	0.54	0.29	0.22
C.of Var.	6.04 %	6.61%	5.19%	9.69%	9.93%

Table 5.6 Repeatability results: Subject 4

(Consecutive tests: joint in place for duration)

Test No.	Torque range (Nm)	Mid. slope ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Flex. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Exten. sl ($\frac{Nm}{deg} \times 10^{-3}$)
1	0.128	2.07	15.2	5.52	2.96
2	0.118	1.83	15.6	5.48	2.70
3	0.112	1.81	14.9	5.25	2.82
4	0.114	1.84	15.8	4.90	3.15
5	0.112	1.86	14.97	4.62	3.32
Mean	0.117	1.88	15.3	5.15	2.99
S.D.	6.72	0.11	0.42	0.39	0.25
C.of Var.	5.7%	5.6%	2.7%	7.5%	8.3%

Table 5.7 Repeatability results: Subject 5

(Consecutive tests: joint in place for duration)

Test No.	Torque range (Nm)	Mid. slope ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)	Flex. sl ($\frac{Nm}{deg} \times 10^{-3}$)	Exten. sl ($\frac{Nm}{deg} \times 10^{-3}$)
1	0.113	1.76	16.1	4.17	4.09
2	0.122	1.74	16.1	5.27	3.96
3	0.112	1.76	15.3	4.34	3.98
4	0.126	1.81	16.5	5.55	4.33
5	0.117	1.79	15.8	5.03	4.01
Mean	0.118	1.77	15.9	4.87	3.93
S.D.	5.96	0.03	0.44	0.59	0.40
C.of Var.	5.0%	1.5%	2.7%	12.2%	10.2%

study of the pattern of variation of the flexion slopes reveals that there was a general decrease in the magnitude of the slope as the number of tests increased. This may have been due to the type of thixotropic or reorientation effects that were mentioned earlier. It should be expected that the parameters that are more towards the limits of displacement will be more effected because the values of torque that occur at these positions are greater than those at the centre of the oscillation. As the coefficients of variation of the flexion and extension slopes were, in general, so high it was decided that these parameters would be unreliable and thus they were not considered in the analysis of results for the main body of experiments.

Torque range, energy dissipation and mid. slope did not appear to exhibit a general decrease in magnitude with the number of tests and thus it was concluded that, as long as the iterative part of the general test procedure was restricted to less than five hysteresis loops, then the results would not be adversely effected.

When the joint remained in the finger holder between tests the coefficients of variation of all the parameters were markedly reduced, although the flexion and extension slopes were still higher than the other three parameters. This result does not seem to be very remarkable as any errors in seating of the joint in the machine would have been eliminated in this series of tests.

5.8 Conclusions

None of the subjects appeared to experience any difficulty in relaxing for the full ten second period of the test even though some of them approached the arthrograph with some trepidation at first. The iterative procedure to superimpose the centre of the cycle on the equilibrium position was fairly rapid and the number of tests before a suitable level of coincidence was attained was not so great that a reduction of the parameters occurred due to the repeated oscillation. In general, the experiment was repeatable but the variability of the flexion and extension slopes was considered to be too high and so these parameters were not included in any further analysis.

5.9 General procedure for the grip strength machine

A warm up time of five minutes was allowed after the device had been switched on to ensure that the signal from the strain gauge amplifiers would be free from drift. The subject was seated with the forearm horizontal and elbow at 90 degrees of flexion. The grip transducer was held vertically with the fingers placed on the appropriate pads. After the test requirements had been thoroughly explained the start button was depressed and the subject applied the best grip force they could manage for six seconds duration.

5.10 Repeatability

It was never the intention to use this apparatus to compile general data on grip-strength for comparative purposes between a large healthy population and a patient population. However, as this was a new device, it was interesting to compare the reaction of subjects and patients in a small pilot study whilst assessing the repeatability of the device and the test procedure.

The experimental group consisted of five healthy males (age 22-27) and eight female patients, five of whom suffered from rheumatoid arthritis and three osteoarthritis. Both left and right grips of each subject were tested three times in the same afternoon. A rest of ten minutes was allowed between the first and second tests to help to eliminate fatigue effects. The second and third tests were performed consecutively.

5.11 Observations

Most subjects found the equipment straightforward and undaunting. In an active test of this kind it is vital for repeatability that the patient produces the same effort each time. Initial consecutive tests produced quite a high degree of variation but it was found that by introducing an element of competition that more consistent results were achieved. It is the latter set of results that will be presented.

Some patients with mild to severe hand deformities experienced difficulty in gripping the transducer in an appropriate manner, particularly when pronounced ulnar deviation of the fingers was involved. It was difficult to foresee any easy way to overcome this problem. An adjustable grip would possibly provide more comfort for the hand but would also introduce an extra variable into the results. It was felt that perhaps the best method to adopt would be a process of familiarization and hence a standard grip technique for each patient. Thus, in the table of results which follow, some zero values were registered due to the inability of patients with severe hand deformities to locate all of their fingers on the four pads simultaneously.

5.12 Results

5.12.1 Healthy subjects

Representative values for three of the healthy subjects are given in tables 5.8, 5.9 and 5.10. The output from the grip machine for the right hand of subject one is shown in figure 5.2

For each subject, the results showed that the repeatability of the maximum total grip force was reasonably good. Values of coefficient of variation, for both hands, varied from a minimum of 3.3% to a maximum of just over 14%. Individual finger contribution showed a higher inter-test variation, with the notable exception of the readings from the middle finger. In all cases the middle finger contribution was predominant throughout the course of the grip (figure 5.2). This finding is consistent with the results of Ohtsuki(1982) and Jones (1984).

It is also interesting to note that the grip of the dominant hand does not appear to be significantly greater than the non-dominant and that there was no noticeable fatigue effect between the consecutive second and third tests as may have been expected.

5.12.2 Arthritic subjects

Tables 5.11,5.12 and 5.13 show representative values from the patient group. The particular data has been selected to show the full spectrum of results. Patient one was suffering from rheumatoid arthritis but at the time of testing the disease appeared to be in a stable phase. The output from the grip machine for this subject's right hand is shown in figure 5.3. RA. was also the complaint of patient two but in this case the disease activity was more active and on questioning, the subject described the feeling of a pronounced stiffness in the morning. The patient with the most chronic disease activity was patient three. Pain was a major complaint of this subject and a combination of this, severe swan-necking and subluxation at the MCP joints of the left hand meant that testing of this hand had to be abandoned. The raw output from the grip machine for patient three is shown in figure 5.4.

The results from patient one demonstrated an unusually good repeatability over the three tests. This was suprising since the grip development (fig. 5.3) was

Table 5.8 Grip repeatability for subject one (healthy male 22)

Test	Hand	Max. Total grip	Max. Index	Max. Middle	Max. Ring	Max. Little
1	L	492	126	236	87	86
	R	405	81	192	95	77
2	L	497	124	221	93	87
	R	394	118	165	73	66
3	L	384	80	195	77	44
	R	379	106	164	90	51
mean	L	457	110	217	86	72
	R	393	102	174	86	65
S.D.	L	63.8	26.0	20.7	8.08	24.5
	R	13.0	19.9	15.9	11.5	13.0
C. of V.	L	14%	24%	9.5%	9.3%	34%
	R	3.3%	19.9%	9.1%	13.4%	20.0%

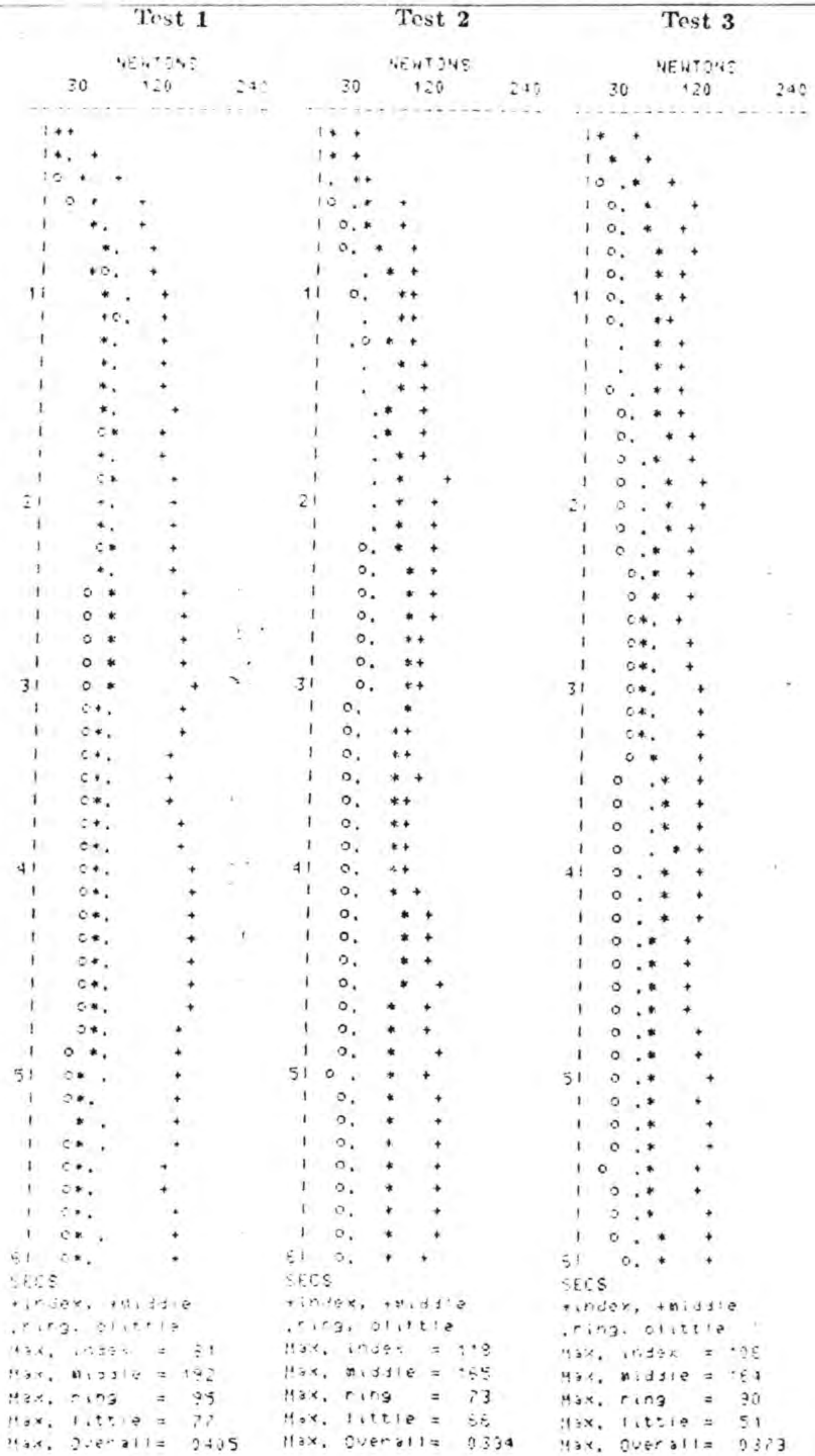
Table 5.9 Grip repeatability for subject two (healthy male 27)

Test	Hand	Max. Total grip	Max. Index	Max. Middle	Max. Ring	Max. Little
1	L	447	105	178	105	70
	R	367	63	190	65	74
2	L	415	93	216	75	74
	R	458	91	203	102	102
3	L	416	114	172	92	58
	R	486	94	225	104	80
mean	L	426	104	189	91	67
	R	437	83	206	90	85
S.D.	L	18.1	10.5	23.9	15.0	8.3
	R	62.2	17.0	17.7	21.9	14.7
C. of V.	L	4%	10%	13%	17%	12%
	R	14%	21%	9%	24%	17%

Table 5.10 Grip repeatability for subject three (healthy male 25)

Test	Hand	Max. Total grip	Max. Index	Max. Middle	Max. Ring	Max. Little
1	L	396	114	160	80	69
	R	400	65	166	76	125
2	L	433	132	172	75	70
	R	447	94	165	84	114
3	L	413	123	177	78	78
	R	492	117	191	80	133
mean	L	414	123	170	77	72
	R	446	92	174	80	124
S.D.	L	18.5	9.0	8.7	2.5	4.9
	R	46.0	26.0	14.7	4.0	9.5
C. of V.	L	4%	7%	5%	3%	7%
	R	10%	28%	8%	5%	8%

Figure 5.2 Grip machine output from subject One (healthy)



```
*index, +middle          *index, +middle          *index, +middle
.ring, olittle           .ring, olittle           .ring, olittle
Max, index  =  81        Max, index  = 119        Max, index  = 105
Max, middle = 192        Max, middle = 165        Max, middle = 164
Max, ring   =  95        Max, ring   =  73        Max, ring   =  90
Max, little =  77        Max, little =  66        Max, little =  51
Max, Overall=  0405      Max, Overall=  0334      Max, Overall=  0373
```

Table 5.11 Grip repeatability for patient one (RA age 55)

Test	Hand	Max. Total grip	Max. Index	Max. Middle	Max. Ring	Max. Little
1	L	90	22	42	12	18
	R	97	27	34	20	27
2	L	83	17	38	15	15
	R	95	15	43	20	25
3	L	86	19	45	12	14
	R	98	15	41	22	35
mean	L	86.3	19.3	41.7	13.0	15.7
	R	96.7	19.0	39.3	20.7	29.0
S.D.	L	3.5	2.5	3.5	1.7	2.1
	R	1.5	6.9	4.7	1.2	5.3
C. of V.	L	4%	12.9%	8.4%	13.3%	13.2%
	R	1.5%	36.4%	11.9%	5.6%	18.2%

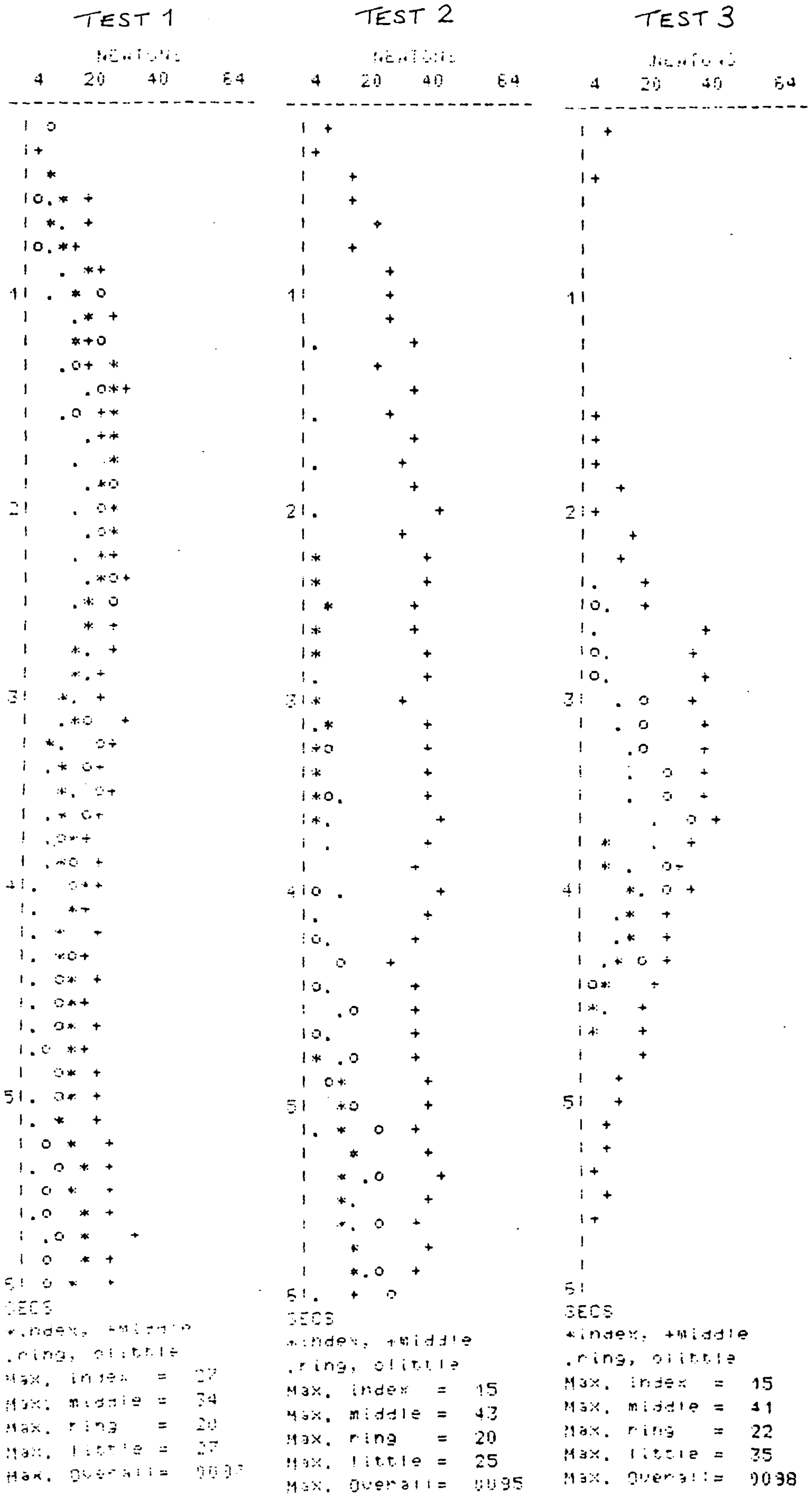
Table 5.12 Grip repeatability for patient two (RA age 54)

Test	Hand	Max. Total grip	Max. Index	Max. Middle	Max. Ring	Max. Little
1	L	94	28	39	12	22
	R	124	36	46	17	36
2	L	91	23	47	13	19
	R	128	45	45	24	26
3	L	86	20	35	17	18
	R	87	16	34	18	37
mean	L	90.3	23.7	40.3	14.0	19.7
	R	113.0	32.3	41.7	19.7	33.0
S.D.	L	4.0	4.0	6.1	2.65	2.08
	R	22.6	14.8	6.7	3.8	6.1
C. of V.	L	4.4%	16.9%	15.1%	18.9%	10.6%
	R	20.0%	45.8%	16.1%	19.3%	18.4%

Table 5.13 Grip repeatability for patient three (RA age 90)

Test	Hand	Max. Total grip	Max. Index	Max. Middle	Max. Ring	Max. Little
1	L	—	—	—	—	—
	R	91	3	67	24	0
2	L	—	—	—	—	—
	R	96	0	62	34	0
3	L	—	—	—	—	—
	R	59	0	50	9	0
mean	L	—	—	—	—	—
	R	82.0	3.0	59.7	22.3	0
S.D.	L	—	—	—	—	—
	R	20.0	n.a.	8.7	12.5	0
C. of V.	L	—	—	—	—	—
	R	24%	n.a	14.6%	56%	0

Figure 5.3 Grip machine output for patient one

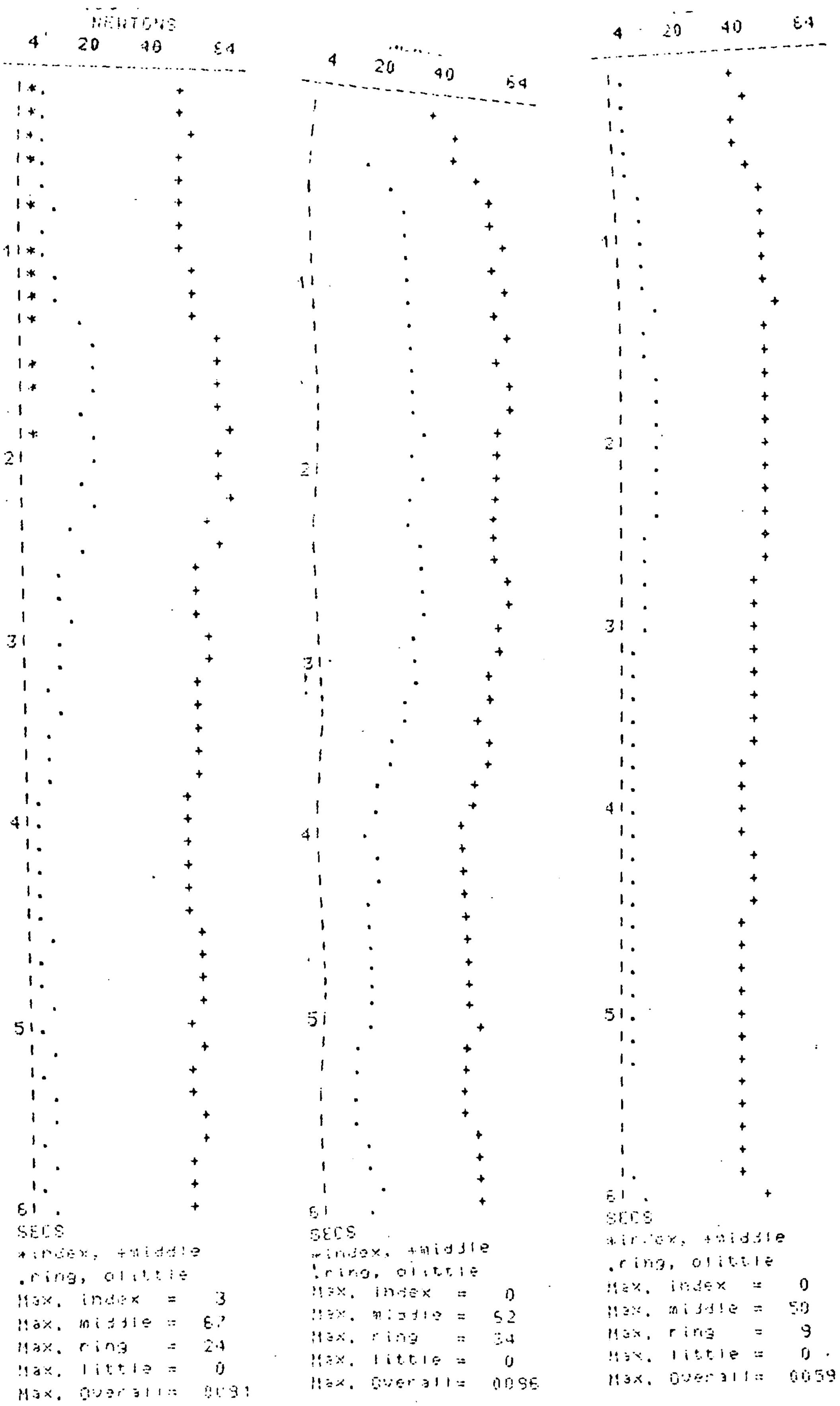


```
*index, +middle
.ring, olittle
Max, index  =  27
Max, middle =  34
Max, ring   =  20
Max, little =  27
Max, Overall=  0037
```

```
*index, +middle
.ring, olittle
Max, index  =  15
Max, middle =  43
Max, ring   =  20
Max, little =  25
Max, Overall=  0095
```

```
*index, +middle
.ring, olittle
Max, index  =  15
Max, middle =  41
Max, ring   =  22
Max, little =  35
Max, Overall=  0038
```

Figure 5.4 Grip machine output for patient three



```
*index, +middle
.ring, olittle
Max, index  =   3
Max, middle =  67
Max, ring   =  24
Max, little =   0
Max, Overall=  0091
```

TEST 1

```
*index, +middle
.ring, olittle
Max, index  =   0
Max, middle =  62
Max, ring   =  34
Max, little =   0
Max, Overall=  0096
```

TEST 2

```
*index, +middle
.ring, olittle
Max, index  =   0
Max, middle =  50
Max, ring   =   9
Max, little =   0
Max, Overall=  0059
```

TEST 3

much more erratic than the healthy subjects and was inconsistent for the three tests. It may be that the delay in developing the grip in the third test, followed by a sharp burst of activity, was the reason that this value was the greater of the three results even though fatigue may have been expected to play a part at this stage.

The magnitude of the results of patient two were similar to patient one but the repeatability of them was not so good. In fact the other five patients tested showed similar values of repeatability which tends to suggest that the results of patient one were uncharacteristic of the whole group. A 20% variation in total grip strength did seem rather disappointing but perhaps this should have been expected in an experiment which was partly under the control of the test subject.

The highest coefficients of variation of the whole group were exhibited by patient three which in view of the level of pain, expressed subjectively, is perhaps not so surprising. Consideration of fig. 5.4 shows that the contributions from the middle and ring fingers were predominant and the little finger did not have any effect. This latter fact was due to the problems of accommodating all the fingers on all the pads simultaneously.

5.13 Conclusions

The high coefficient of variation amongst the patient group was disappointing. However, in six out of eight cases the effects of disease were judged to be fairly severe and hence it seems likely that the estimate of variation from this small series of experiments is probably unreasonably pessimistic. In most cases the patients experienced some initial difficulty in gripping the transducer, but this improved with practice. Pain was an important factor amongst the patient group and this must have had a considerable bearing on the higher coefficients of variation when compared with the healthy group. For both groups the middle finger contribution was predominant.

Overall, it was felt that the repeatabilities were not unusual for an active test of this kind and that the information from the grip force versus time graphs would be useful in analysing the patterns of grip, from the point of view of rate of grip development, endurance and maximum contribution from each finger.

CHAPTER SIX

CIRCADIAN VARIATION OF STIFFNESS AND GRIP STRENGTH

6.1 Introduction

The aim of this series of experiments was to investigate the variation in passive joint stiffness, in both healthy and diseased joints, over a 24-hour period. Subjects for the healthy population were male and female volunteers in the age range 19-28 years. None of these volunteers had any previous history of joint problems and were requested not to indulge in any activity, immediately prior, or during, the experimentation that would put undue stress on their fingers or wrists. The patients were all in temporary residence at the rheumatology ward at Hemlington Hospital and were selected on the basis of disease type and the degree of hand involvement. The mean and range of ages amongst the patients was considerably higher than the healthy subjects which clearly presents a problem if comparisons are to be made between the two groups. Ideally the two groups would be age matched, but attempting to organise this in practice was not felt to be an expedient approach. In fact, this contrast in the composition of the healthy and diseased populations did enable some interesting comparisons to be made. Testing was performed on twelve healthy subjects, equally split between the sexes, and eighteen patients. For each group the experimental method was the same.

6.2 Method

The standard arthrographic test was performed on each subject every two hours, for a period of twenty four hours. During the course of the tests the subjects were requested to follow a normal daily routine and to attempt to sleep as naturally as possible in the circumstances. In the waking hours the arthrograph was situated in a suitable test environment and subjects attended for testing at their appointed times. The arthrograph and any other associated equipment was placed on a trolley and wheeled to the subjects bedside to perform the testing during the normal sleeping hours.

Interruption of sleep patterns, and therefore obtaining data from an unnatural situation, was a major concern prior to the experimentation. However, apart from 'knocking the subjects out 'for a predetermined period, it did not seem possible to avoid this problem. In an attempt to minimize this factor testing was carried out as quietly and unobtrusively as possible and was successful to the point that many of the subjects did not experience any periods of wakefullness but rather a state of semi-slumber during each test. All of the subjects were questioned about the interruption of their sleep patterns and none complained that this had caused them extended periods of wakefullness or prevented them from getting a normal nights sleep. Indeed, some of the patients, used to awaking during the night because of pain, commented that their sleep during the period of testing was better than average.

For the patient group, grip readings were also taken, both with a proprietory grip meter of the inflated cuff type and the grip machine described in chapter four. The grip meter was the type manufactured by the Boots company and was pre-inflated to 30 mm of mercury. The averages of three maximum pressure readings for each hand were taken as the final grip values. It was necessary to use this meter, despite the drawbacks stated earlier (sec.2.3), because the grip machine was not available for use until the last series of tests. Thus, in the results which follow the assessment of the circadian variation of grip strength amongst the patients is largely based on the results from the inflated bag of the grip meter. The results from the grip machine will be presented for comparative purposes only.

6.3 Analysis of results from healthy joints

The composition of the healthy group was as follows :-

Table 6.1 Composition of the Healthy group

Variable	Number
No. of subjects	12
Age range	20-27
Mean age	22
Sex ratio F:M	1:1
om. hand ratio R:L	11 : 1

The healthy volunteers awakened at approximately 7.30 to 8.00 a.m. and retired around 11.00 to 12.00 pm. On questioning, only one of the subjects complained of any stiffness of the finger joints and even in this case the subjective feeling was one of sluggishness and not profound stiffness or immobility.

To give an idea of the data obtained, the means and standard deviations of each of the joint stiffness parameters will be presented, followed by a qualitative description of some characteristic individual results.

Table 6.2 Mean and standard deviation of the healthy group

Male subjects : no. = 6

Parameter	T.R.	units : $Nm \times 10^{-3}$	Mid. sl.	units: $\frac{Nm}{deg.} \times 10^{-3}$	Energy dissip.	units $J \times 10^{-3}$
Time	mean	S.D.	mean	S.D.	mean	S.D.
0.00	57.9	20.6	0.94	0.32	8.41	2.27
2.00	59.5	19.5	0.99	0.34	8.60	2.35
4.00	59.6	25.1	0.84	0.50	8.10	2.83
6.00	57.6	21.0	0.89	0.30	8.41	2.40
8.00	52.6	16.6	0.85	0.29	8.00	2.41
10.00	58.4	24.2	0.89	0.31	8.31	3.18
12.00	61.1	25.8	0.98	0.37	9.08	3.60
14.00	60.3	20.3	0.91	0.30	9.38	2.69
16.00	52.2	21.0	0.93	0.32	8.80	2.44
18.00	51.6	18.5	0.94	0.40	8.71	3.09
20.00	54.2	20.5	0.83	0.36	7.64	2.47
22.00	50.8	19.4	0.74	0.29	7.73	2.99

Female subjects : no.= 6

Parameter	T.R.	units : $Nm \times 10^{-3}$	Mid. sl.	units: $\frac{Nm}{deg.} \times 10^{-3}$	Energy dissip.	units $J \times 10^{-3}$
Time	mean	S.D.	mean	S.D.	mean	S.D.
0.00	40.2	11.8	0.62	0.25	6.4	1.65
2.00	41.4	13.5	0.89	0.45	6.12	1.47
4.00	45.1	12.8	0.63	0.23	6.11	1.20
6.00	39.7	9.1	0.64	0.31	5.93	2.70
8.00	48.4	15.5	0.74	0.28	7.00	2.76
10.00	38.3	8.2	0.52	0.29	5.50	2.46
12.00	40.7	11.1	0.63	0.22	6.34	1.89
14.00	42.1	11.7	0.68	0.21	6.59	1.70
16.00	42.3	8.8	0.60	0.15	6.91	2.08
18.00	36.1	7.9	0.53	0.18	6.74	2.09
20.00	43.6	10.3	0.60	0.10	5.94	0.91
22.00	40.0	7.3	0.63	0.10	6.26	1.59

When the results were combined in this way there appeared to be no observable peaks for any of the joint stiffness parameters for either the male or the female subjects. Any differences in the mean values were well within the error bounds of one standard deviation at either side of the mean. However, an observation of this kind is prone to error because of the differences in stiffness levels between one subject and another and the times at which a particular individual may have achieved maximum stiffness. Both these factors may combine to cloud what may be significant results, on an individual basis at least. This can be seen more clearly if individual cases are considered.

6.3.1 Some individual results

Figures 6.1,6.2 and 6.3 are some typical results from the healthy male group. It can be seen that the parameters of torque range and energy dissipation did not display any major change over the twenty four hour period. The mid slope parameter seemed to show some significant changes for subjects one and six but these changes were not consistent. For example, the mid. slopes of subject one appeared to be elevated from the afternoon to the evening whereas those of subject six showed the reverse trend, with a very sharp peak occurring at 4.00 a.m.. The results of subject five, shown in fig. 6.2, were unvarying and the joint parameters were very low, when compared with the other male subjects. Tissue bulk was not measured in these tests but it was noted that subject five had extremely small and slim hands and this general lack of tissue bulk seems to be the probable explanation of the very low values.

Figures 6.4, 6.5 and 6.6 show the variabilty of each joint stiffness parameter for the female group. The general trend of the results was the same as those for the male group. Torque range and energy dissipation showed little, or no change, over the test period. The mid. pos. slopes of subjects twelve and ten showed some variation but it can be seen that this was not consistent. Subject twelve exhibited elevated mid. pos. slopes in the early morning with the peak level occuring at 4.00 a.m.. A variation of this kind was not exhibited by any other subject in the group.

Figure 6.1 Circadian plots for healthy male subject no. 1

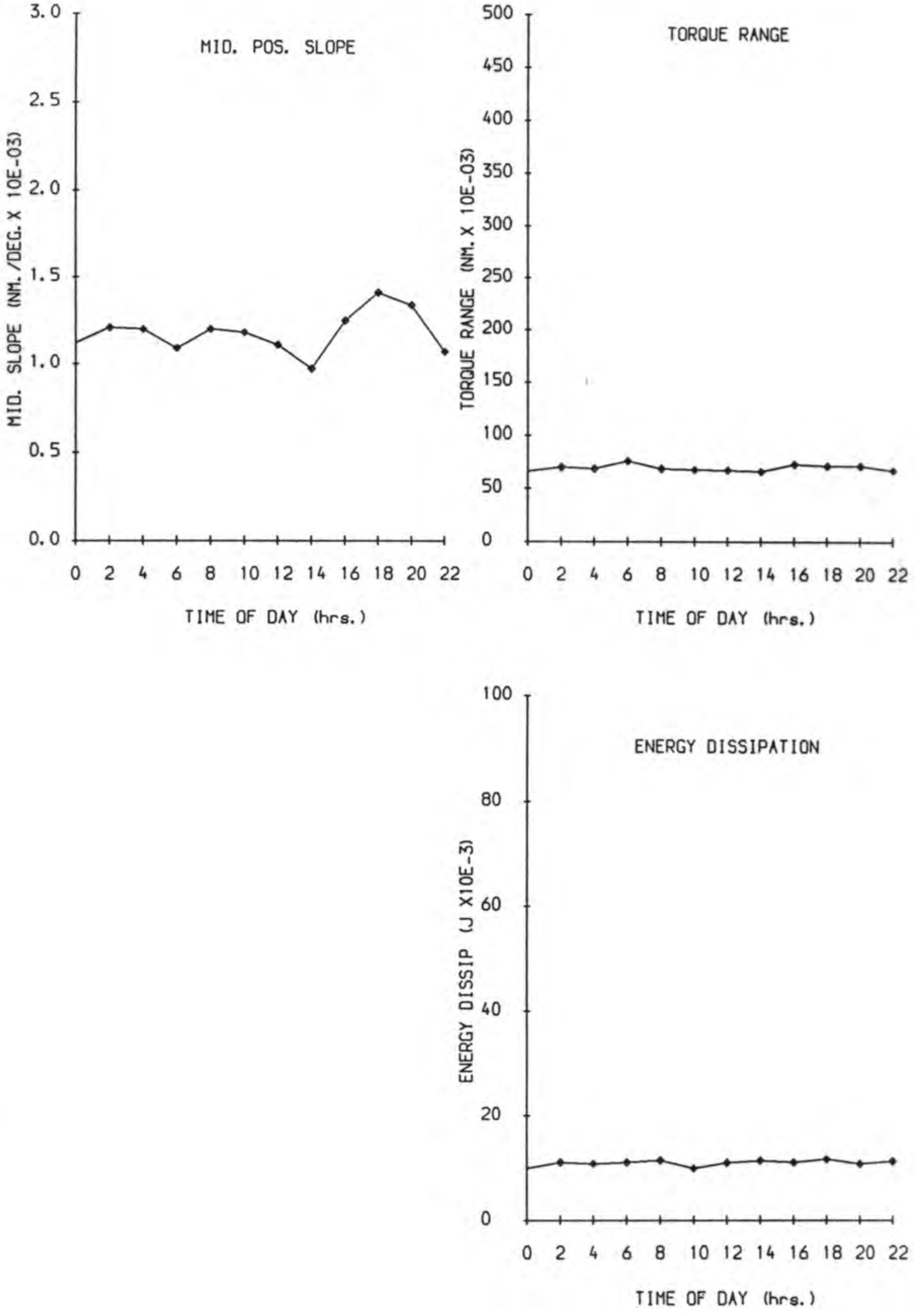


Figure 6.2 Circadian plots for healthy male subject no. 5

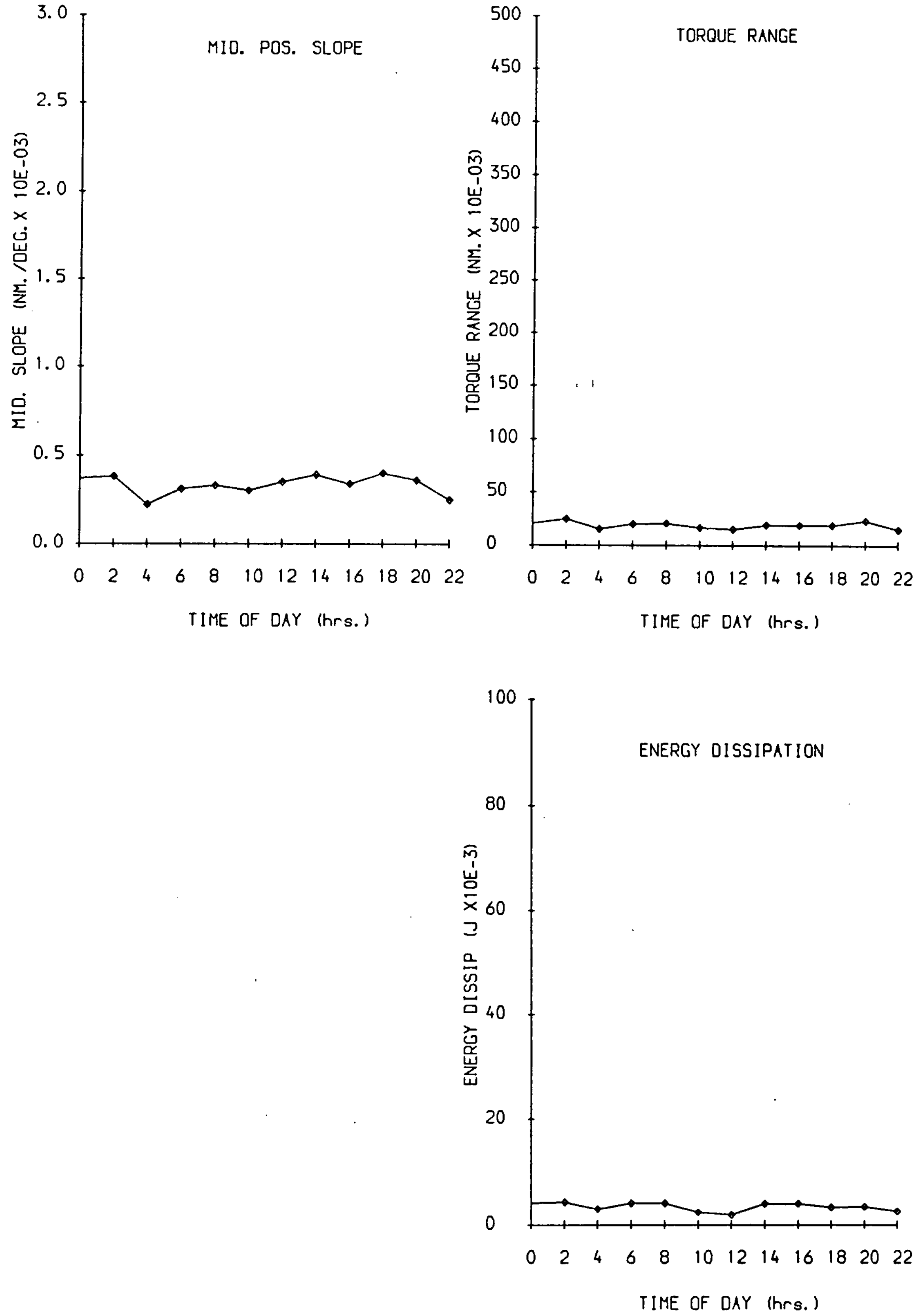


Figure 6.3 Circadian plots for healthy male subject no. 6

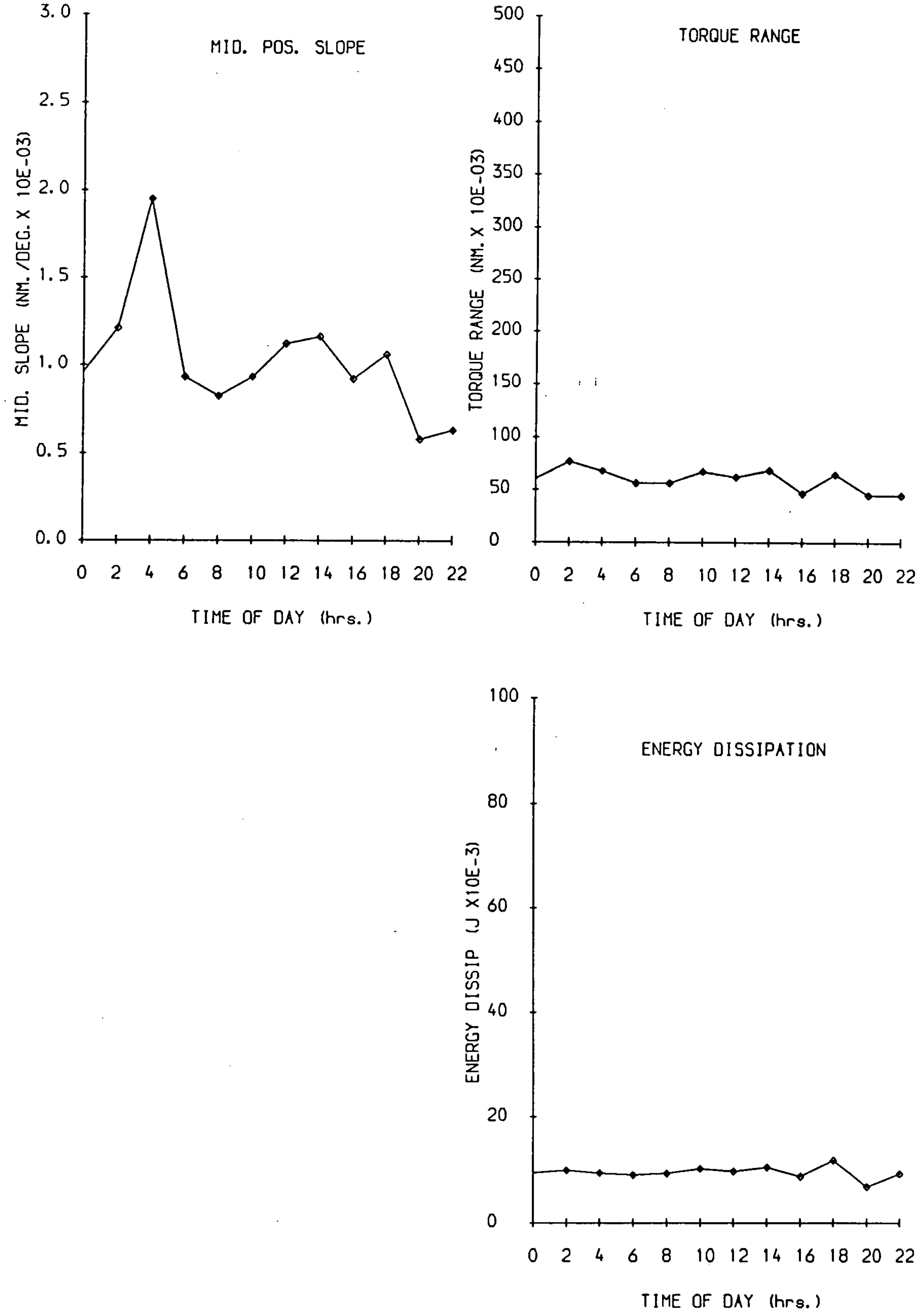


Figure 6.4 Circadian plots for healthy female subject no. 7

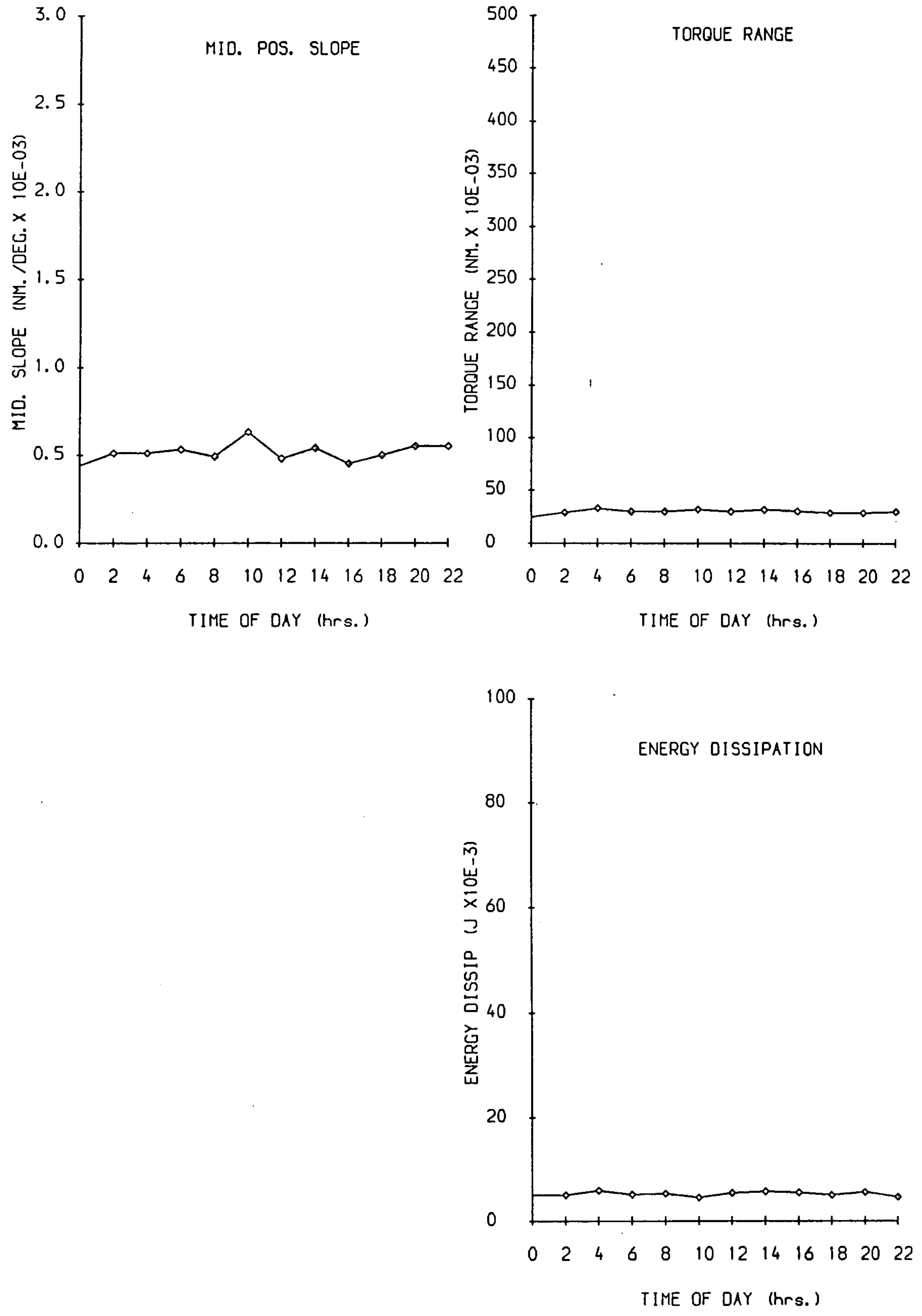


Figure 6.5 Circadian plots for healthy female subject no. 10

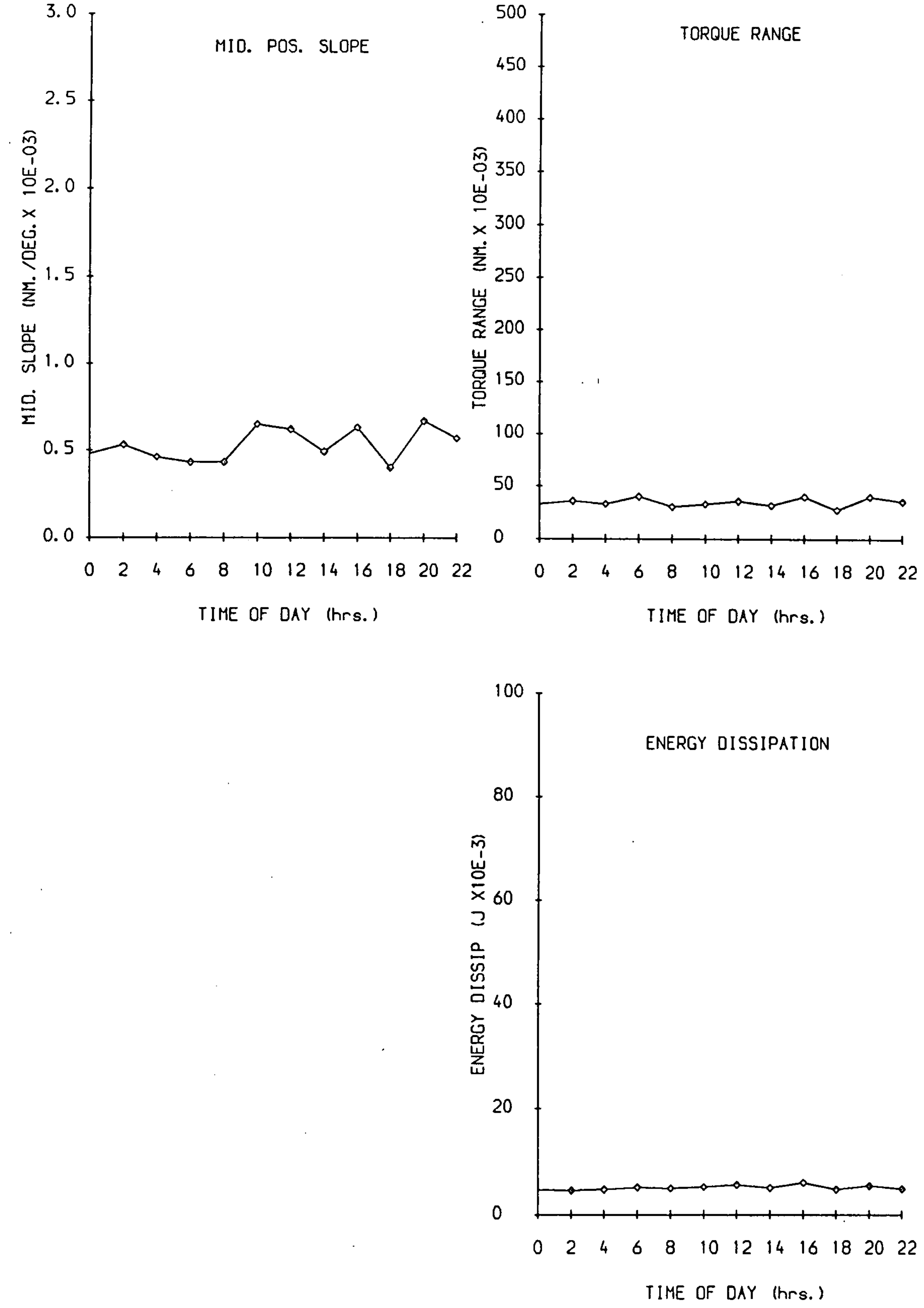
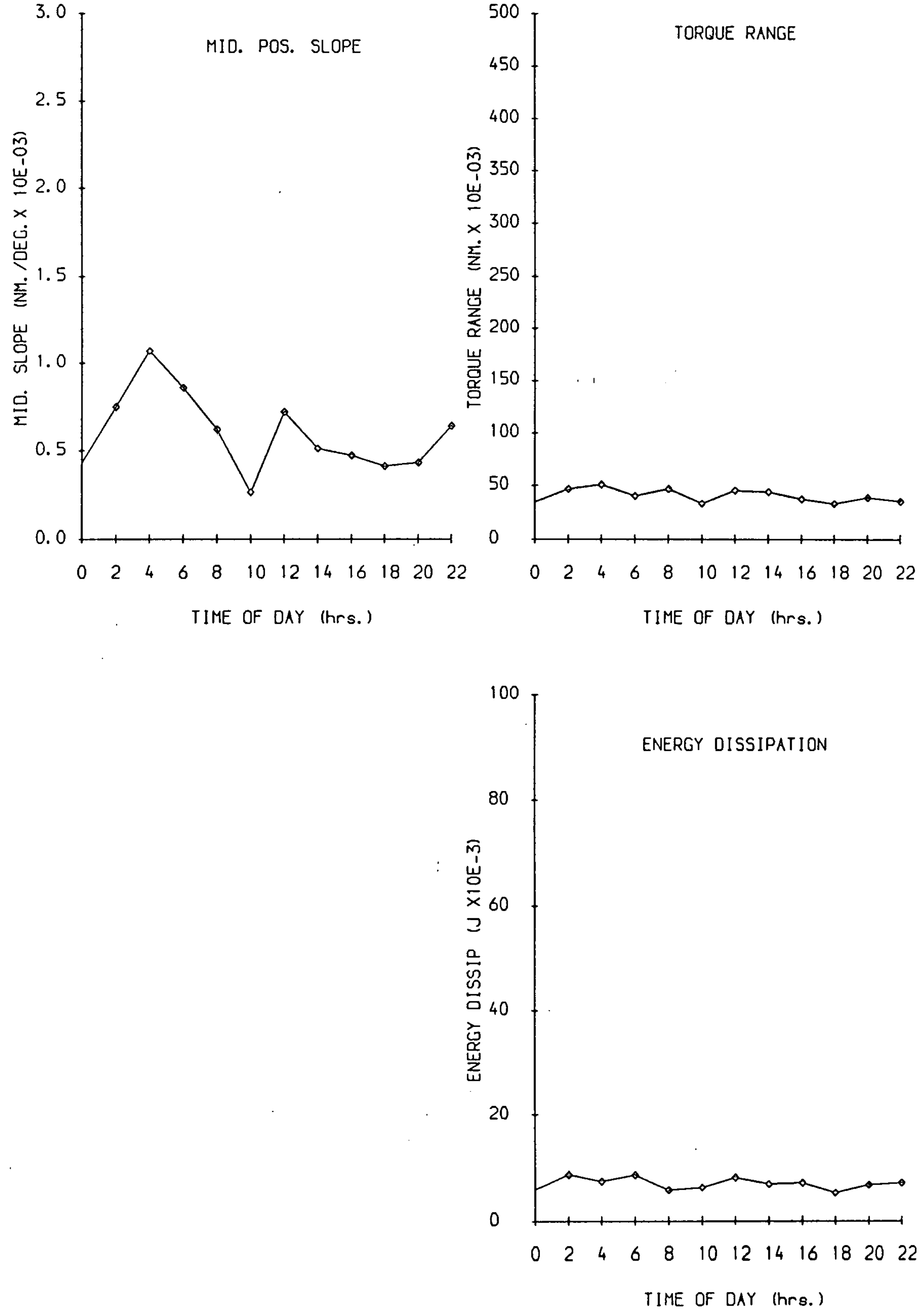


Figure 6.6 Circadian plots for healthy female subject no. 12



6.4 Observations

The general pattern of variation of joint stiffness for the healthy subjects was one of little or no change for any of the parameters. When changes were observed they occured in the mid. pos. slope parameter but were inconsistent in nature, some peaks occurring in the early morning, others in the late afternoon or evening.

In order to highlight any changes that may have been masked by their insignificance in relation to the level of the parameters of the rest of the subject group, the results were normalized. For each subject, each of the parameters from the two hourly results was divided by it's respective maximum value during the 24 hours. A manipulation of this kind also allowed the results to be combined without some of the errors mentioned in section 6.3.1. The mean and standard deviations for the normalized results are shown in figs. 6.7 to 6.12. These results show clearly that any variations in the mean values of the parameters was within the error bounds of one standard deviation either side of the mean.

From these experiments it must be concluded that the passive stiffness of healthy joints appeared to have no consistent pattern of circadian variation and for the majority of cases no significant variation at all.

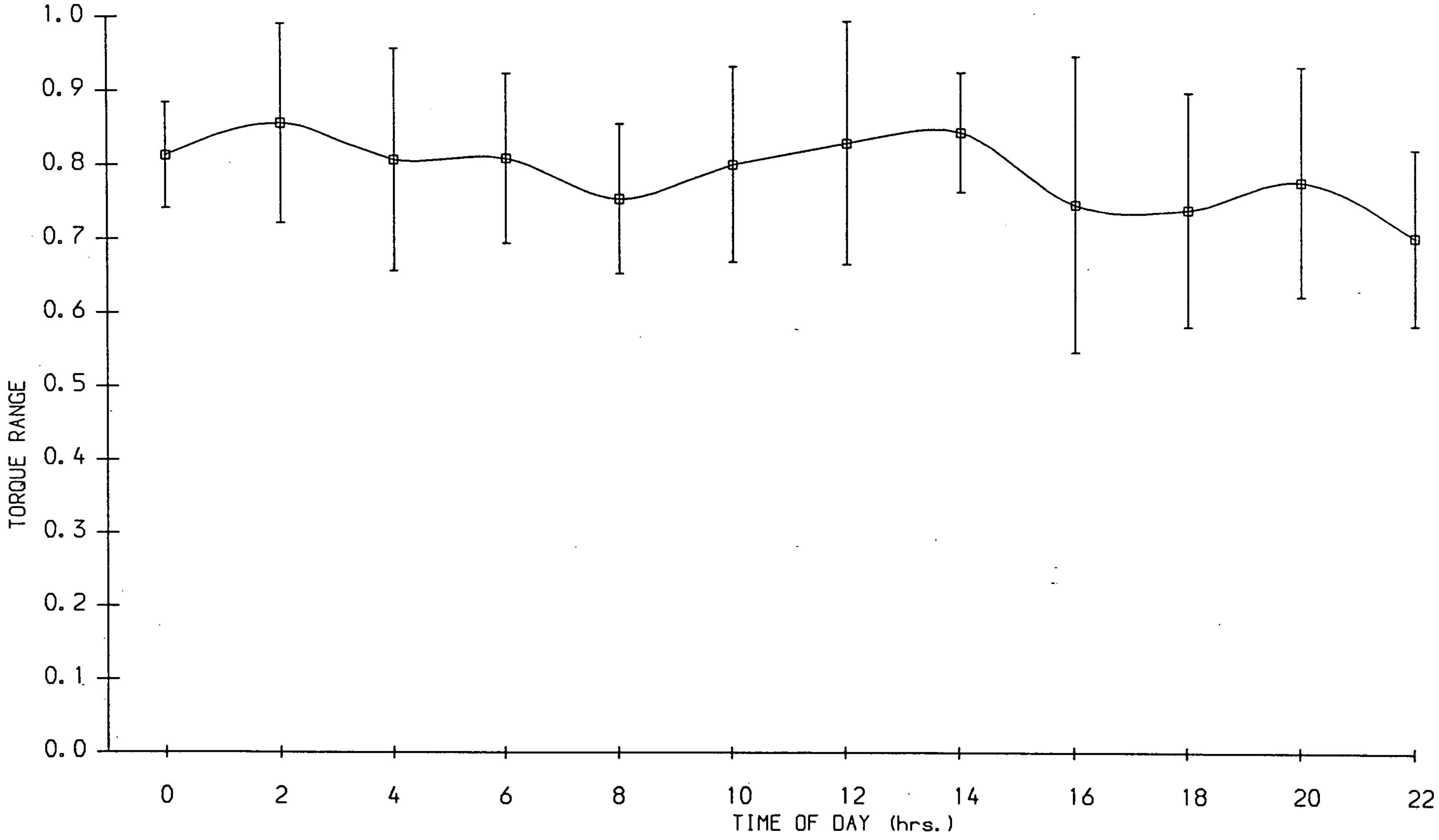


Figure 6.7 Normalised mean and S.D.: Torque range : healthy male subjects

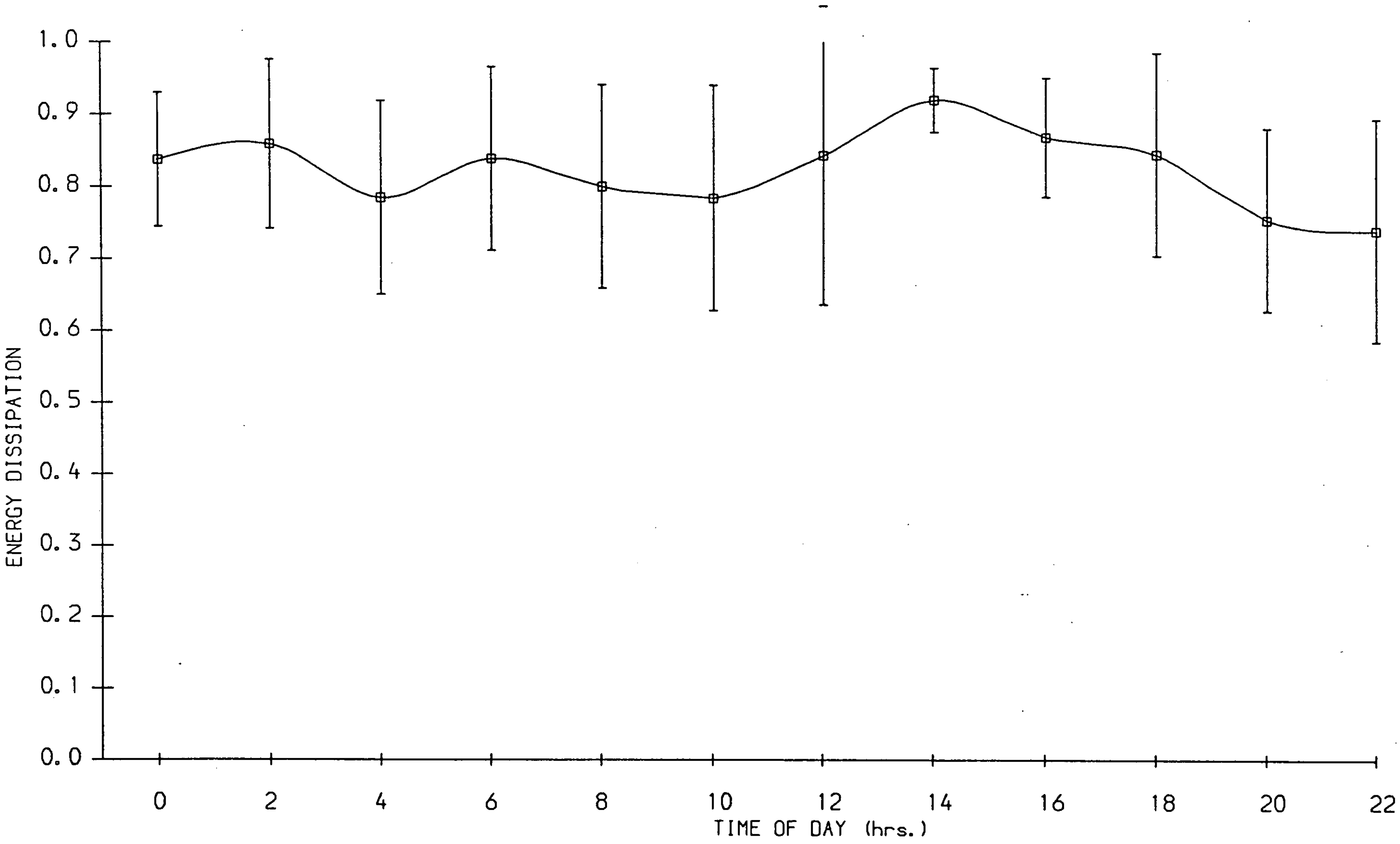


Figure 6.8 Normalised mean and S.D.: Energy dissipation: healthy male subjects

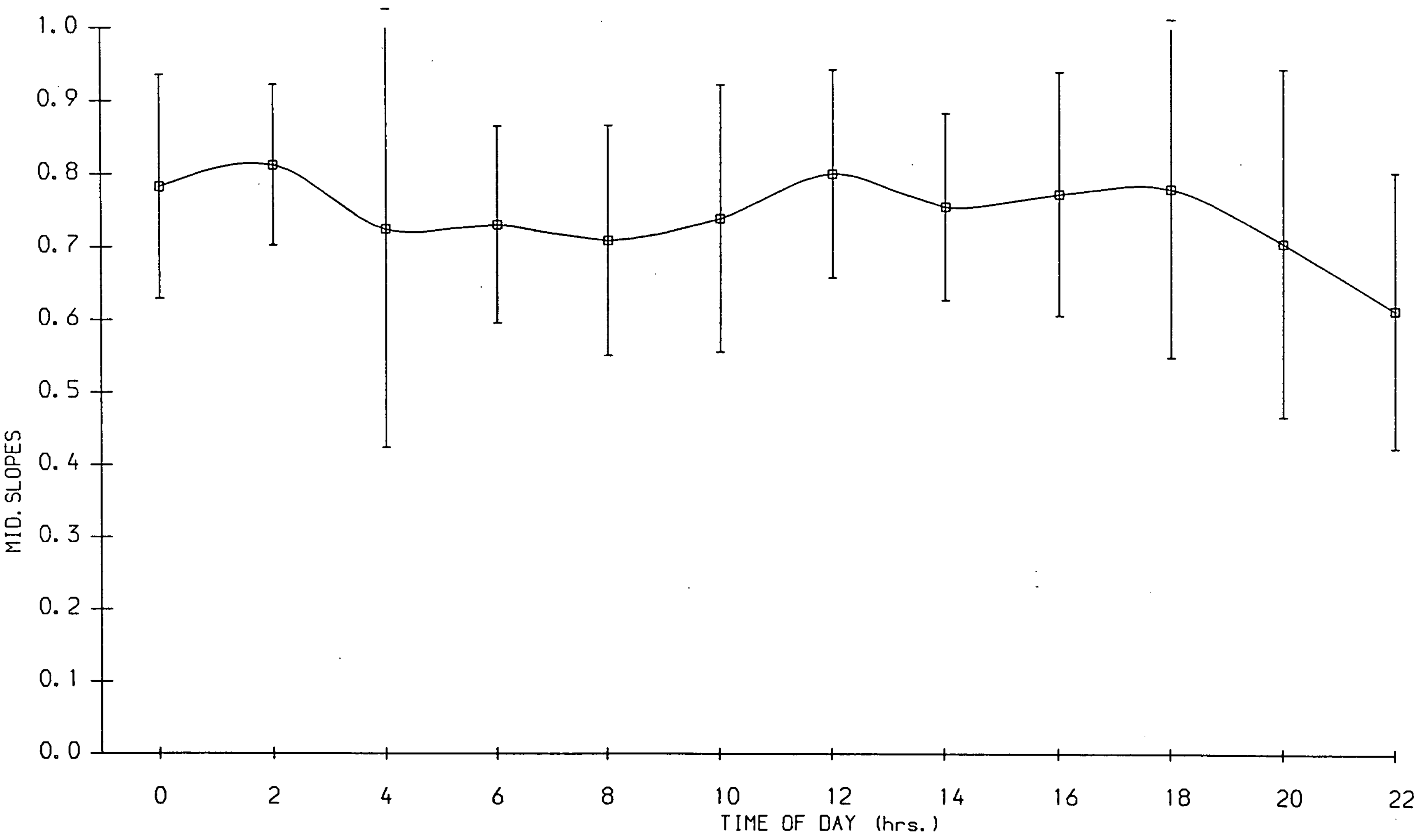


Figure 6.9 Normalised mean and S.D. : Mid. Slopes : healthy male subjects

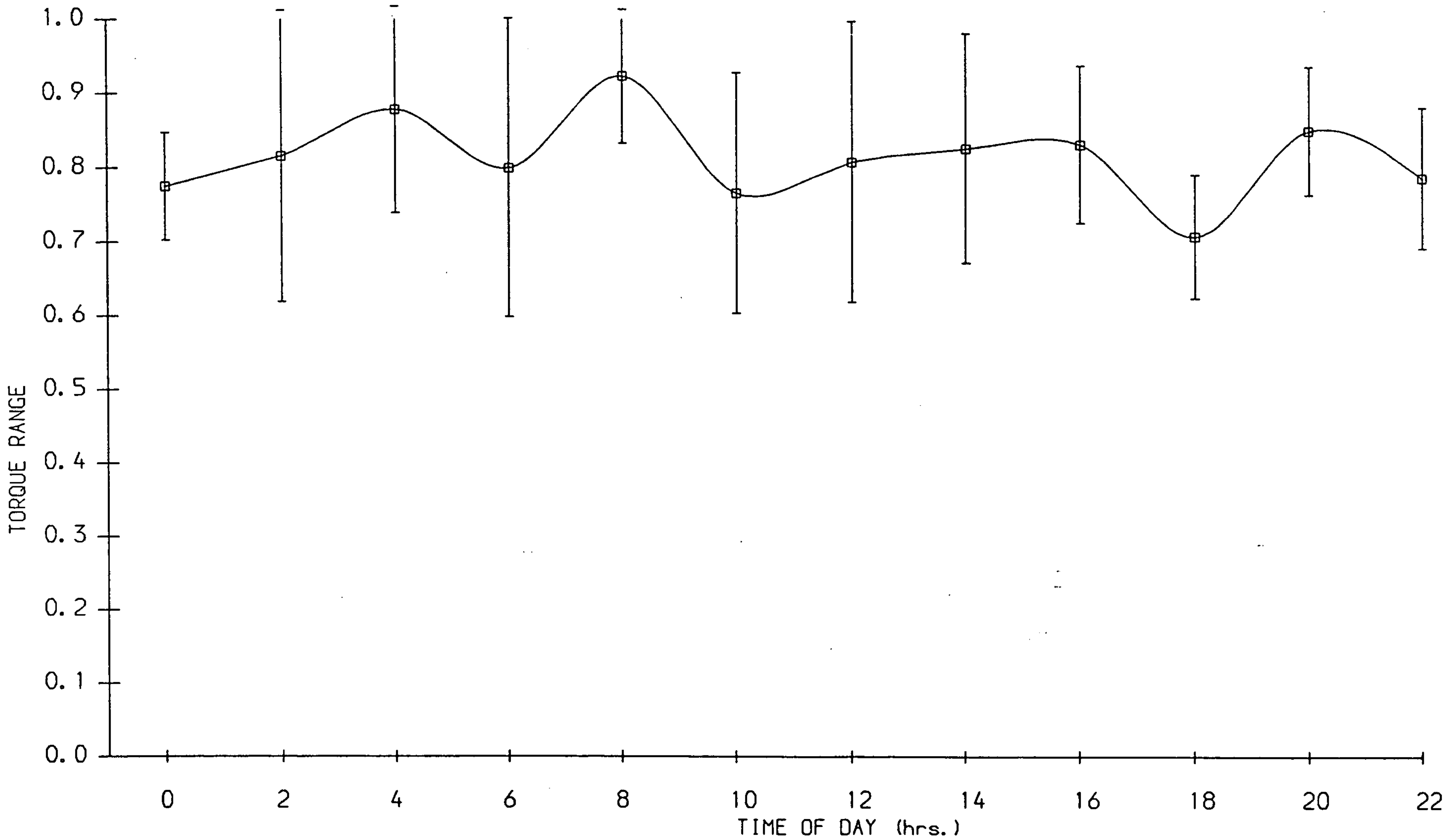


Figure 6.10 Normalised mean and S.D. : Torque range : healthy female subjects

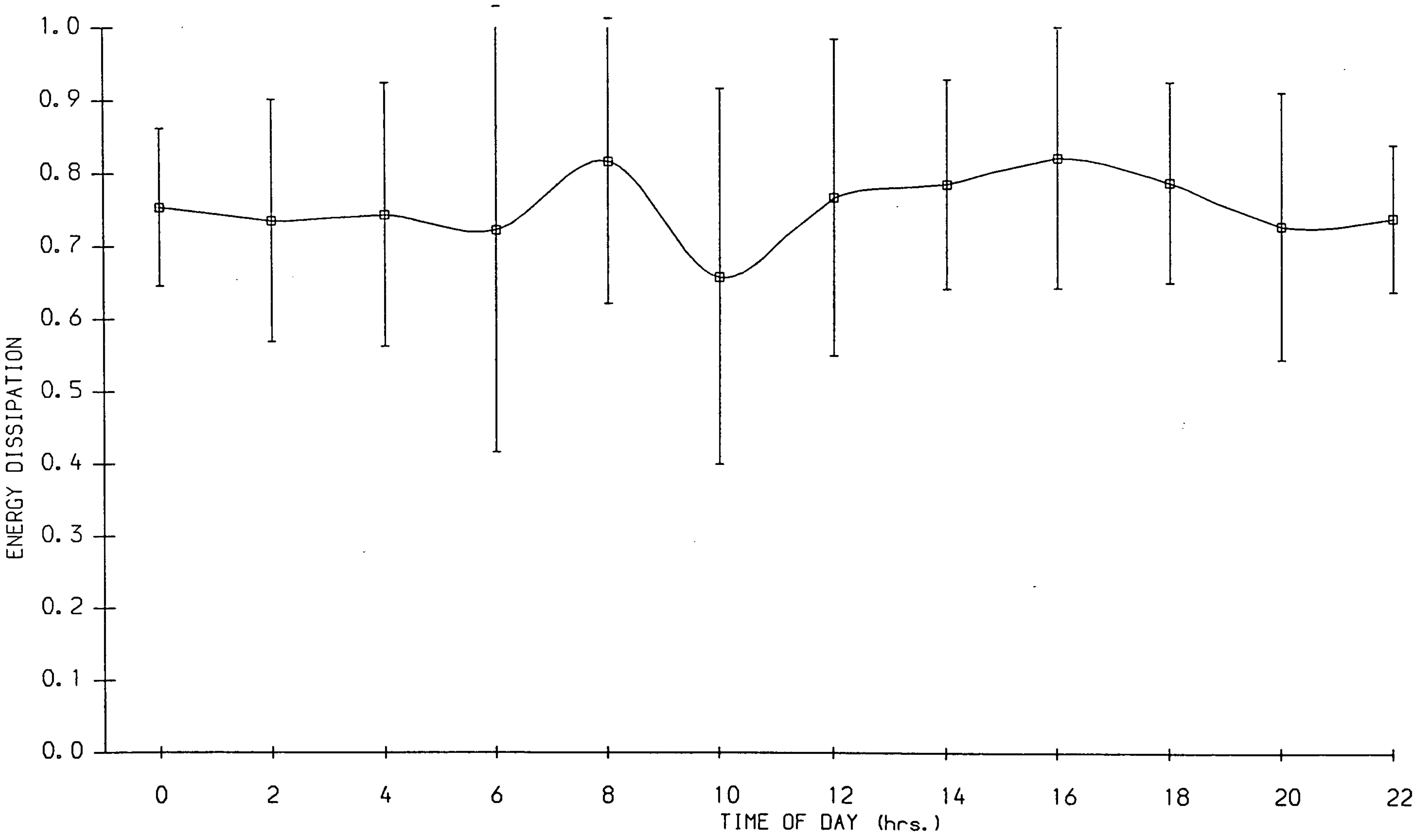


Figure 6.11 Normalised mean and S.D. : Energy dissipation : healthy female subjects

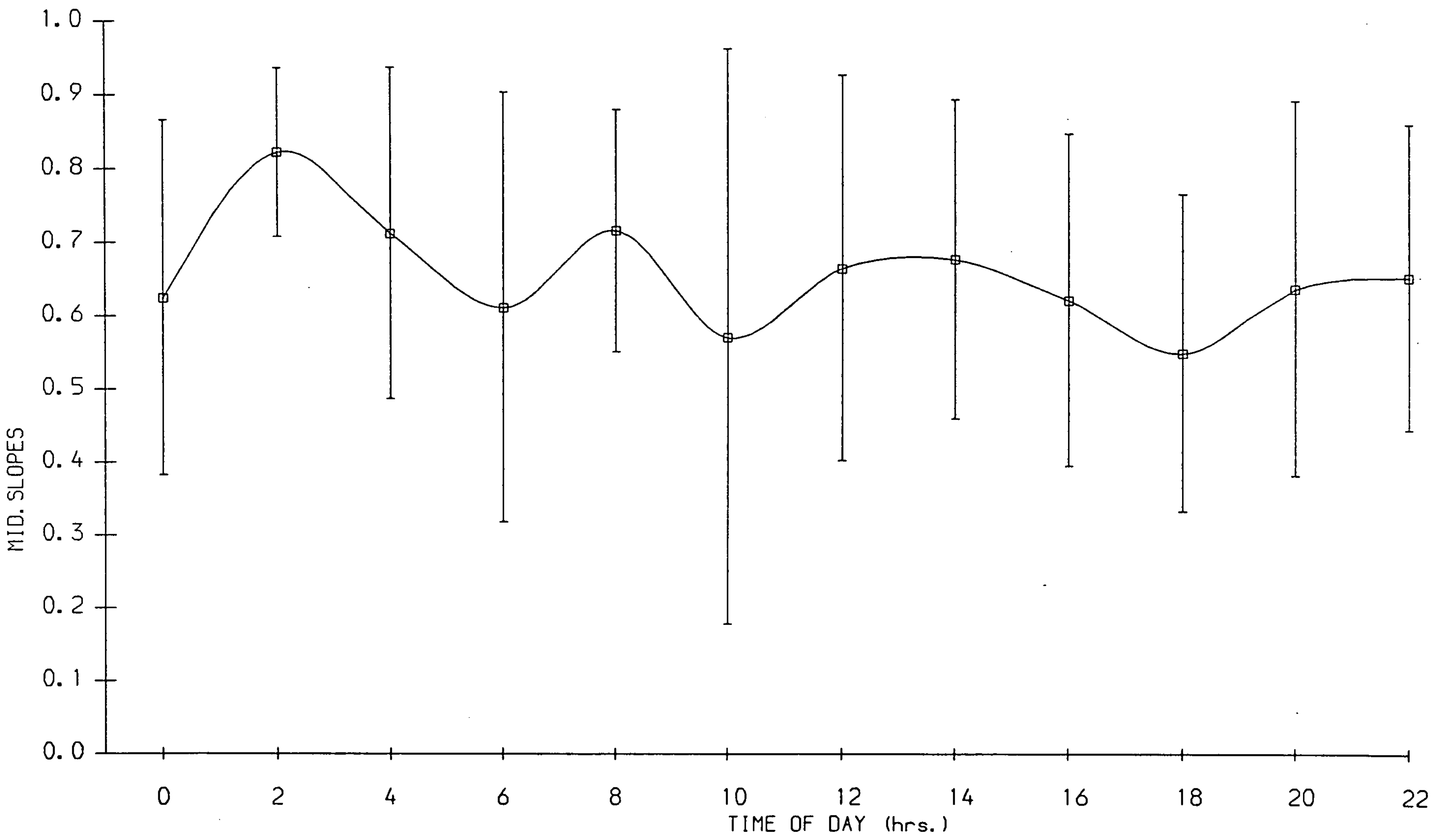


Figure 6.12 Normalised mean and S.D. : Mid slopes : healthy female subjects

6.5 Analysis of results from diseased joints

The composition of the diseased groups was as follows:-

Variable	Number
No. of subjects	18
Age range	21-83
Mean age	57
Sex ratio F:M	1:1
R.A.	17
O.A.	-
Others	1
Dom. hand ratio R:L	8 : 1

Table 6.3 Composition of the diseased group

The majority of the patients selected for this survey were suffering from rheumatoid arthritis and complained of quite profound morning stiffness. Only three out of the eighteen patients tested complained of stiffness following periods of immobility.

A major problem that was foreseen in the testing of patients was the lack of control as regards the type and frequency of administration of anti-inflammatory and analgesic drugs. For example, a course of intravenous pulsed steroids undertaken at any time during the test period may have caused the level of the stiffness parameters to be depressed or circadian stiffness patterns to be modified. In practice, only one of the patients in the diseased group did undergo any significant change in their course of drug therapy and this patient will not be considered as part of the general analysis which follows. The other seventeen subjects, although not receiving identical drugs, had been on their particular course of treatment for a long time. Thus, it was felt that any changes in joint stiffness observed during the tests could be attributed to a stable circadian variation.

6.6 Qualitative analysis of some individual results

A representative sample of the results from the diseased group are shown in figures 6.13 - 6.19. The patient numbers are taken straight from data records and thus are not sequential.

Patient Two - Figure 6.13

Patient two was a 61 year old, right handed female who had been suffering from R.A. for over seven years. The patient complained of morning stiffness but not of increased stiffness following periods of immobility.

The results show predominantly high values in the early morning for all stiffness parameters. The variation in the mid slope parameter is perhaps the most distinctive with the peak value occurring at 10 a.m. Peak values for torque range and energy dissipation did not coincide with this time, occurring at 6 a.m. and 8 a.m respectively.

Grip pressure readings were low and very similar for both left and right hands. There does not appear to have been any significant change in grip pressure over the 24 hour period, but grip pressures in the early hours of the morning were depressed.

Patient Six - Figure 6.14

This patient was a 54 year old, right handed female. Although patient six had been suffering from R.A. for a similar length of time to patient two the disease had recently ‘flared up ’with classic symptoms of pain, swelling and tenderness present in all joints of the hand. On questioning the patient complained of profound increases in stiffness in the early morning and late evening.

Very large peaks in all stiffness parameters in the morning and evening were immediately apparent, the sharp evening peak being the most striking. It should be noted that the scale on the axes normally used had to be changed to accommodate the results from this patient. The maximum torque range was four times the maximum value recorded for patient two.

Grip pressure readings for both hands were very similar and appeared to be minimal at 3.00 a.m.. In view of the large changes in the joint stiffness parameters it may have been expected that the grip pressure readings would exhibit an inverse circadian pattern. However, this lack of correlation between stiffness and grip pressure readings was consistent with the general findings from the group as a whole.

Patient Nine - Figure 6.15

The results shown in figure 6.15 are from a right handed, 62 year old male suffering from R.A.. Disease activity appeared to be in remission and on questioning prior to testing the patient did not admit to any feelings of morning stiffness or stiffness following periods of immobility.

Figure 6.13 Circadian plots for patient no. 2

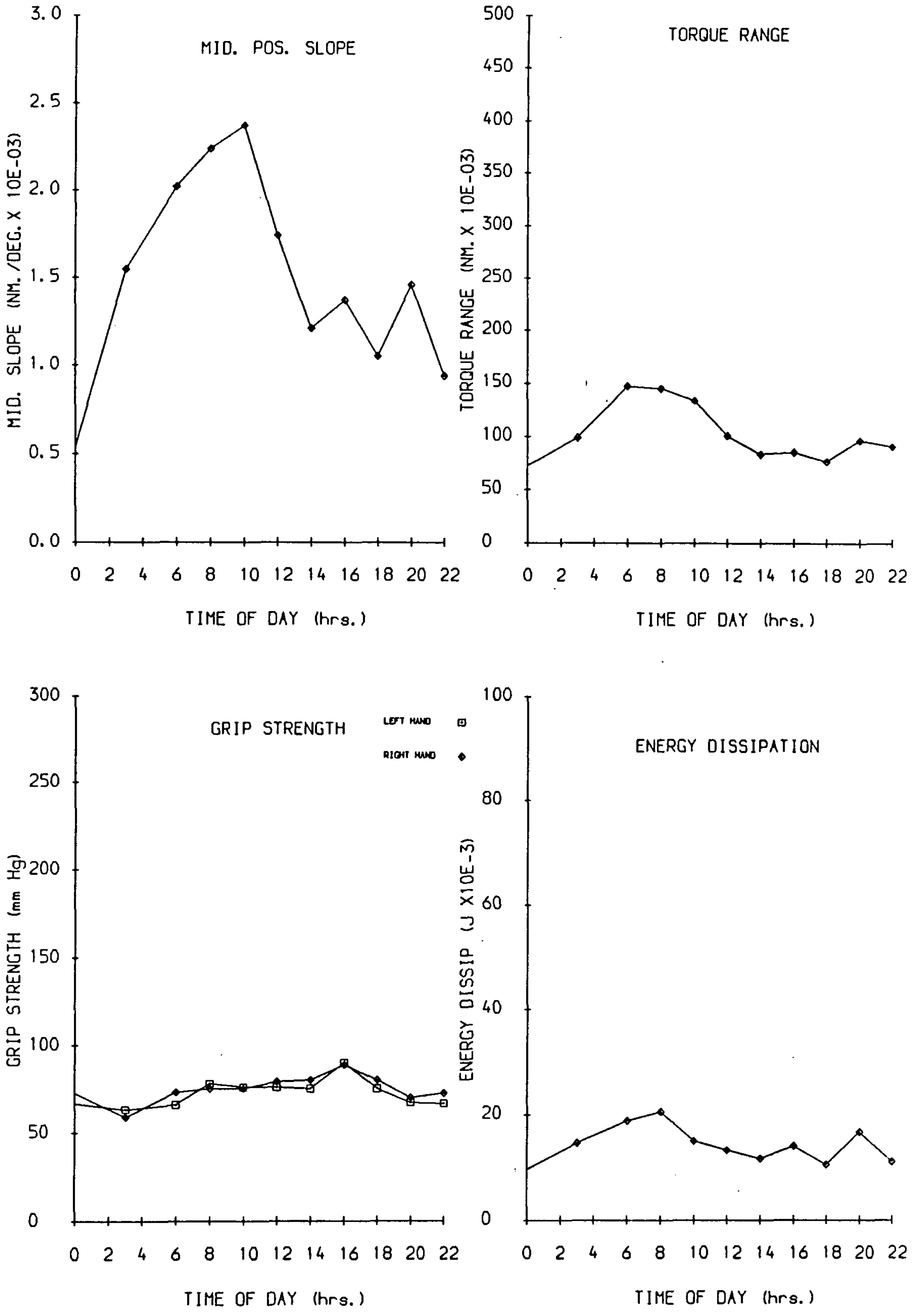


Figure 6.14 Circadian plots for patient no. 6

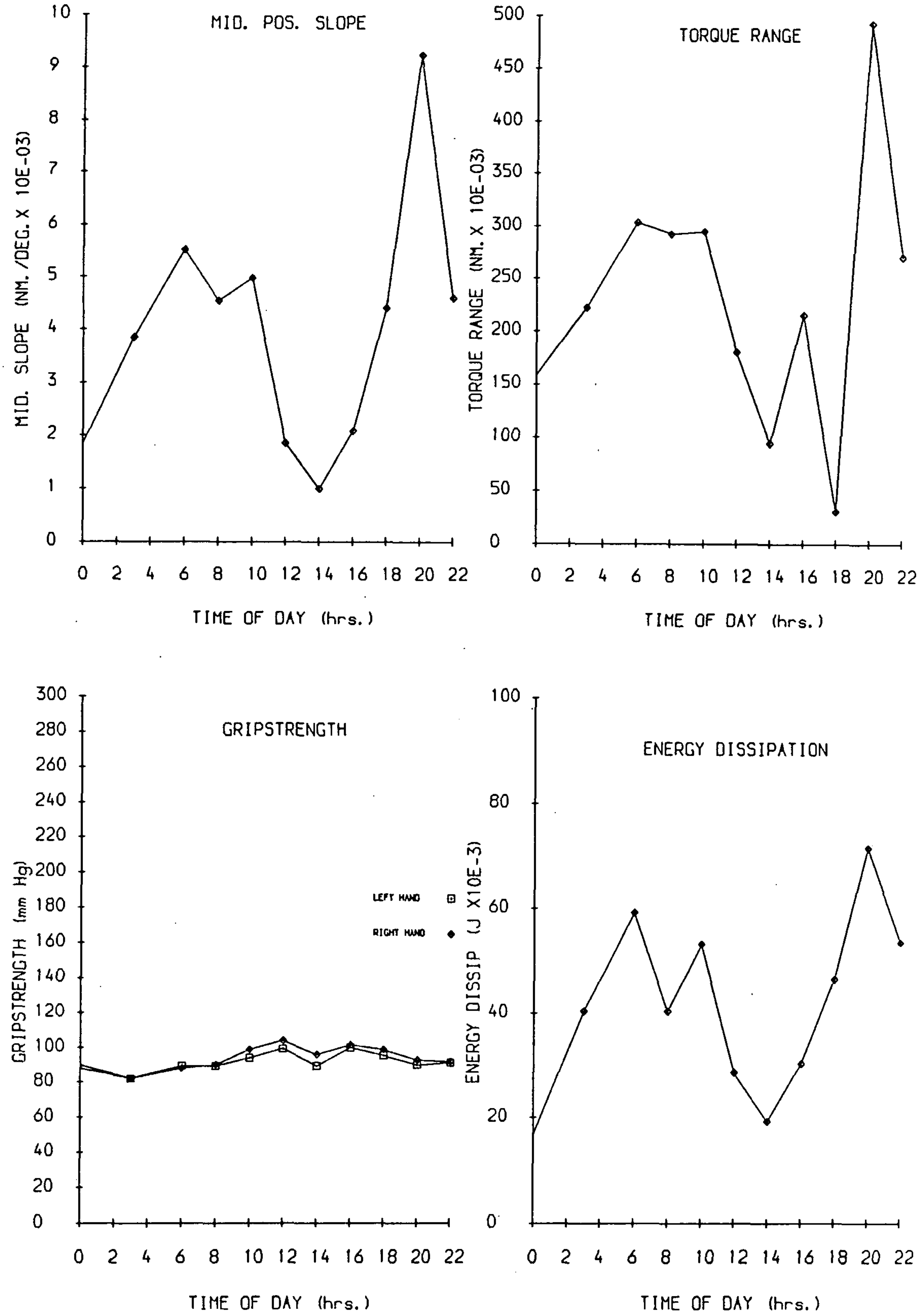
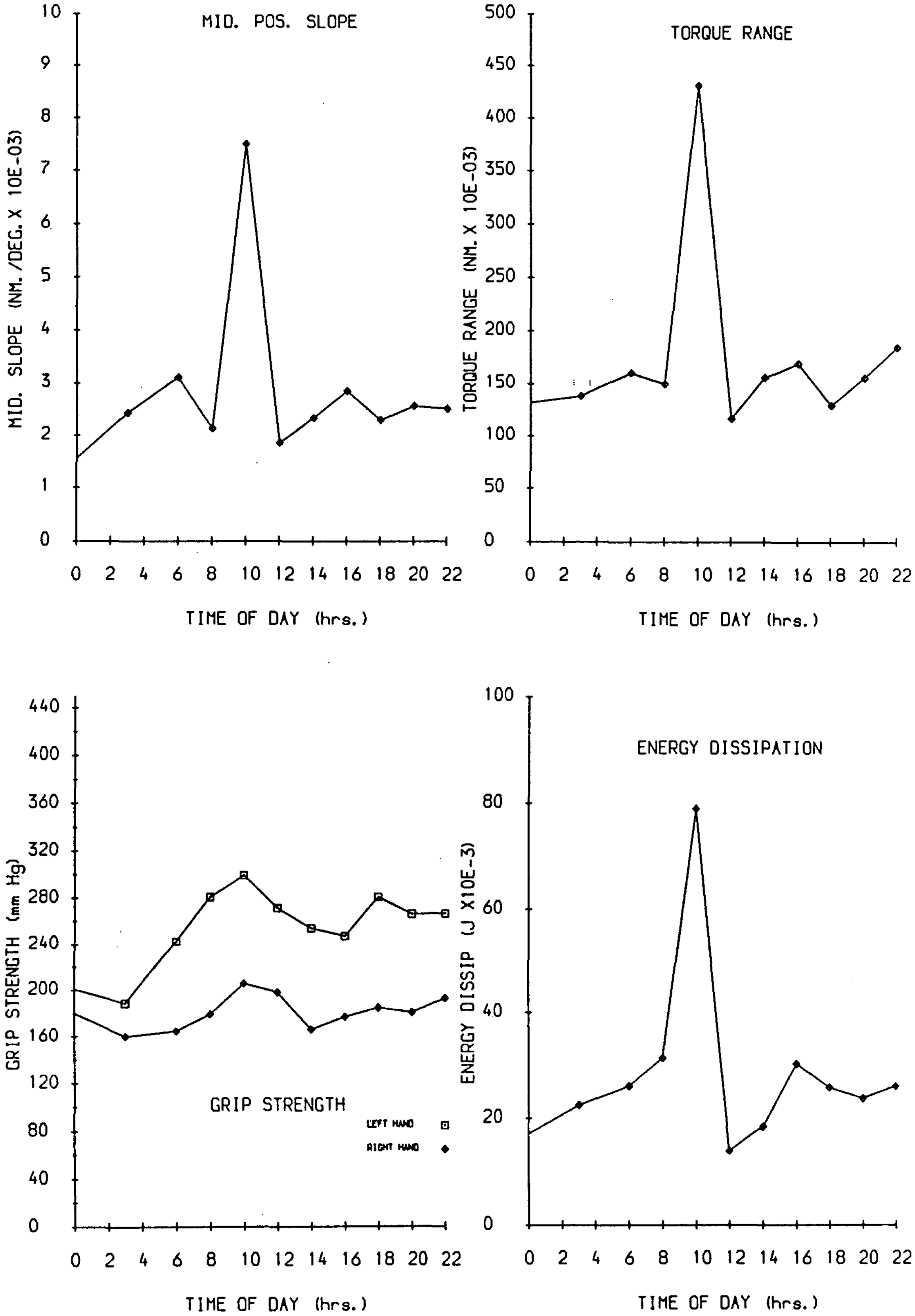


Figure 6.15 Circadian plots for patient no. 9



The sharp peak in all stiffness parameters, occurring at 10 am., is the obvious feature of this set of results. Although the patient did indicate prior to the 10 am. reading that his joints felt 'tight 'the magnitude of the readings was so surprising that the experiment was repeated. The second set showed a slight decrease in the values but they were still very high. In figure 6.15 the first set of results have been plotted.

The circadian pattern of joint stiffness for this patient is certainly strange but is felt worthy of inclusion in this section of representative results if only to emphasise the general lack of consistency in the variation of joint stiffness in this series of experiments.

The variations in grip pressure readings were also markedly different from those of the two patients previously described. The left hand readings were considerably higher than those of the right which was surprising in view of the right hand dominance of this patient. The left hand readings in particular appearred to show a significant variation from a 3.00 am. minimum to a 10.00 am. maximum value. Readings of grip pressure and joint stiffness showed maximum values at 10.00 am.. This coincidence demonstrates that, for this patient at least, grip strength was not adversely affected by increases in joint stiffness.

Patient Twelve - Figure 6.16

Patient twelve was a 56 year old, left handed female suffering from R.A. The joint stiffness profiles for all parameters were very similar to those of patient number two (Fig. 6.13). Predominantly high readings in the early morning were followed by a drop in the early afternoon to a consistently low level which persisted into the night. Close similarity with patient two was also demonstrated by the slight depression of the grip pressure readings in the early hours and the near duplication of values for the left and right hands.

Patient 18 - Figure 6.17

This patient was a 23 year old, right handed male. At the time of testing no diagnosis had been made but he was complaining of pain and stiffness in the shoulders, elbows and wrists. There appearred to be no MCP joint involvement and hence this patient was regarded as a control for this series of experiments.

The joint stiffness parameters showed little variation and were similar in pattern to those of subject one from the healthy group (Fig. 6.1). A circadian variation in grip pressure readings appearred to be present, the minimum values occurring between 4 am. and 6 am. The magnitudes of the grip pressure readings were significantly higher than those patients with diseased joints.

Figure 6.16 Circadian plots for patient no. 12

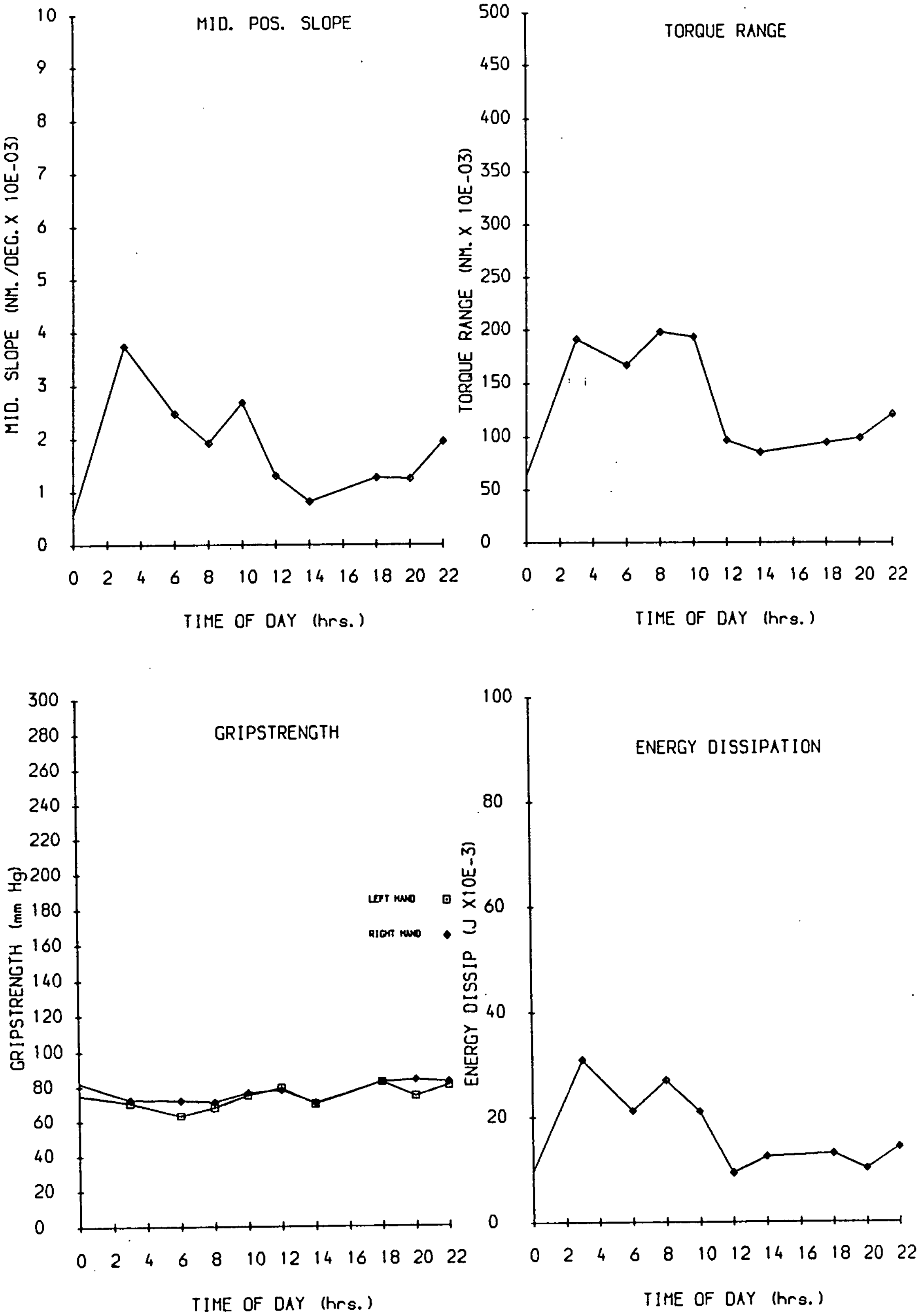
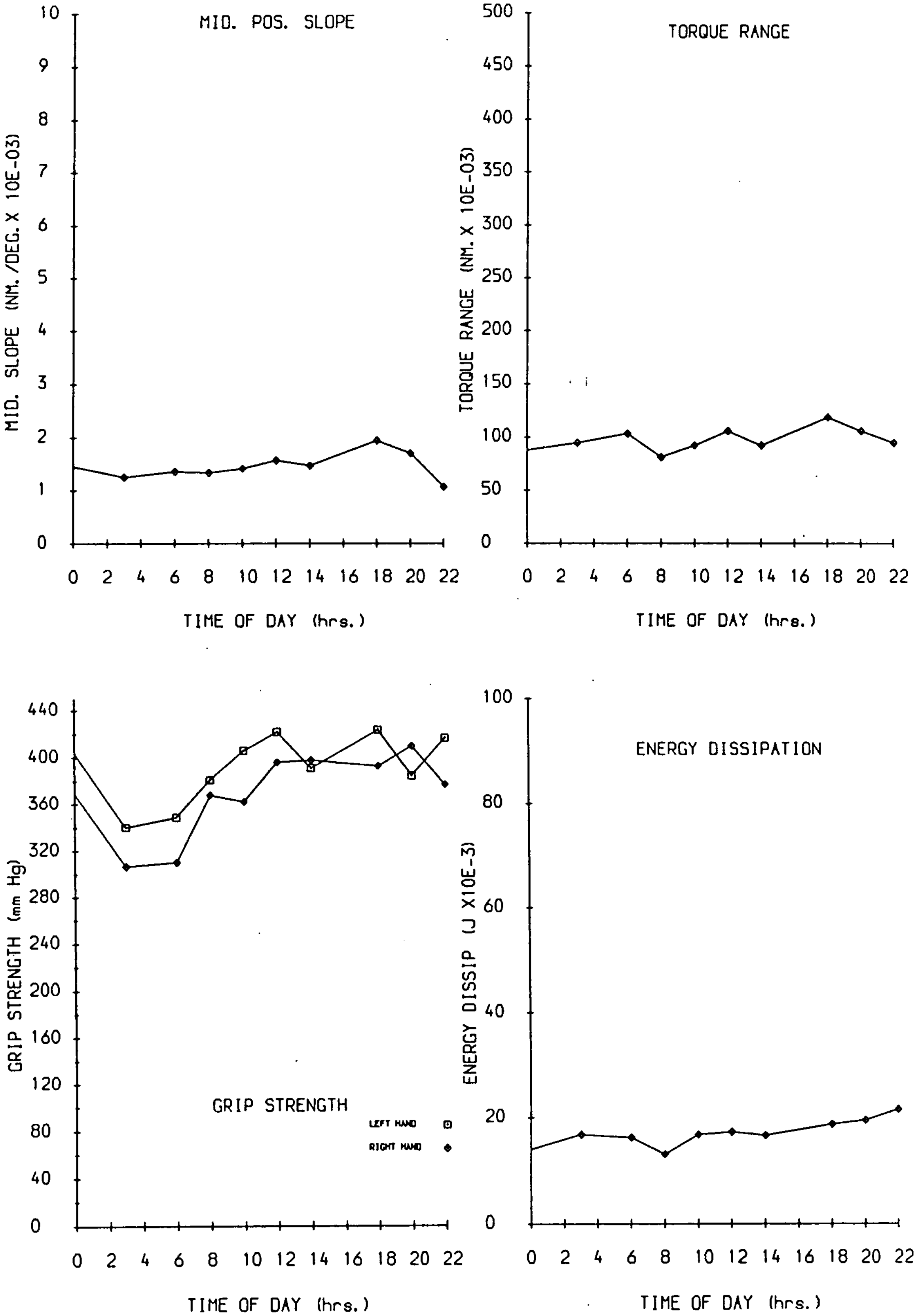


Figure 6.17 Circadian plots for patient no. 18



6.7 Observations

On an individual basis the results were extremely variable. Some patients showed little or no change in joint stiffness parameters, others exhibited predominantly high readings in the morning and for two patients very sharp stiffness peaks were observed.

Significant changes in one stiffness parameter were generally paralled by changes in the other two. This would seem to imply a high degree of inter-dependence in them. It is interesting to compare this observation with those from the healthy group. For the healthy group changes in mid-position slope did not seem to be reflected by a similar level of change in either of the other parameters.

The pattern of variation of grip pressure readings did show some consistency between patients. Minimum values generally occurred between 2 am. and 4 am. There was no noticeable correlation between large increases in stiffness and decreases in grip pressure. In one notable case the grip pressure was elevated when the joint stiffness was elevated.

6.8 Combination of results from diseased joints

The results were normalised and combined in exactly the same manner as for the healthy subject group. Plots of the mean normalised values, and the corresponding error bands of plus and minus one standard deviation, against time of day are shown in figures 6.17-6.20. For torque range, energy dissipation and mid position slope there was no change in normalised mean value which approached the magnitude of the error bands. It must be concluded that for the group as a whole there was no significant variation in joint stiffness.

Analysis of individual cases has shown that in some patients there was a distinct variation in stiffness parameters. However, the timing of significant peaks of stiffness varied from patient to patient and thus it seems likely that a 'cancelling out 'process occurred when the results were combined. This suggestion is supported by the very high standard deviations indicated in the diagram. It was tempting to perform some kind of rotation of the time datum so that significant peaks came into alignment and then to repeat the analysis. Although it may be reasonable to suppose that individual circadian variation patterns could be similar but out of phase a manipulation of this kind is too close to performing an analysis until the expected results are obtained.

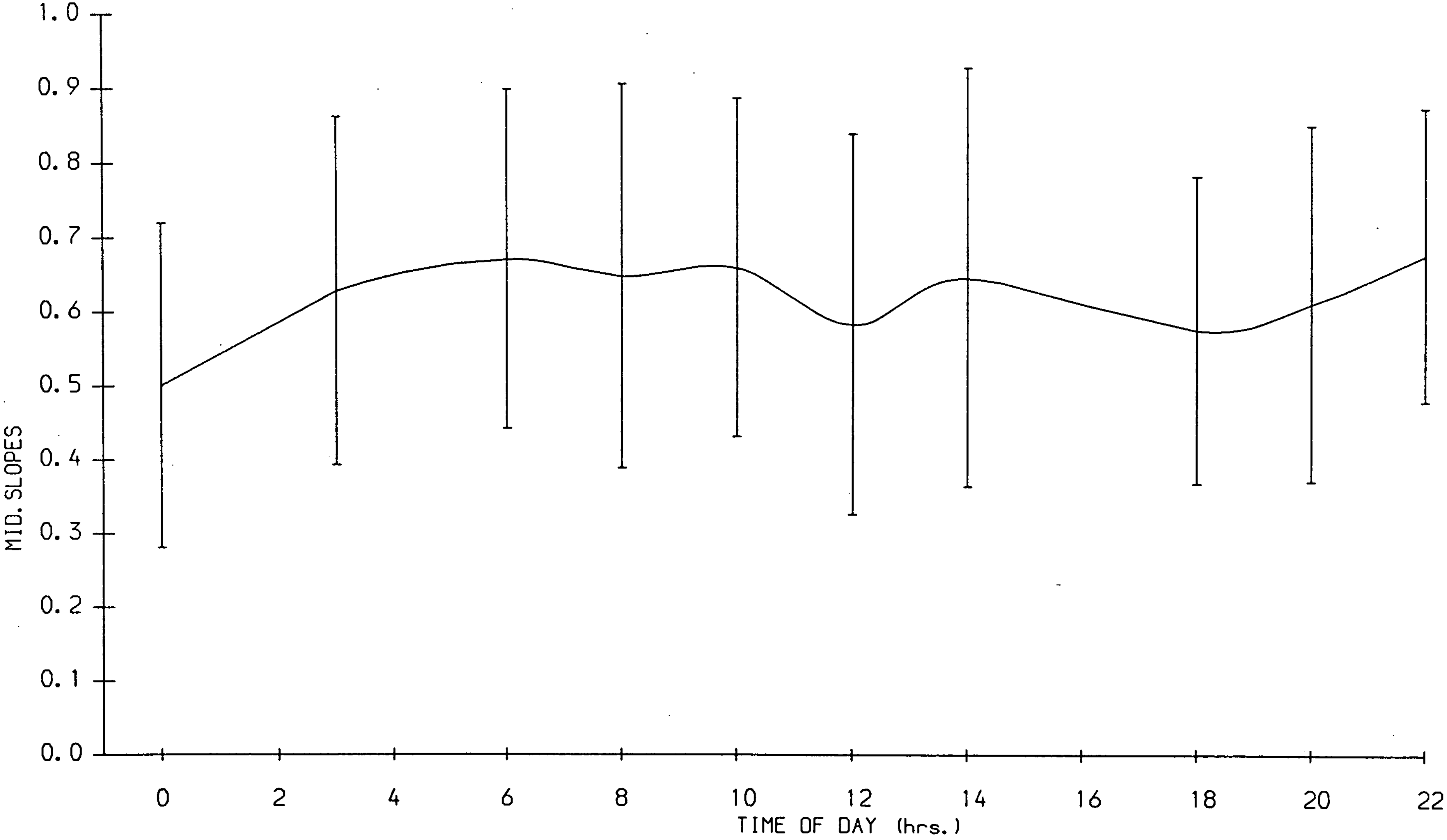


Figure 6.18 Normalised Mean and S.D. for Mid-slopes (patients)

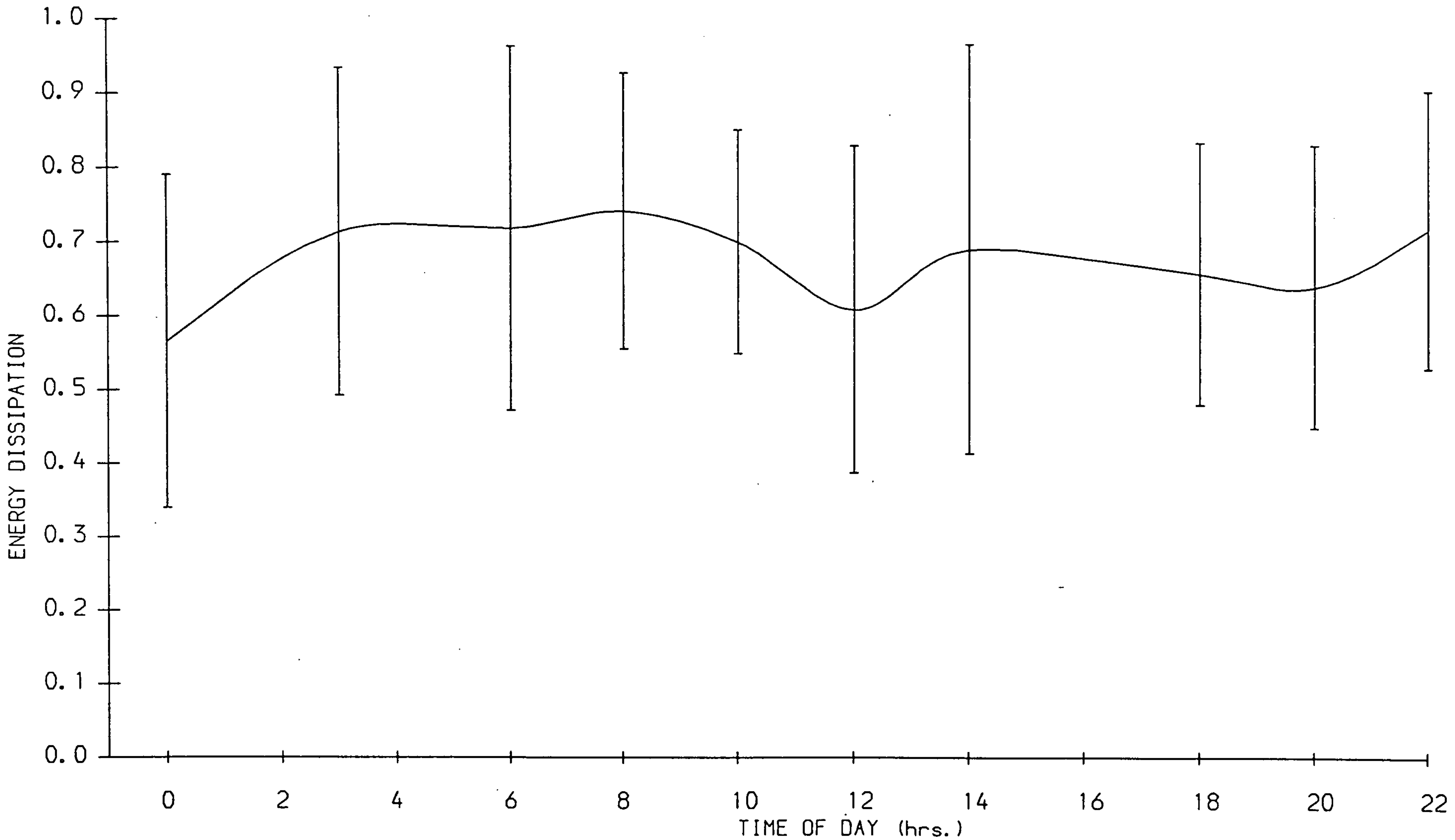


Figure 6.19 Normalised Mean and S.D. for Energy dissipation (patients)

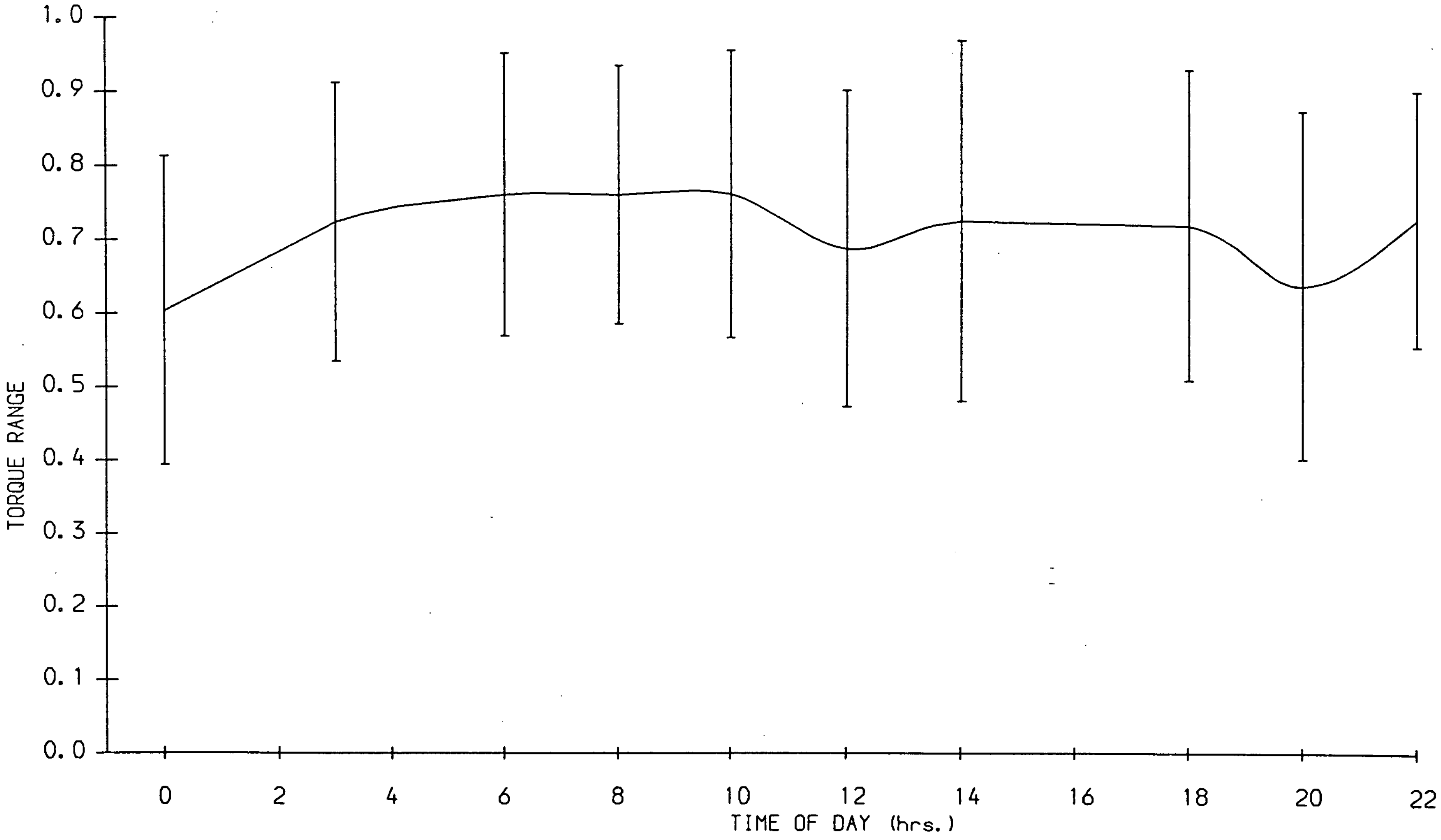


Figure 6.20 Normalised Mean and S.D. for Torque range (patients)

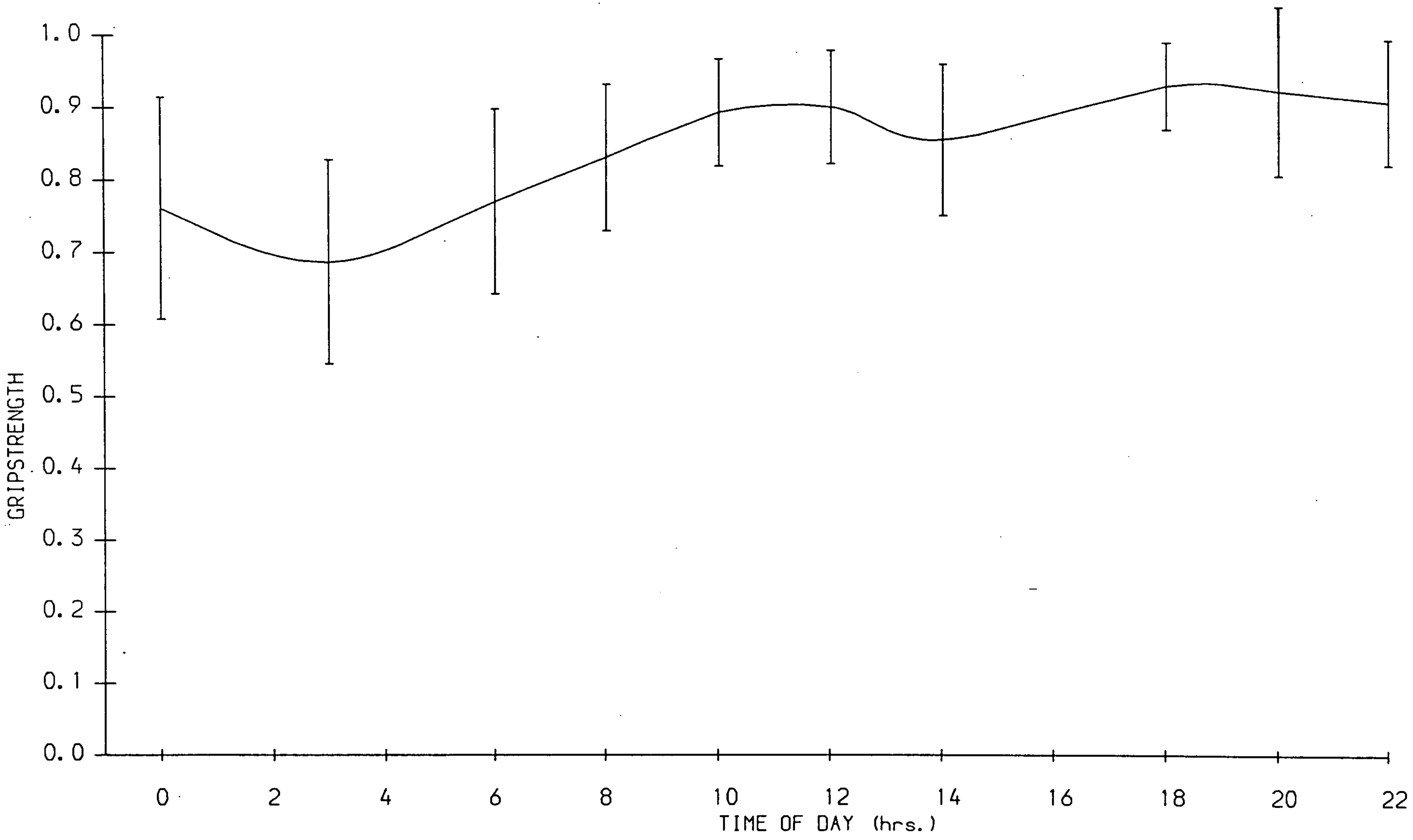


Figure 6.21 Normalised Mean and S.D. for Grip strength (patients)

6.9 Circadian variation of grip strength

On an individual basis the circadian variation of grip strength was much more consistent than that of joint stiffness. Minimum grip strength occurred between 2 and 4.00 a.m. in the majority of patients. The combined normalised results of figure 6. did not show any dramatic peaks and troughs probably due to the timing differences mentioned earlier. However, the small size of the error bands at midday suggested that circadian variation of grip strength did occur in arthritic subjects.

6.10 Comparison of grip machine and inflated bag

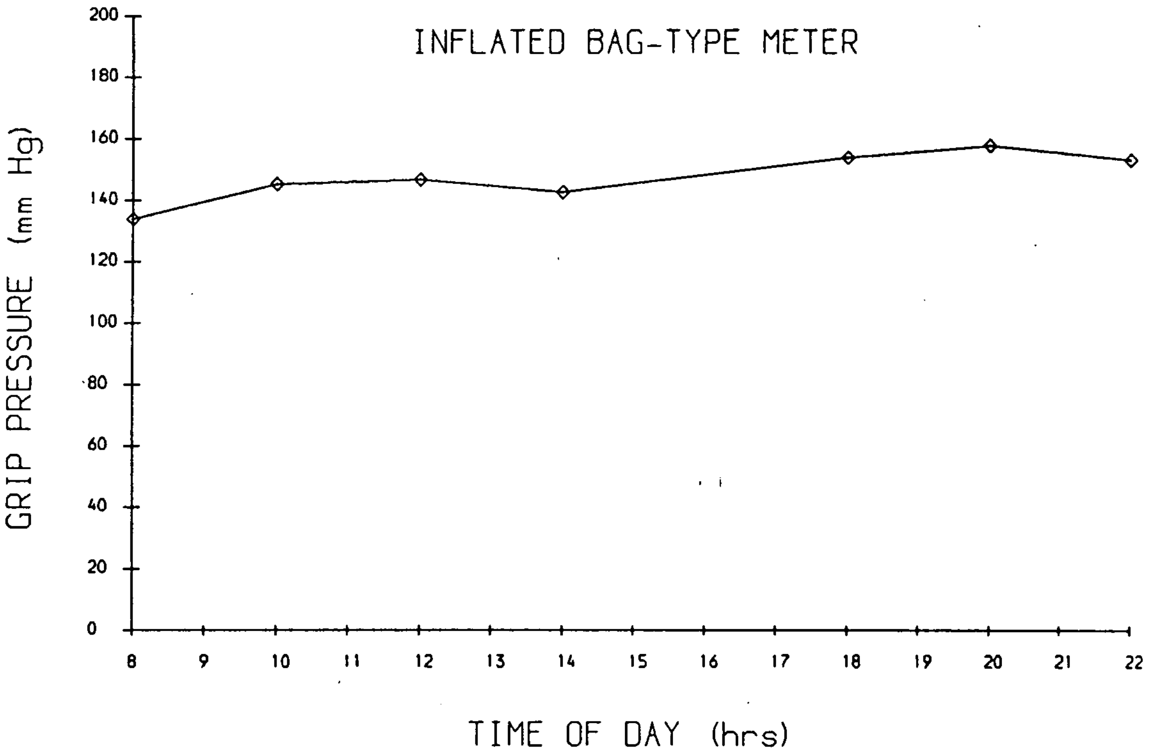
The grip machine was not available for use until the last series of tests and so the data from it cannot be used as part of the general circadian analysis. In the last series of tests some patients were tested using the grip machine as well as the inflated bag grip meter. Comparisons of the results obtained from each are shown in figures 6.22 and 6.23. The time axis in the figures is only shown from 8.00 a.m. to 11 pm. because it was found that the noise of the dot-matrix printer was extraordinarily loud in the quiet of a hospital ward in the early hours of the morning. This was one problem that was not anticipated in the design of the machine and in retrospect is an obvious flaw.

The results are however very interesting. It can be seen that maximum grip force appeared to be much more sensitive to changes in grip strength than did maximum grip pressure. In figure 6.22 the maximum grip force rises from a minimum at 8.00 a.m. to a maximum at 2.00 p.m.. In figure 6.23 the grip force was again minimum at 8.00 a.m. but increased progressively throughout the course of the day.

Only six patients were tested in this manner but the results were consistent. The grip machine appeared to be amplifying the changes exhibited by the inflated bag meter. The readings that were taken at 2.00 and 4.00 a.m. indicated that grip strength was minimal at these times but these were too few for any significance to be attached to the result.

It was noted that some patients were so weak they almost failed to register any force readings at all for some fingers. This suggested that it may be necessary in the future to improve the resolution of the grip machine if larger scale studies of arthritic patients are to be undertaken.

Figure 6.22 Comparison of grip machine and inflated bag meter.(1)



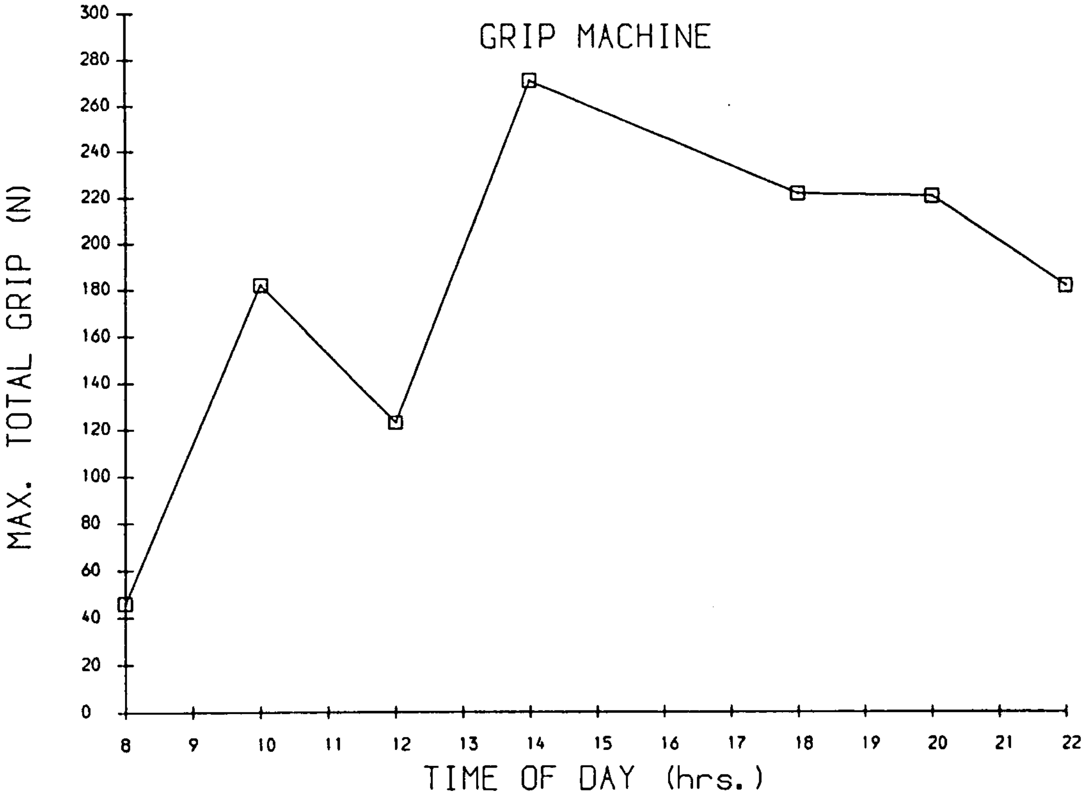
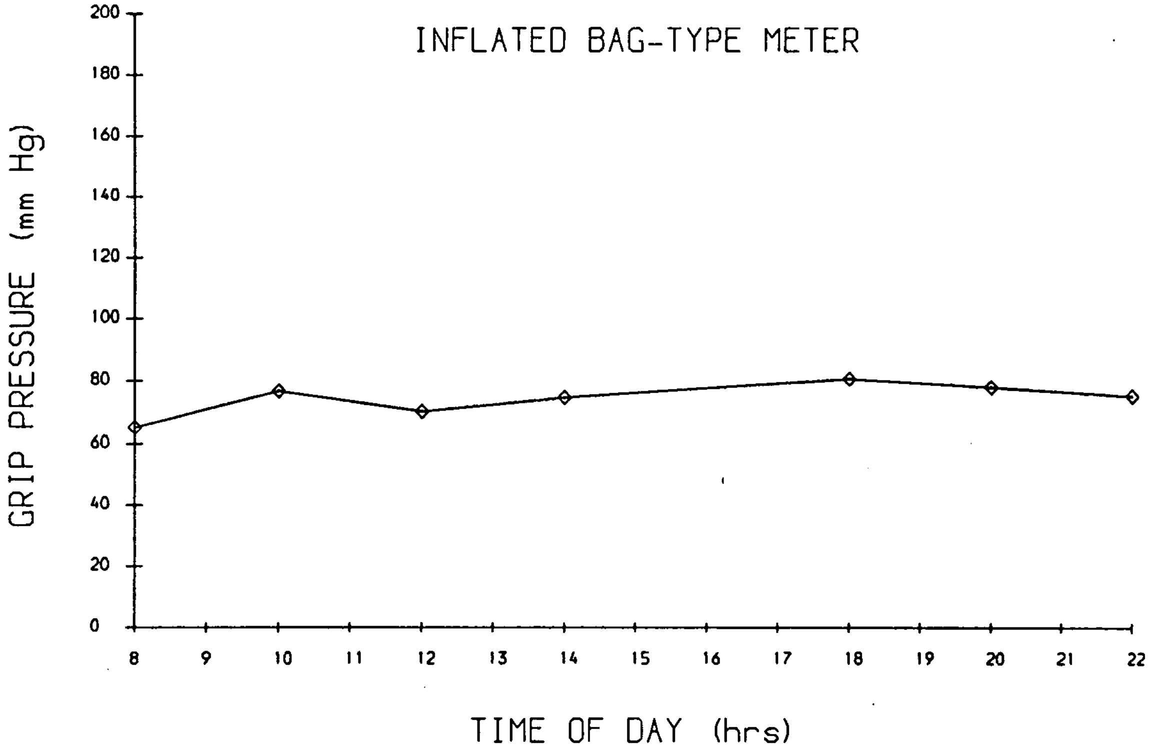
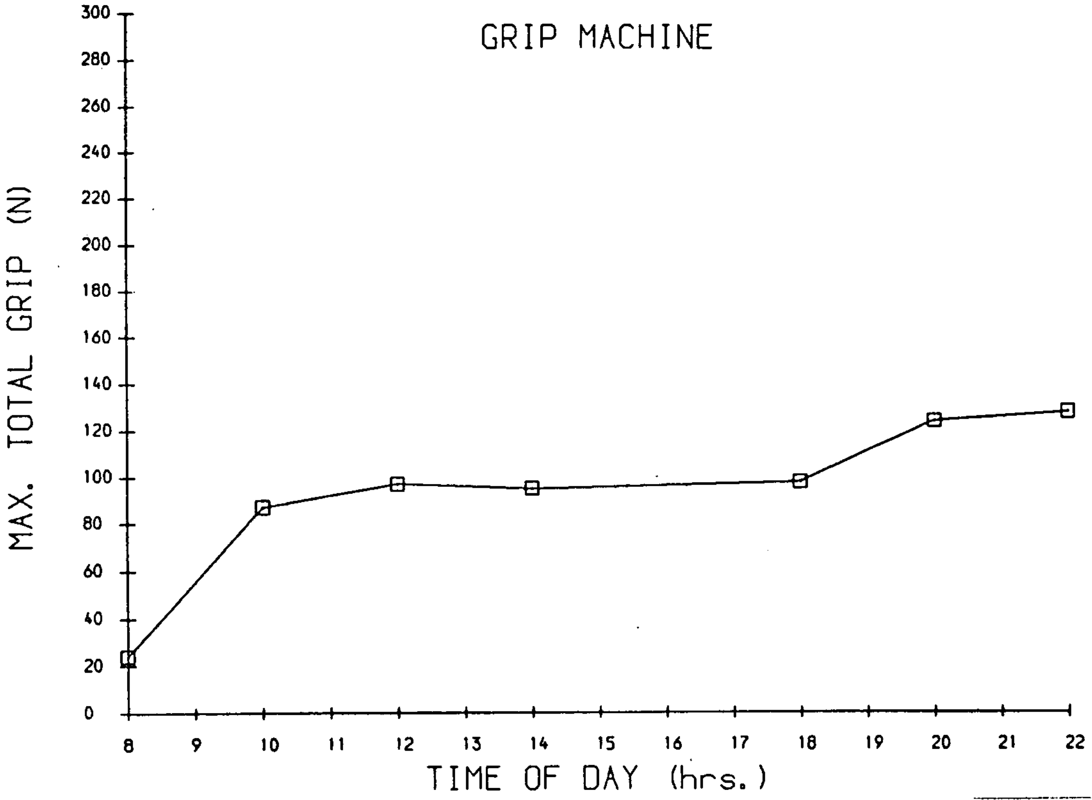


Figure 6.23 Comparison of grip machine and inflated bag meter.(2)





6.11 Comparison of the healthy and diseased groups

It has been shown that when individual results were combined no variation in joint stiffness was evident in either the diseased or the healthy group. However, this conclusion apart, it was apparent that the nature of the two sets of results differed greatly in other aspects. To highlight these difference, the absolute means and standard deviations, for each of the joint stiffness parameters, for each group, at 6.00 a.m., 12.00 noon and 6 p.m. are shown in table 6.4

Table 6.4 Mean and Standard deviations at key times

H.M - Healthy male

H.F. - Healthy female

Dis. - Diseased

Group	time	Torque range $\bar{x}$	S.D.	Mid-Slope $\bar{x}$	S.D.	Energy dissipation $\bar{x}$	S.D.
H.M.	06.00	57.6	21.0	0.89	0.30	8.41	2.40
H.F.	06.00	39.7	9.1	0.64	0.31	5.93	2.70
Dis.	06.00	110.6	63.9	1.70	1.27	17.1	13.0
H.M.	12.00	61.1	25.8	0.98	0.37	9.08	3.60
H.F.	12.00	40.7	11.1	0.63	0.22	6.34	1.89
Dis.	12.00	79.2	34.8	1.14	0.52	12.0	4.9
H.M.	18.00	51.6	18.5	0.94	0.40	8.71	3.09
H.F.	18.00	36.1	7.9	0.53	0.18	6.74	2.09
Dis.	18.00	79.3	25.6	1.30	0.94	15.2	9.7

By applying the variance ratio test (F test) to pairs of groups it was possible to determine whether the joint stiffness values for each group belonged to the same population of stiffness values.

The results of these calculations are summarised in table 6.5

Table 6.5 Degree of significance between the populations for each parameter

D v Hm - Diseased versus healthy male

D v Hf - Diseased versus healthy female

Hf v Hm - Healthy male v healthy female

Torque Range

Pair	0600	12.00	18.00
D v Hm	97.5 %	N.S.	N.S.
D v Hf	99 %	99 %	99 %
Hm v Hf	95 %	95 %	95 %

Mid. Slope

Pair	0600	1200	1800
D v Hm	99%	N.S.	95%
D v Hf	99%	95%	99%
Hm v Hf	N.S.	N.S.	90%

Energy dissipation

Pair	0600	1200	1800
D v Hm	99%	N.S.	99%
D v Hf	99%	97.5 %	99%
Hm v Hf	N.S.	90 %	N.S.

Clearly, significant differences did exist between all three groups. The differences between the healthy male and the healthy female populations were generally less significant than those between the diseased and healthy populations.

The mean stiffness values of the diseased group were higher than those of the healthy groups at all times and particularly so at 6.00 a.m.. This finding seems to be in contradiction to recent theories which suggest that stiffness levels in diseased and healthy groups are similar (Yung et al (1985), Helliwell et al (1987)). Perhaps the reason for this lies in the in the type of patients selected for this study. Wright et al (1969) observed that the joints of arthritic subjects with active R.A. were stiffer than healthy joints. It could be that more patients with active R.A. were tested here than in the studies of Yung or Helliwell. However, when the difference in means was tested statistically, it was found that none of the differences were significant at the 90% confidence level. This lack of statistical significance was attributed to the much higher variance of the stiffness parameters for the patient group as a whole.

6.12 Circadian variation of stiffness in healthy MCP joints

Previous work in this area has been conducted by Scott (1960), Backlund and Tiselius (1967) and Yung et al (1985). Of these, only Yung et al have shown any circadian variation in healthy MCP joint stiffness.

The only parameter which appeared to show any sizeable change at all in the present study was that of mid-position slope. There is some suggestion therefore that elastic stiffness may vary in healthy joints. However, the pattern of variation was inconsistent. Certainly, the striking changes in resistive torque and energy dissipation, in the early morning, observed by Yung et al, were not observed in any of the healthy subjects considered here.

Scott and Backlund and Tiselius did not take measurements over a full 24 hour period and so stiffness variation in the early morning is unknown for these two studies. Differences between the findings of Yung et al and the present study cannot be explained so easily, as in both cases testing was carried out over 24 hours.

Although an arthrographic technique was used by Yung et al, the test procedure was different to the one used here in that a number of small amplitude rotations were performed instead of one large oscillation. However, values of resistive torque were considered relative to the equilibrium position of the joint, which is the same basic principle as the present study. It is not felt that differences in experimental procedure can explain the obvious contradictions in the two sets of results.

The only consclusion that can be made is that the question of absence or presence of circadian variation in healthy joints remains unresolved. The results of this study agree with the findings of Scott and Backlund and Tiselius.

6.13 Circadian variation of stiffness in diseased MCP joints

A summary of previous work in this area was presented in chapter 2 (table 2.2). Only Helliwell et al (1987) have concluded that no circadian variation of stiffness occurs in diseased joints. The combined results, presented here, agree with this consclusion. However, individual results suggested that circadian variation of joint stiffness did occur but that the pattern of variation was not consistent from one individual to another.

The only other study of any reasonable size was that of Ingpen (1968). Helliwell et al commented that the test method of Ingpen was difficult to evaluate biomechanically. The inability of it to distinguish between elastic and dissipative effects has been discussed in this text (section 2.1.3). Whilst interpretation is difficult, the results of Ingpen are still of interest. He showed that fall times of diseased joints were significantly increased in the morning compared with the rest of the day. This implies that either diseased joints were less elastic in the morning or that dissipative effects within them were greater.

Presumably, arthrographic studies of the patients tested by Ingpen would have shown a decrease in mid-position slope in the early morning or an increase in energy dissipation. In the present study some patients exhibited increased energy dissipation in the early morning. This could be the same phenomenon that was observed by Ingpen.

It has been shown in this study that pronounced circadian stiffness variation, in all parameters, occurred in a small number of subjects. These subjects appeared to be those with the stiffest joints. The results of patient number six, shown in figure 6.14, are a particularly good example of this observation. In view of the discussions in section 6.11, one explanation of this observation is that patients with particularly active R.A. are likely to experience more significant changes in joint stiffness than those patients in whom the disease is less active. Further experimentation with carefully selected patients groups is necessary to confirm this observation.

No obvious relationship was observed between changes in joint stiffness and changes in grip strength, even in those patients with a pronounced variation in joint stiffness. Therefore, it seems possible that circadian variations of joint stiffness and grip strength are two separate phenomena. However, it should be noted that the ability to measure significant changes in grip strength, in patients that were very weak, was limited.

In contrast with the present study, Helliwell et al did not report any significant individual variation in joint stiffness. The reasons for this disagreement can possibly be explained by three factors.

Firstly, the planes of motion considered for the stiffness measurement were not the same. Helliwell oscillated the MCP joint in the adduction/abduction plane not flexion/extension. The stiffness of many materials is not the same along different axes and there is no reason to suppose that joint stiffness characteristics should be the same in perpendicular planes.

Secondly, the oscillations of Helliwell were of amplitude 4 degrees and frequency 0.2 Hz, whereas those of the present study were 20 degrees and 0.1 Hz. The response of a simple viscoelastic joint model to harmonic oscillations has been shown to be heavily dependent upon amplitude and frequency of oscillation. For one model, energy dissipation was shown to vary with the square of the amplitude. The small magnitude of a parameter, such as energy dissipation, resulting from a small amplitude oscillation, may therefore make observation of any changes in it difficult.

Thirdly, the passive properties of muscle have been shown to be important in stiffness measurements in the flexion/extension plane. The muscles of the forearm, stretched during flexion/extension are considerably larger than the intrinsic muscles which are stretched in adduction/abduction. Any changes in the passive stiffness properties of muscle may be expected to cause greater changes in the overall joint stiffness measurement in the flexion/extension plane.

In addition to these three factors, there is no way of knowing whether the level of disease activity in the patients considered by Helliwell was the same as those of the present study. It is suggested that the patients considered in the present study may have been more severly affected by arthritic disease.

6.14 Morning Stiffness

The vast majority of patients tested complained of morning stiffness. As variations were observed in both joint stiffness and grip strength it is not possible to say which of these may be the predominant factor in the subjective feeling of morning stiffness. It could be that morning stiffness is a combination of increases in joint stiffness and decreases in grip strength. However, the lack of correlation between joint stiffness and grip strength suggests that this is not the case.

The grip results of patient eighteen, the control, shown in figure 6.19, and the results of Scott (1960) and Wright and Plunkett (1966) suggest that grip strength does vary in healthy subjects in a similar manner to those subjects with diseased joints. If circadian variation is not present in healthy joints, then there is a possibility that the feelings of morning stiffness voiced by arthritic subjects may be more closely associated with changes in joint stiffness rather than grip strength.

From the point of view of 24 hour drug trials, objective measurement of joint stiffness and grip strength would both appear to be of use in providing corroborative evidence of any alleviation of arthritic symptoms. Furthermore, there is a possibility that changes in grip strength and joint stiffness are related to different physiological changes. For example, decreases in grip strength may be closely associated with increases in pain. Measurement of both quantities during a drug trial may help to distinguish between whatever mechanisms cause these physiological changes.

CHAPTER SEVEN

INVESTIGATION OF SHORT AND LONG TERM EFFECTS OF PHYSIOTHERAPEUTIC TREATMENT

7.1 Introduction

Physiotherapy has an important part to play in the management of the arthritic patient. Wright and Haslock (1977) describe this form of treatment as 'the application of physical aids and forces to reduce pain and to maintain or improve function'. The same authors also comment that out-patient physiotherapy for rheumatic patients is of questionable value because of the exposure to cold weather and the stresses of travelling. However, it still seems to be common practice and the hand clinics at Middlesbrough General Hospital, where the majority of the following experiments were undertaken, were invariably busy.

The improvement of the stiffness of diseased joints is but one aspect of the wide area of pain reduction and functional improvement but never the less an important factor. For example, it is usually desirable that as fuller a range of movement as possible is restored and the hand is generally in good condition before any surgery is undertaken (Wynn Parry 1966).

Nichols (1980) stated that 'rheumatoid arthritis presents a challenge in general and specific management and emphasizes the need for close cooperation between physician, surgeon, and all those concerned with rehabilitation.'The aims of this type of cooperation are:-

(1) Relief of pain

(2) Prevention of deformity

(3) Correction of existing deformity

(4) Improvement of functional capacity

(5) Control of systemic manifestations

During the acute phase of R.A. the physiotherapist can be of some assistance by immobilizing the joint with splints and as disease activity subsides more active forms of treatment can be introduced. The common forms of treatment, used at the hand clinic at Middlesbrough General Hospital, that form the basis of this study, will now be discussed in more detail.

7.2 Different types of treatment

The effects of four different forms of physiotherapeutic treatment were investigated, all of which were commonly in use at the out-patient hand clinic at Middlesbrough General Hospital. These were ; hot wax, pulsed ultrasound, active and passive exercise and wax and ultrasound together.

Hot Wax

Wax baths are commonly used for the treatment of rheumatoid hands. The patient's hands are coated by repeatedly dipping in a bath of molten paraffin wax. These are then wrapped in terry towels to provide insulation. The idea behind this method is that the latent heat of solidification of the wax will be transferred to the underlying tissues and that this heat transferrence will have some sort of beneficial effect.

Ultrasound

Ultrasonic transducers utilise the piezoelectric effect to produce high frequency soundwaves. Most ultrasound machines provide for either continuous or pulsed production of the sound waves. When applied to joints the ultrasonic transducer is held in close contact with the joint, usually with water or jelly as a couplant to eliminate air. The sound waves cause the underlying tissues to oscillate and the resulting periodic tensioning and compression of tissue layers has led to the term 'micromassage 'being used to decribe this form of therapy.

In continuous operation there is also a localised heating effect. Pulsed operation is meant to allow the heat to disperse during the 'off 'period.

In this study the ultrasound was applied in pulsed form in the ratio 1:4 (on/off), at a frequency of 1 MHz, for a period of three minutes and administered to the joint in a thermostatically controlled water bath. The temperature of the water was maintained at 35 degrees centigrade.

Wax and Ultrasound

Some patients attending the clinic regularly received both forms of the aforementioned treatments. For the purposes of experimental consistency it was ensured that the hot wax treatment was always administered prior to the ultrasound therapy.

Active and passive exercise

Passive exercise involved gentle but frequent flexion and extension of the patient's finger joints by the attending physiotherapists. Patients were also encouraged to perform their own active exercises which involved gripping of soft rubber objects or precision handling.

Performance of these exercises was common to all patients attending the hand clinic, including those receiving other forms of therapy. Therefore, the results from the group of patients who received exercise alone form a background upon which all the other physiotherapeutic regimes should be judged.

7.3 Aims

The beneficial effect of forms of heat treatment are by no means certain, due to the lack of any objectively based measurement technique. Attempts to draw general conclusions about different forms of physiotherapy by investigating joint stiffness alone are clearly inadequate. There are many other factors such as pain, muscle strength and psychological factors which are mediated to some degree by physiotherapy. However, if the treatment regimes are to be based on some rational basis, objective quantification needs to be introduced and this investigation is a step in this direction. Following the work of Yung et al (1984) in which the short term effects of different forms of physiotherapeutic treatment were investigated, it was decided to extend this research by investigating both short and long term effects of different forms of treatment on passive MCP joint stiffness.

7.4 Problems and patients

The problems of devising an experimental protocol in an area with so many uncontrollable variables are great. These problems in themselves should not, however, prevent meaningful and important experimentation from being undertaken. General conclusions can be only be made if the limitations of the experiment are understood and taken into account in the stage of results analysis.

The experiments described in this chapter were performed on subjects of different ages, different sex and at different stages of disease activity, all of whom were subjected to a wide range of circumstances outside of the more controlled environment of the hospital. For example, one major difference would be the mode of transport which was used by the patients to attend the out-patient clinic. Some patients arrived by ambulance, others by car and others by public transport. The effects of any of these modes of transport on the passive stiffness of joints is extremely difficult to assess but it seemed sensible to assume that the exposure to different environments should have some part to play in the pre-treatment state of the joint being tested.

Other external factors include different courses of drug therapy, administered but taken in parallel with the course of the physiotherapy, different levels of diligence in performing exercises at home and other unknown psychological conditions that may influence the course of disease activity. However, close control of test conditions and procedures should help to reduce some of the inherent variability of the experiments and give some basis for rational deduction.

The patients were assessed by the physiotherapist on first attendance at the out patient clinic and the type of treatment was not changed thereafter, for the particular series of visits at least. Thus the patients in each treatment group were not a true random sample but to some extent preselected according to subjective observation. It is necessary therefore to examine the significance of the differences between the treatment groups prior to any treatment.

Firstly it is necessary to establish whether or not the patients in each treatment group truly belonged to the same population. Although, on first reflection this may appear to be a reasonable assumption to make it must be remembered that arthritic disease by its very nature is continuous, variable and unpredictable. The disease activity in the patients attending the clinic could be either active or stable and structural or functional damage to the joints may or may not have been present. Other possible differences were the length of time the patients had had the disease, a difference in the spread and mean values of ages between different treatment groups and differences in the ratio of female to male patients. Thus, in the the tables that follow the composition of each treatment group will be presented.

Table 7.1 Distribution of age, sex, hand dominance and disease types within the treatment groups.

Treatment group : Wax plus pulsed ultrasound

Variable	Number
No. of patients	13
Age range	25 - 81 yrs
Mean age	54.8 yrs
Sex ratio F:M	10 : 3
R.A.	11
O.A.	2
Others	-
Dom. hand ratio R:L	11: 2

Treatment group : Wax alone

Variable	Number
No. of patients	10
Age range	37 - 84 yrs
Mean age	57.8 yrs
Sex ratio F:M	8 : 2
R.A.	6
O.A.	1
Others	3
Dom. hand ratio R:L	8 : 2

Treatment group : Pulsed ultrasound alone

Variable	Number
No. of patients	11
Age range	17-74 yrs
Mean age	45.27 yrs
Sex ratio F:M	11 : 0
R.A.	7
O.A.	1
Others	3
Dom. hand ratio R:L	10: 1

Treatment group : Active and passive exercise

Variable	Number
No. of patients	6
Age range	46 - 66 yrs
Mean age	55.83 yrs
Sex ratio F:M	3 : 3
R.A.	4
O.A.	-
Others	2
Dom. hand ratio R:L	5 : 1

It can be seen from table 7.1 that although the compositions of each treatment group were not an exact match they did exhibit broad similarities. The mean age of the patients was within ten years and the range of ages within the groups was quite large and the standard deviation small. Rheumatoid arthritis was the predominant disease, females were the predominant sex and the right hand was usually used in preference to the left. From these data it seems reasonable to assume that the variables presented will not prevent sensible deductions from being made between the groups. However, this is not the whole story. If one form of treatment was shown to be beneficial or otherwise to the passive stiffness of the joint in contrast with the others it must first be demonstrated that initial condition of the joints, prior to any treatment, were not significantly different from those in the other groups. Thus, the variability of the joint stiffness parameters within each group will now be presented.

Table 7.2 Mean, SD, and variance of stiffness parameters of the treatment groups prior to treatment.

Stiffness parameter : Torque range (T.R.) : units $Nm \times 10^{-3}$

n - number, $\bar{x}$ - Mean, S_x - Standard deviation, S_{x^2} - Variance.

Group Parameter	Wax + Pus T.R.	Wax T.R.	Pus T.R.	Ex. T.R.
n	10	10	10	6
$\bar{x}$	90.6	61.4	84.5	82.4
S_x	34.4	26.0	55.1	52.5
${S_x}^2$	1181	677	3037	2760

Stiffness parameter : Mid. slope (Mid. sl.) : units $\frac{Nm}{deg} \times 10^{-3}$

Group Parameter	Wax + Pus Mid. sl.	Wax Mid. sl.	Pus Mid. sl.	Ex. Mid. sl.
n	10	10	10	6
$\bar{x}$	1.31	0.85	1.41	1.18
S_x	0.70	.57	1.13	0.72
${S_x}^2$	0.49	0.32	1.28	0.52

Stiffness parameter : Energy dissipation (E.D.) : units $J \times 10^{-3}$

Group	Wax + Pus	Wax	Pus	Ex.
Parameter	E.D.	E.D.	E.D.	E.D.
n	10	10	10	6
$\bar{x}$	9.58	7.62	10.92	11.39
S_x	2.82	4.44	8.33	9.43
${S_x}^2$	7.9	19.7	69.4	88.9

7.5 Statistical analysis of the Pre-treatment parameters

The natural statistical test to apply to the pre-treatment data would be a comparison of the mean values between each group using the one-sided Student's t statistic. Before this test can be applied it must be ensured that the samples being compared have standard deviations which belong to the same population of standard deviations. If two samples were compared then the well known variance ratio test (F-test) would suffice, but for multiple variances a test for homogeneity known as Bartlett's test can be applied. Essentially this is a special application of the Chi squared test (a full explanation is given in Kennedy and Neville, 1976). and has the rather complicated form below:-

$$\chi^2 = 2.3026\Big[\log \bar{s}^2 \times \sum(n_i - 1) - \sum(n_i - 1)\log {s_i}^2]\Big]$$

where, n_i is the sample size for a particular group, $\bar{s}^2$ is the pooled estimate of variance, and ${s_i}^2$ is the estimate of variance of a particular group. When chi squared was calculated in this manner the following results were obtained:-

Table 7.3 Testing of the homogeneity of variances of the pre-treatment parameters

Parameter	Torque range	Mid. Sl.	Energy dissip.
χ^2	5.99	4.79	12.66

The number of degrees of freedom for this test is the number of sample being compared minus one. In this this case the chi squared values for three degrees of freedom are the ones of interest.

From statistical tables :-

D. of f	$p = 0.10$	$p = 0.05$	$p = 0.01$	$p = 0.001$
3	6.25	7.81	11.34	16.27

From these results it was concluded that the variances for the parameters of torque range and mid. slope were homogeneous but the variances for the energy dissipation parameter were not. Therefore the one sided t test can be used for the comparison of the mean values of the first two parameters but for the comparison of energy dissipation a different approach must be adopted.

7.5.1 Calculation of the t statistic

The t values in the table below have been calculated in the following manner :-

$$t = \frac{|\bar{x}_1 - \bar{x}_2|}{s_d}$$

where,

$$s_d = s_c\sqrt{\frac{n_1 + n_2}{n_1 n_2}}$$

and,

$$s_c^2 = \frac{s_1{}^2(n_1 - 1) + s_2{}^2(n_2 - 1)}{(n_1 - 1) + (n_2 - 1)}$$

The number of degrees of freedom is given by:-

$$(n_1 - 1) + (n_2 - 1)$$

where $\bar{x}_i$, n_i and s_i are the mean, number and standard deviation of sample i.

Table 7.4 Values of the single sided t statistic for comparison of mean values of parameters between each treatment group

Parameter being compared : Torque range

Group	Wax + Pus	Wax	Pus	Ex.
Wax + Pus	-	2.03	0.28	0.35
Wax	2.03	-	1.14	1.00
Pus	0.28	1.14	-	0.07
Ex.	0.35	1.00	0.07	-

Parameter being compared : Mid. slopes

Group	Wax + Pus	Wax	Pus	Ex.
Wax + Pus	-	1·60	0·24	0·28
Wax	1·60	-	1·39	1·0
Pus	0·24	1·39	-	0·44
Ex.	0·28	1·0	0·44	-

When these values for t were compared with tabulated values for the appropriate degrees of freedom it was found that the only significant difference between any of the parameters was that of torque range between the treatment groups of wax and wax plus ultrasound. This parameter was significantly different at $p = 0.10$. Clearly, this finding must be taken into consideration in any subsequent analysis of differences between the wax and wax plus ultrasound treatment groups.

It was established that the variances of the energy dissipation parameter were not homogeneous and as this is an implicit assumption in the Student's t-test then the means are analysed by an alternative method.

7.5.2 Case of non-homogeneous variances

The ratio of the standard deviation of the two sample means $s_{\bar{x}_1}$ and $s_{\bar{x}_2}$ is considered in determining the significance of the difference of the means. The difference is considered significant if :-

$$\frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{{s_{\bar{x}_1}}^2 + {s_{\bar{x}_2}}^2}} > d$$

Where d is obtained from tables using the two degrees of freedom of the sample means and the ratio of the sample mean variances (Kennedy and Neville pages 213-214).

When this test was carried out between each of the treatment groups it was found that the energy dissipation parameter was not significantly different ($p = 0.10$) between any of the groups prior to treatment.

7.5.3 Observations on the Pre- treatment state of each group

The method of selection of the patients for each treatment group was based on the previous experience of the physiotherapists at the hand clinic. Therefore it may have been expected that the groups would differ significantly. Excepting one joint stiffness parameter, between two treatment groups only, this has been shown not to be the case.

7.6 Control experiments

The hand clinics were held in the afternoon, commencing usually at 1:30 pm. and finishing at around 4:30 to 5.00 pm depending on the number of patients treated during the particular afternoon. On each attendance at the hand clinic the patient was tested once before treatment and then again immediately after treatment. The average duration of the treatment period was 30 minutes and thus this was the average inter-test interval. For the analysis of short term effects of treatment to be meaningful the natural variation of the joint stiffness parameters at this time of day, over the same test interval, had to be investigated.

A number of arthritic patients, receiving no physiotherapeutic treatment, were tested in a similar manner to those patients receiving physiotherapy. These control experiments were conducted at approximately the same time of the day with an interval of thirty minutes between test one and test two. The data resulting from the controls is given in table 7.5.

To be absolutely sure that legitimate comparisons could be made between the control and treatment groups, the variances and mean values of the control group were compared with each of the treatment groups in the same manner as has already been described. The results of this comparison were that no significant differences existed between the control group and any of the treatment groups for any parameter. The means and spread of the first test parameters for each group are shown graphically in figures 7.1, 7.2 and 7.3.

As the data for the control experiments were truly paired, a paired Student's t-test, in which the difference between the values in any one pair is taken as the variable, could be used. Table 7.5 shows that there was no significant difference between the first and second test values indicating that natural variation in joint parameters would not lead to erroneous conclusions being drawn from the short term analysis of the treatment groups.

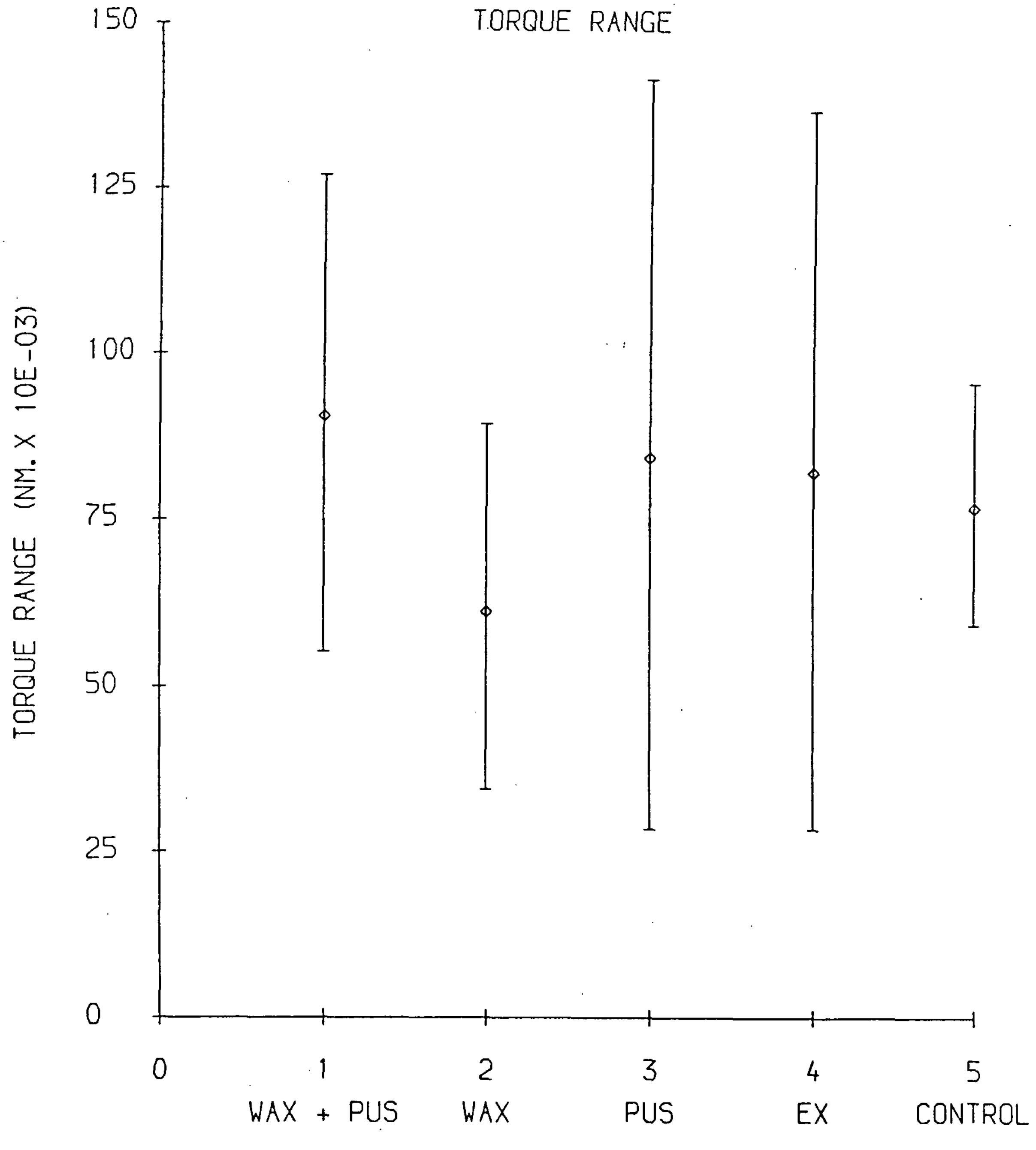
Table 7.5 Data from physiotherapy control experiments

Subject	Test no.	Torque range ($NM \times 10^{-3}$)	Mid.sl. ($\frac{NM}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
1	1	66	1.0	8.0
	2	80	1.0	9.0
2	1	92	1.2	18.0
	2	132	1.8	14.5
3	1	98	2.3	11.0
	2	76	1.2	6.0
4	1	74	1.0	8.5
	2	68	0.9	9.0
5	1	81	1.2	11.5
	2	86	0.9	10.0
6	1	92	1.8	9.5
	2	73	1.2	9.0
7	1	104	1.6	19.5
	2	173	2.6	18.5
8	1	69	1.2	7.5
	2	76	0.9	10.0
9	1	57	0.9	5.0
	2	40	0.7	5.5
10	1	51	0.7	7.5
	2	77	1.2	8.0
11	1	90	1.5	10.0
	2	105	1.3	9.0
12	1	66	0.9	8.0
	2	66	1.0	9.0
13	1	65	0.9	6.0
	2	54	0.8	6.0
$\bar{y}$		-7.77	0.054	0.42
S_y		25.88	0.535	1.81
$S_{\bar{y}}$		7.18	0.148	0.50
t (paired)		1.08	0.36	0.84
D of f		12	12	12

Where:
y is the difference variable between the first and second readings.
$\bar{y}$ is the mean of y.
S_y is the standard deviation of y.
$S_{\bar{y}}$ is the standard deviation of $\bar{y}$.
t is the Student t statistic for paired data.
D of f is the number of degrees of freedom for the test.
For twelve degrees of freedom, statistical tables for Student t give the following values:-

D of f	$p = 0.10$	$p = 0.05$	$p = 0.01$
12	1.78	2.18	3.06

Figure 7.1 Mean and standard deviation of the torque range parameter for each of the treatment groups prior to any treatment.



RANGE LIMITS , PLUS AND MINUS ONE STANDARD DEVIATION

Figure 7.2 Mean and standard deviation of the energy dissipation parameter for each of the treatment groups prior to any treatment.

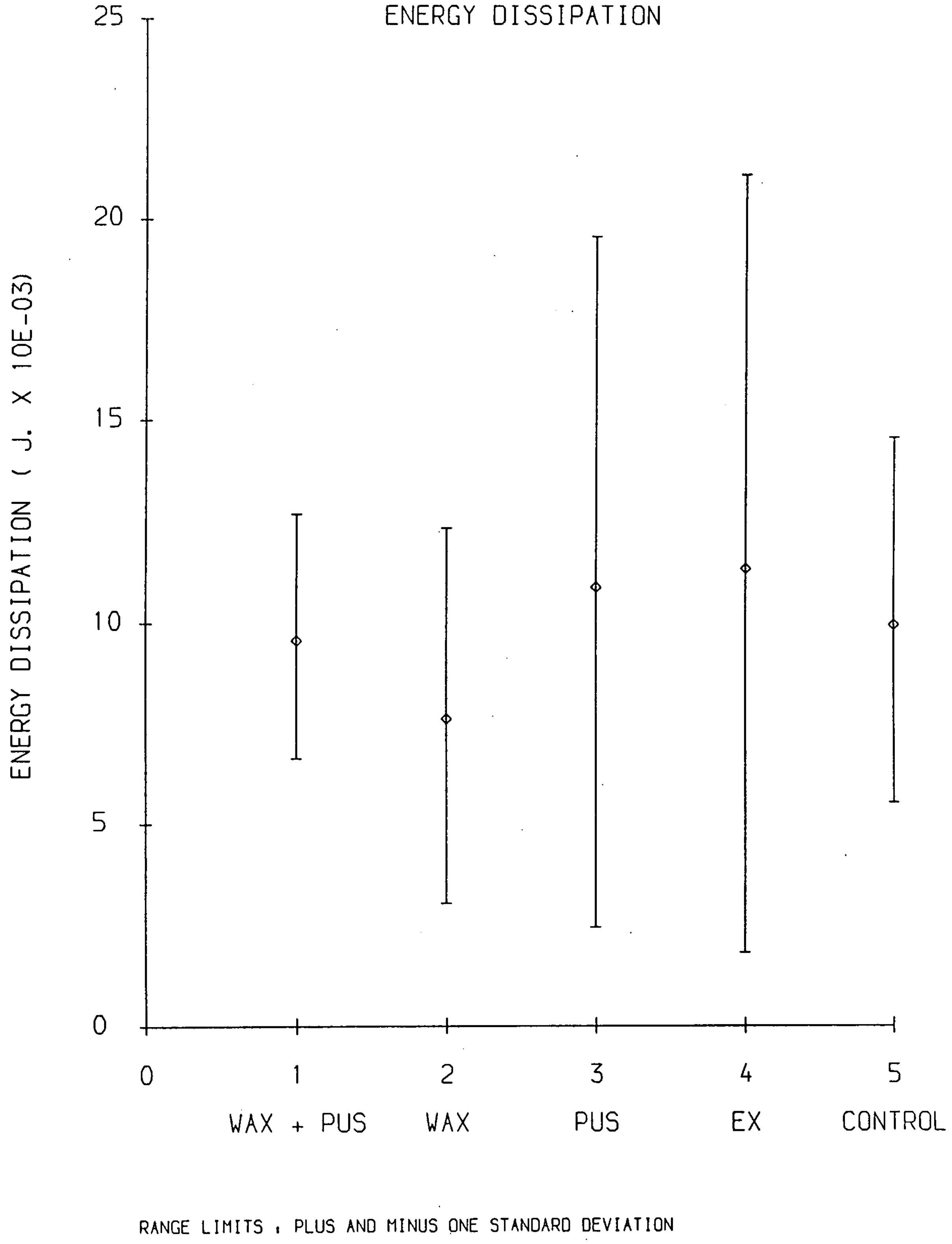
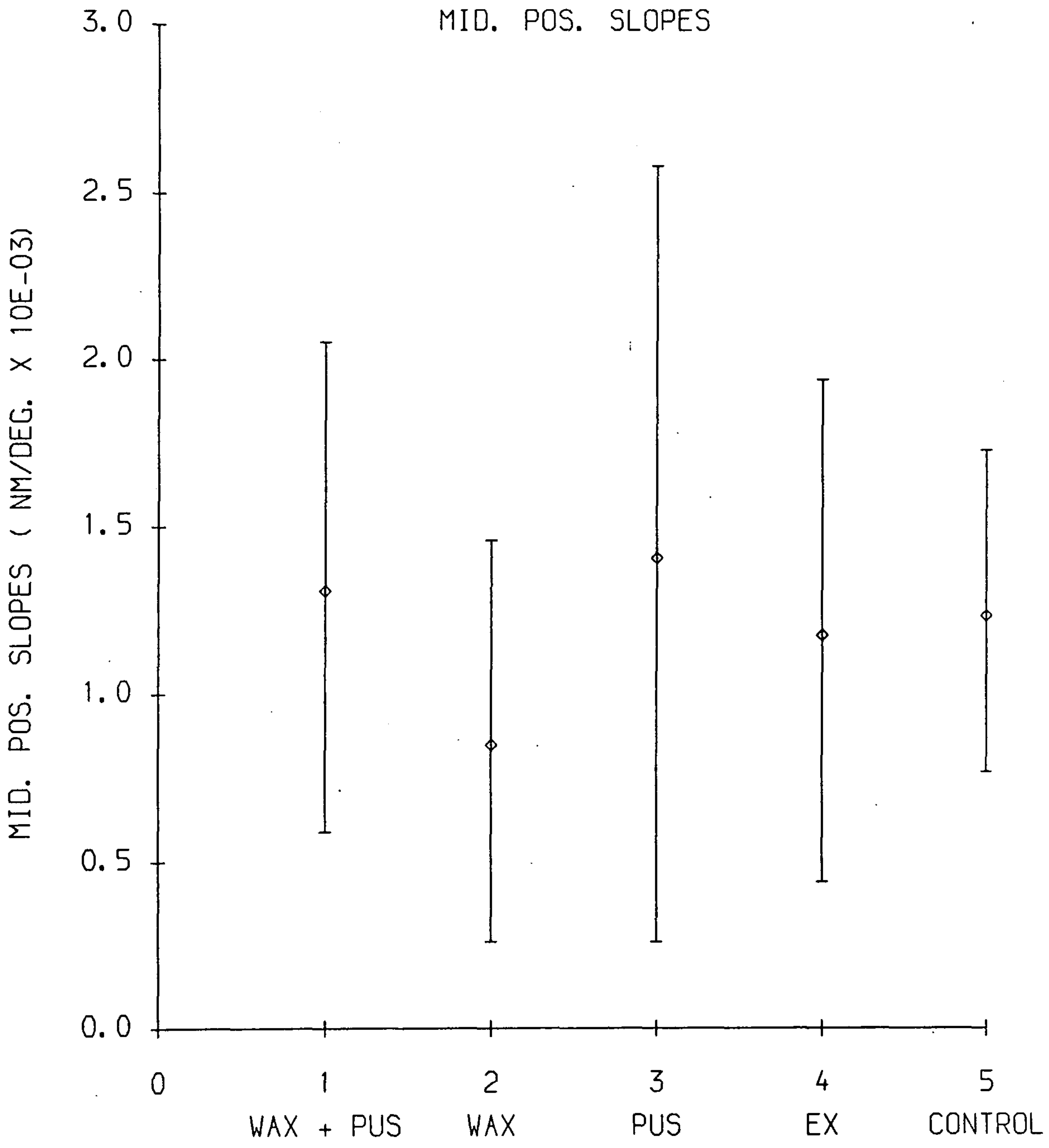


Figure 7.3 Mean and standard deviation of the mid. slope parameter for each of the treatment groups prior to any treatment.



RANGE LIMITS : PLUS AND MINUS ONE STANDARD DEVIATION

7.7 Results from the treatment groups

The patients were tested for the duration of their attendance at the out-patient clinic. The period and frequency of treatment varied according to how well the patient appeared to respond to the treatment. Thus, some patients were tested twice a week for a period of six or seven weeks and some were tested once a week for three or four weeks. Such a discrepancy in the amount of treatment between patients was a problem when trying to analyse the long term effects of the different treatments. Therefore in the analysis which follows only those patients who attended the clinic for a minimum of five weeks will be considered. Each of the treatment groups will now be examined individually.

7.8 Hot wax and pulsed ultrasound

7.8.1 Qualitative analysis of some Typical results

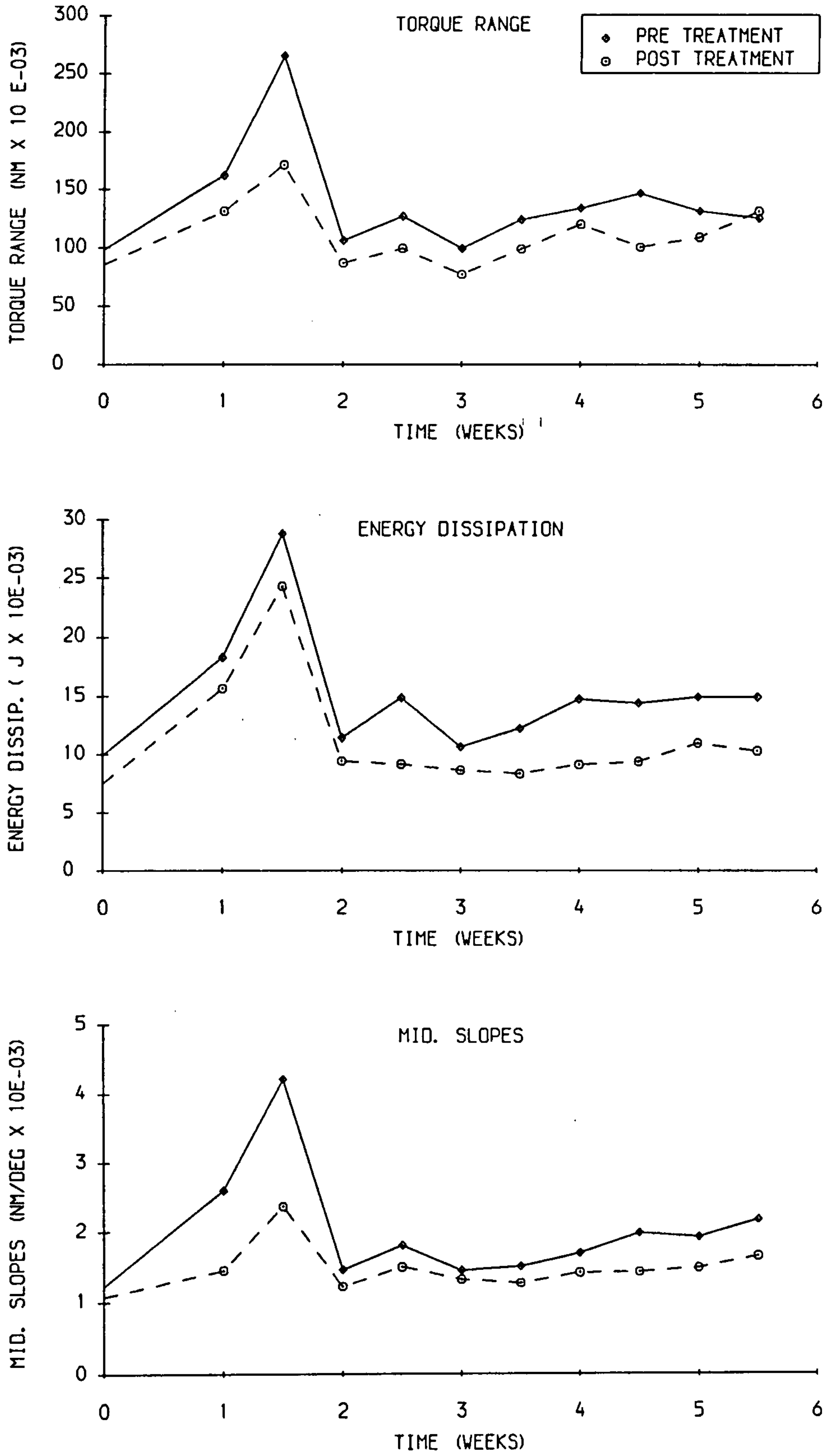
The results from some of the patients will be analysed in more detail and have been selected to give an idea of the spectrum of results obtained from this particular group. The patients numbers referred to are taken straight from the data records and thus are not sequential.

Patient one

The results from patient number one are presented in figure 7.4. This patient is a 59 year old male, predominantly right handed who had been suffering from R.A. in both hands for a period of at least six years. He had undergone synovectomies for the MCP and PIP joints and also for both wrists. At the time of the first test, prior to any treatment, patient one complained of stiff PIP and DIP joints but felt that his MCP joints were in relatively good condition although pain was present when flexing the fingers of the right hand.

Figure 7.4 shows that there was a consistent reduction in each joint parameter after each treatment session. However, this short term reduction was not carried forward from one session to the next and after the total period of treatment none of the parameters was significantly changed. The large peak at one and a half weeks perhaps serves to emphasise the variability of arthritic disease with its periods of exacerbations and remissions. It is interesting to note that when the peak occurred the effectiveness of the treatment in reducing the parameters torque range and mid. slope appeared to be considerably enhanced.

Figure 7.4 Stiffness pre/post treatment : Patient One : WAX + PUS



Patient Three

The results presented in figure 7.5 are from a right handed 59 year old female who was suffering from osteoarthritis, particularly in the wrists and the PIP joints. The purpose of the physiotherapy treatment was to increase the range of movement of all the joints of the hand, particularly both thumbs which were restricted in flexion/extension and also abduction/adduction and to reduce the pain in both hands and wrists. Patient three had experienced pain for the past two years but felt that the level had increased considerably over the last two months prior to initial test.

The 'lazy tong 'character of the graphs in fig.7.5 indicates that the treatment had an inconsistent short term effect on any of the joint stiffness parameters. There appeared to be a slight reduction pre/post treatment during the first four sessions but the magnitude of the change was of, or within, the order of repeatability of the test itself. Comparison of the joint parameters before and then after the full treatment period shows a similar result to subject one, ie. no change.

Patient five

This patient was a 25 year old, right handed, female who had recently developed classic symptoms of R.A. She was experiencing period of pain, swelling and complained of difficulty in moving the joints of both hands on first waking and then later in the evening.

Figure 7.6 shows that there was a striking reduction of all joint parameters following treatment but that the magnitude of the reduction decreased with increasing treatment sessions. In contrast to patients one and three the reduction of stiffness parameters did appear to have some degree of permanence. Patient five was the only patient in the whole group who showed a reduction in parameters in both the short and long term.

Patient nine

The results are presented in fig. 7.7 and were selected to demonstrate that the reduction, if any, of the stiffness parameters did not always occur most markedly in the initial stages of treatment. Patient nine was a 57 year old, right handed female who had been suffering from R.A. for a number of years but was still subject to the occasional 'flaring up 'of symptoms. Fig. 7.7 shows that in the midst of the course of treatment(weeks 2.5 to 4.5) the pre treatment joint parameters increased and the short term reduction of the parameters was maximal at this time. Once again the long term effects of treatment appeared to be negligible as far as the parameters of passive joint stiffness are concerned.

Figure 7.5 Stiffness pre/post treatment : Patient Three : WAX + PUS

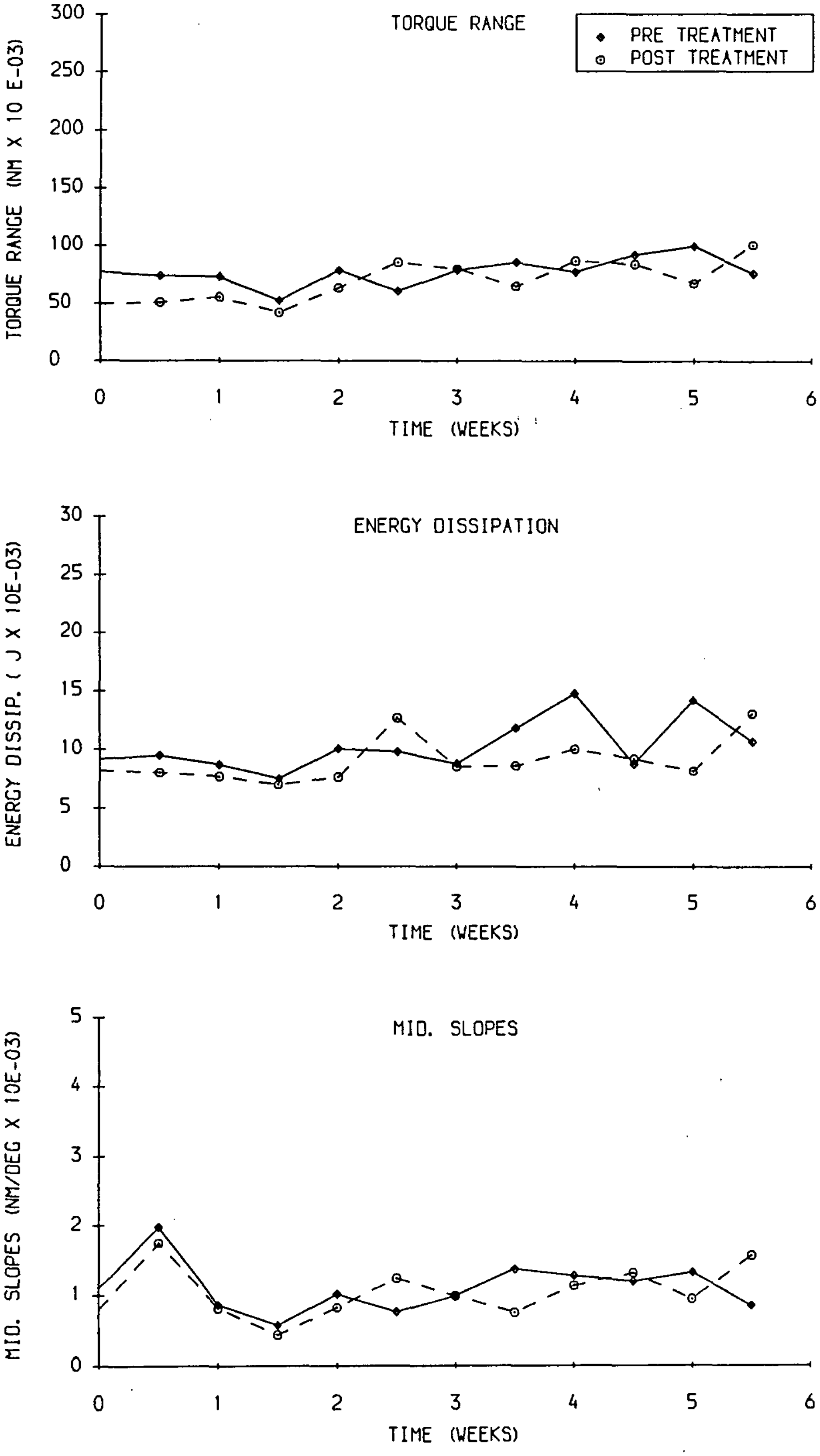


Figure 7.6 Stiffness pre/post treatment : Patient Five : WAX + PUS

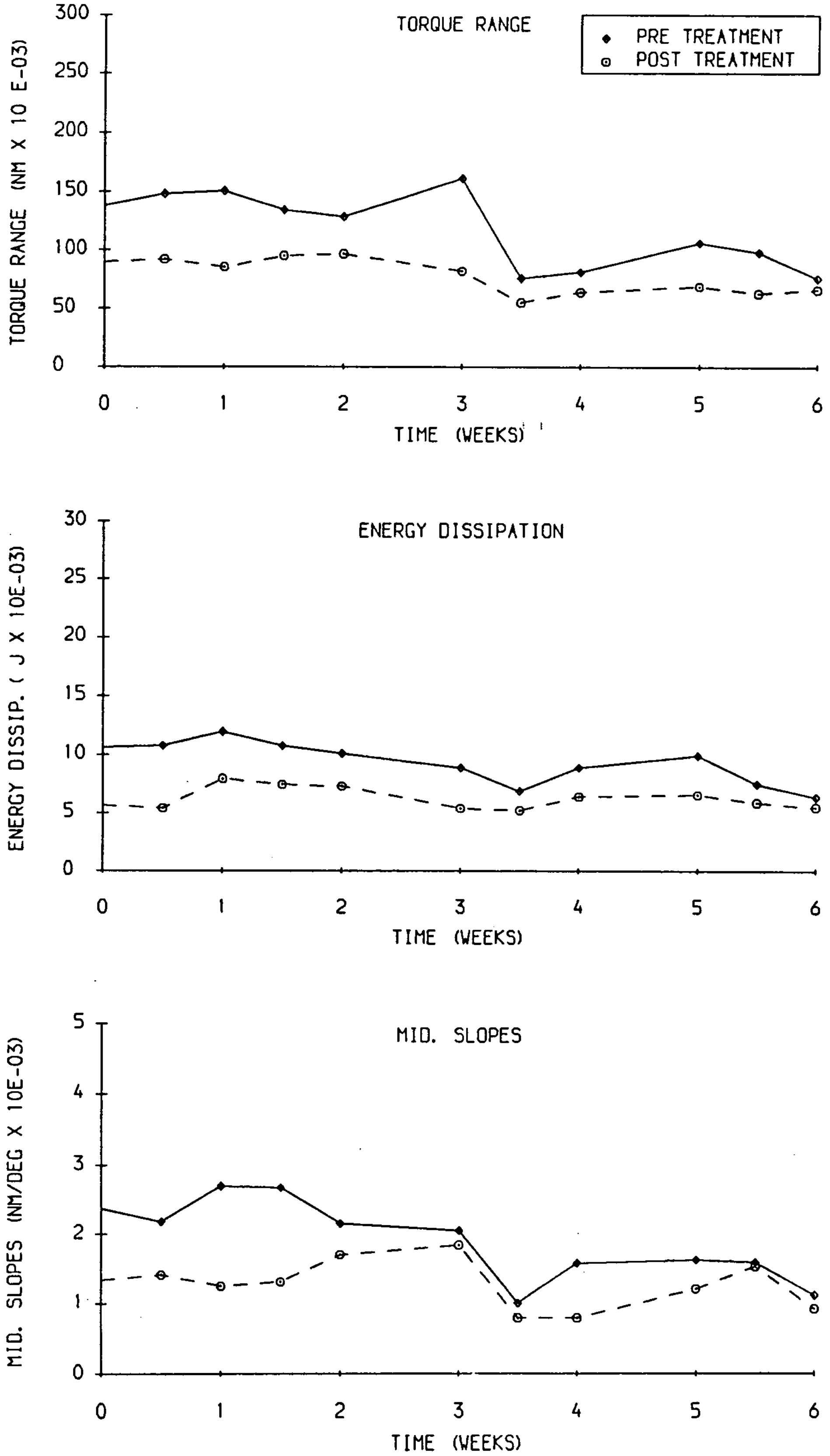
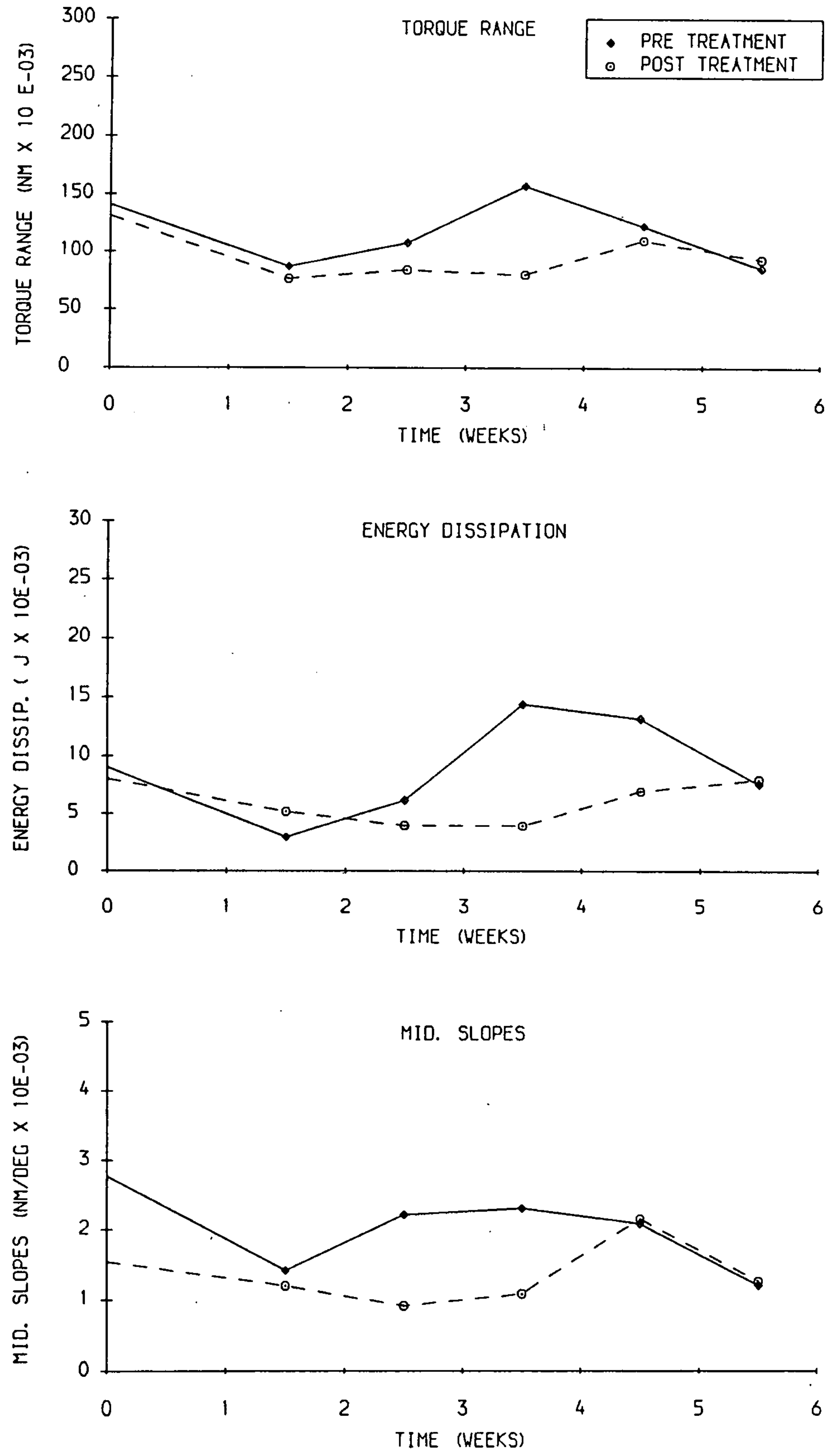


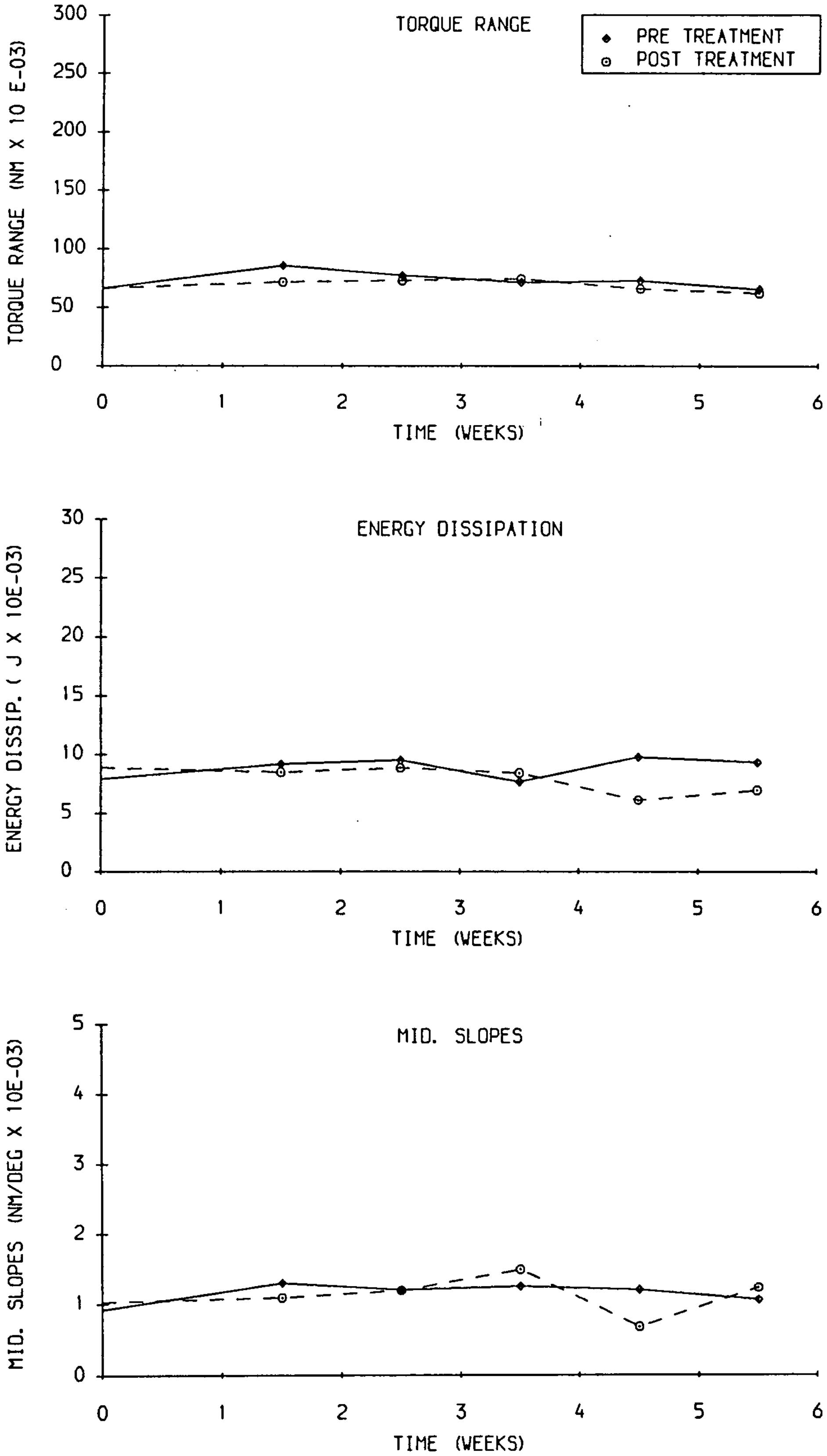
Figure 7.7 Stiffness pre/post treatment : Patient Nine : WAX + PUS



Patient eight

To complete the qualitative analysis of this treatment group the results of a 59 year old, right handed female, who had been suffering from R.A. for a number of years are presented (fig. 7.8). Subjectively, patient eight complained of a moderate degree of pain but no profound symptoms of stiffness. The results obtained show little variation in any of the joint parameters in either the long or the short term. Indeed, the pre/post short term results are remarkably similar when experimental repeatability is considered.

Figure 7.8 Stiffness pre/post treatment : Patient Eight : WAX + PUS



7.9 Statistical analysis of the effects of treatment

As the data for each pre/post treatment session were truly paired for each subject then the difference in the values was the variable used to determine the significance of the short term effects of treatment for a particular group. For long term analysis the difference between the initial pre-treatment state of the joint and the final pre-treatment state of the joint was considered as the variable. In both cases a paired t-test, as was carried out for the data from the control experiment (sec. 7.6), is the statistical method used.

Table 7.6 Results of short term pre/post analysis

Treatment group : Wax + Pulsed ultrasound

No. of subjects = 13

Total number of pre/post pairs = 89

Number of pre/post pairs considered for the analysis = 60

Test period : five weeks minimum.

Parameter	Torque range ($Nm \times 10^{-3}$	Mid. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
$\bar{y}$	14.0	0.17	1.43
S_y	29.5	0.86	4.63
$S_{\bar{y}}$	3.81	0.11	0.60
t	3.67	1.53	2.39
D of f	59	59	59

For fifty nine degrees of freedom, statistical tables for Student t give the following values :-

D of f	$p = 0.10$	$p = 0.05$	$p = 0.01$	$p = 0.001$
59	1.67	2.00	2.66	3.46

Hence, from this analysis it has been shown that the application of hot wax in combination with pulsed ultrasound produced a short term reduction in all the joint stiffness parameters. The reduction in torque range was highly significant ($p = 0.001$) as was the reduction in energy dissipation ($p = 0.05$ to $p = 0.01$). The mid. position slope parameter did not show a significant reduction at $p = 0.10$ but the value of t was sufficiently close to the tabulated value at this level to suggest a real trend of reduction in this parameter.

Table 7.7 Results of the Start/finish analysis (long term)

Parameter	Torque range ($Nm \times 10^{-3}$	Mid. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
$\bar{y}$	-22.1	-0.5	-2.92
S_y	45.5	1.55	5.70
$S_{\bar{y}}$	14.4	0.49	1.80
t	1.54	1.02	1.62
D of f	9	9	9

For nine degrees of freedom statistical tables for Student t gives the following values :-

D of f	$p = 0.10$	$p = 0.05$	$p = 0.01$	$p = 0.001$
9	1.83	2.26	3.25	4.78

The long term analysis of the data therefore shows that hot wax in combination with pulsed ultrasound did not, overall, produce a significant change in any of the joint stiffness parameters. Interestingly the results show a negative trend (increasing stiffness from start to finish) which was more pronounced for the parameters of torque range and energy dissipation.

7.10 Pulsed ultrasound alone

7.10.1 Qualitative analysis of some typical results

Patient twenty four

The results presented in figure 7.9 are for a 74 year old, right handed female, suffering from a combination of osteoarthritis and schleroderma. Consequently the purpose of the physiotherapy was to reduce the pain and profound stiffness of which the patient complained.

The most striking feature of the graphs of fig. 7.9 is the level of all the joint parameters which is very high compared with those of other patients. The ultrasound therapy appears to have reduced the stiffness parameters of torque range and mid. slope in the short term for the first six treatment sessions. After the sixth session the short term effect disappears and the character of the graphs becomes as variable as the one for energy dissipation. In the long term the ultrasound treatment appears to have had no effect on the passive stiffness of the joint.

Patient thirty two

This patient was a thirty year old, left handed, female who was suffering from synovitis in the joints of the index and middle fingers of the right hand. 'Morning stiffness ', sudden swelling of the joints and immobility, following excessive use of her hand, were all factors of which the patient complained.

It can be seen from fig. 7.10 that there were certain similarities in the character of the graphs from this patient and those of patient 24. The very first joint parameters, prior to any treatment whatsoever, were relatively high and were dramatically reduced by the first treatment session. A less dramatic reduction was evident for the next two or three sessions after which the pre/post difference became inconsistent as did those of patient 24. Perhaps of most interest is the 'knock on 'effect of the first treatment session. Comparison of the joint parameters at the finish of the treatement with those at the start appears to demonstrate a permanent reduction in all of them. However, this reduction is largely due to the effects of the first treatment session.

Figure 7.9 Stiffness pre/post treatment : Patient twenty four : PUS

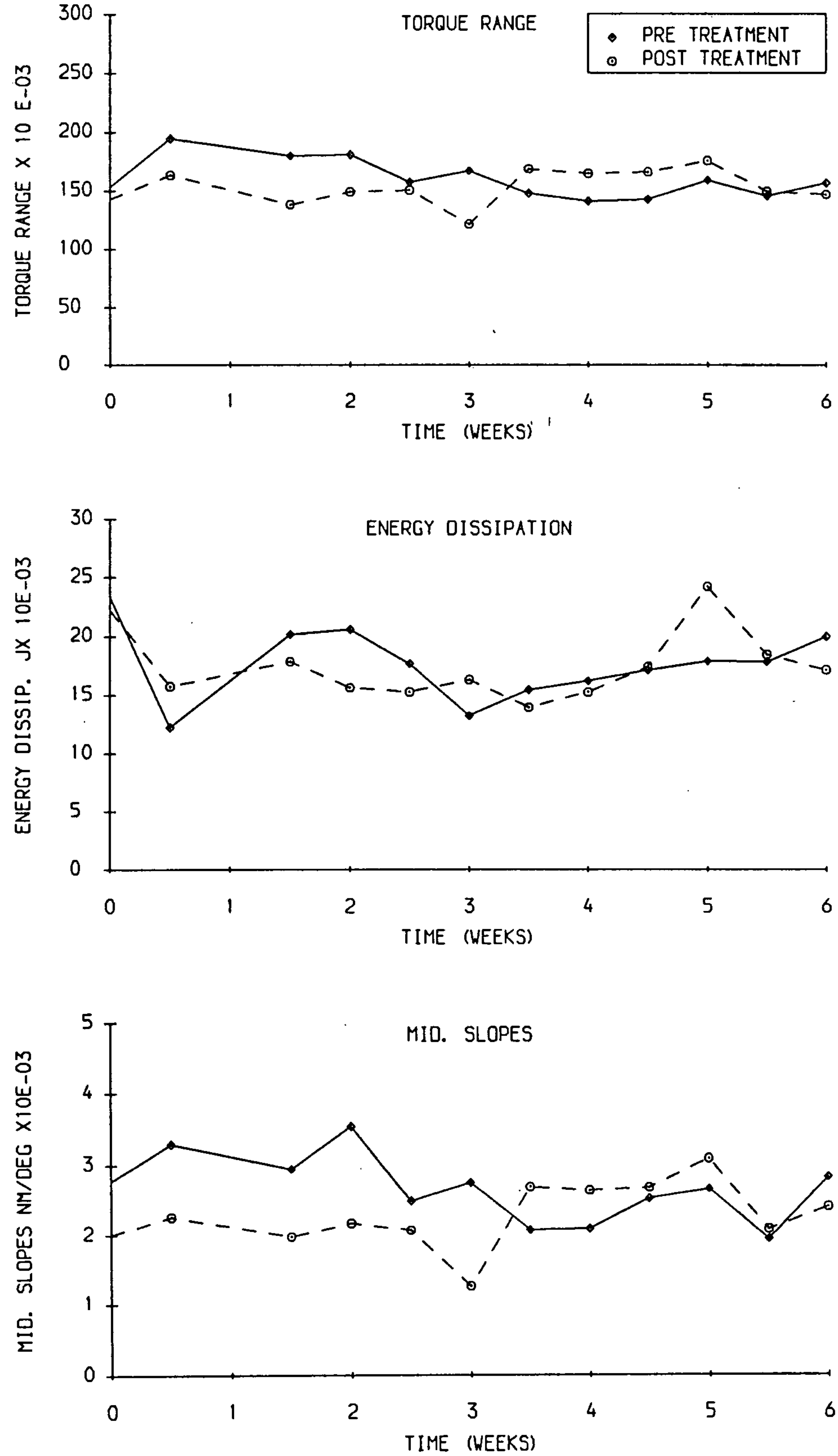
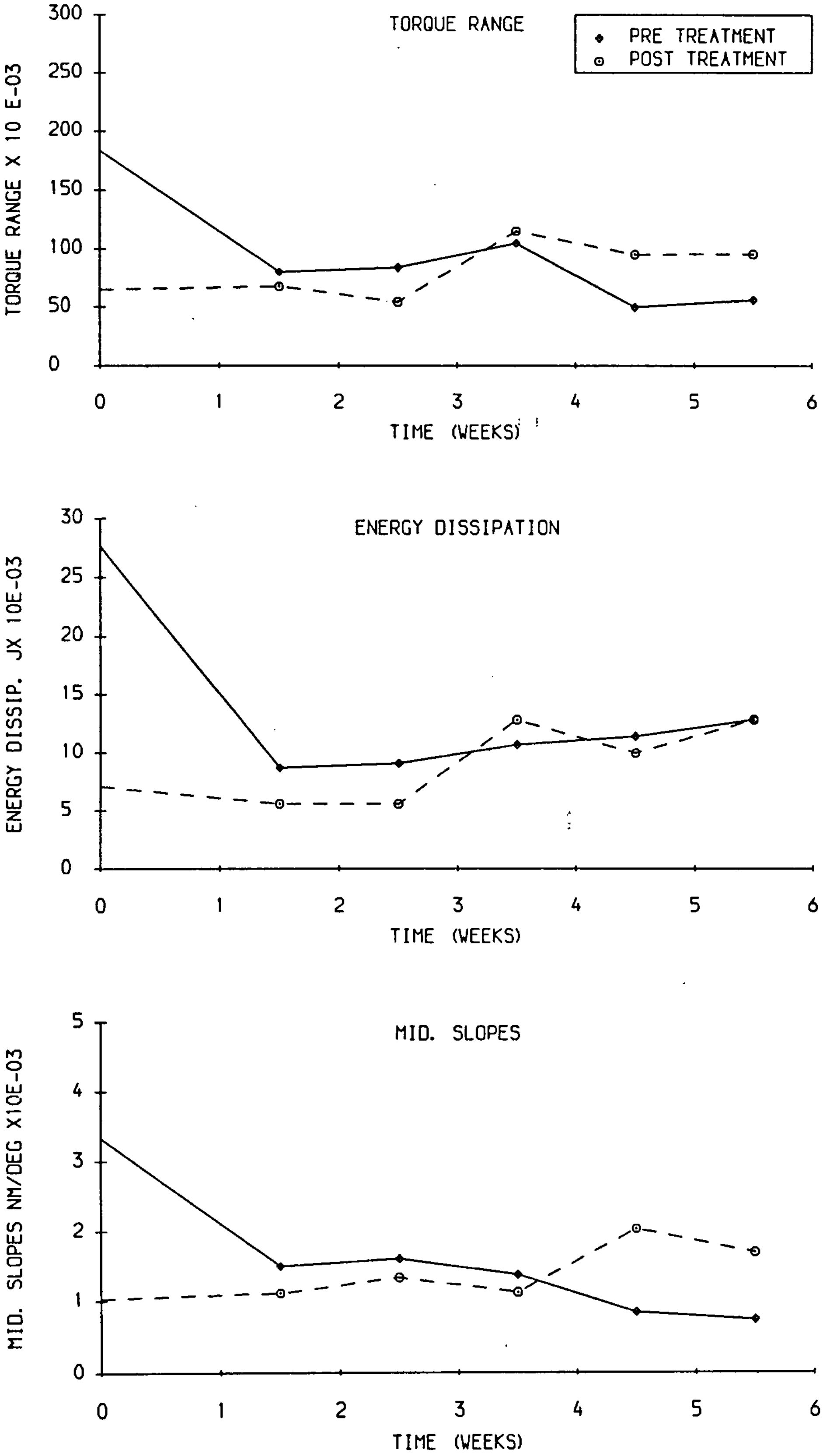


Figure 7.10 Stiffness pre/post treatment : Patient thirty two : PUS



Patient twenty five

Figure 7.11 shows the results from a 17 year old, right handed, female who had been diagnosed as hypermobile in all joints. Physiotherapy was advised to attempt to stabilize the joints and reduce pain.

The results of this patient are not typical of the group as a whole but they are included here to demonstrate the differences between a hypermobile joint and a healthy joint and also because there are similarities between this type of joint and arthritic joints that have become lax and unstable.

The magnitudes of the all the joint parameters are very small and apart from a pertubation at week three of the mid. slope, show little variation over the five week treatment period. For torque range and energy dissipation the pre/post treatment lines are almost identical. It is of interest that the increase in the mid slope mid-way through the treatment was not reflected by an increase in either of the two other parameters which is suprising in view of the correllation which appears to exist between the parameters for most other patients.

Table 7.8 Results of short term pre/post analysis

Treatment group : Pulsed ultrasound

No. of subjects = 11

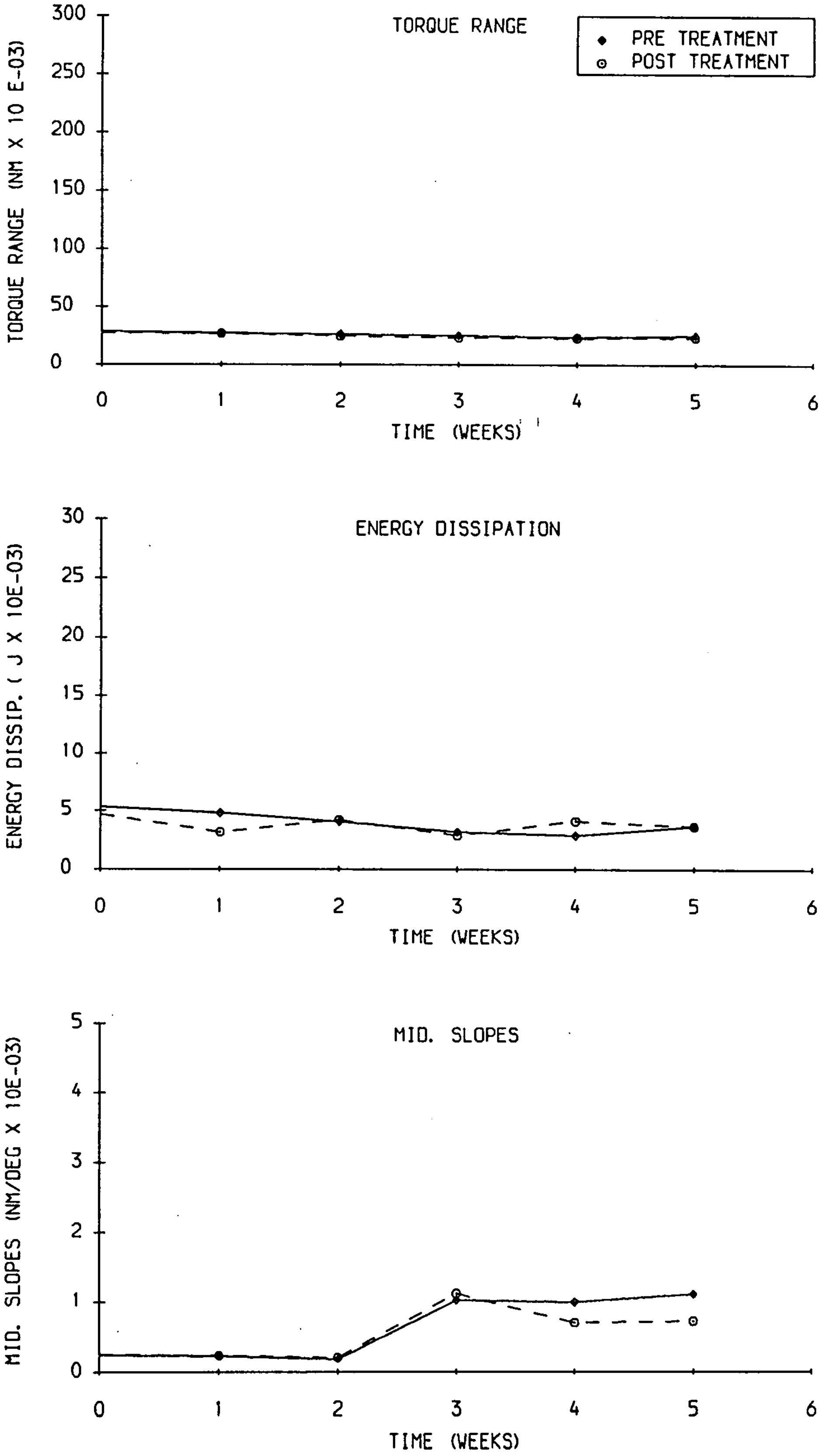
Total number of pre/post pairs = 73

Number of pre/post pairs considered for the analysis = 60

Test period : five weeks minimum.

Parameter	Torque range ($Nm \times 10^{-3}$	Mid. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
$\bar{y}$	-1.59	-0.04	0.36
S_y	30.0	0.67	4.06
$S_{\bar{y}}$	3.87	0.09	0.52
t	-0.41	-0.40	0.68
D of f	59	59	59

Figure 7.11 Stiffness pre/post treatment: Patient twenty five: PUS



Comparison of the t-statistics with the tabulated values already presented shows that pulsed ultrasound when used in isolation does not produce a significant short term reduction of any of the joint stiffness parameters. However, from the qualitative assessment of some typical results from this group, it did seem reasonable to suppose that a significant short term reduction may have been present in the earlier treatment sessions.

When the pre/post pairs from the early sessions were analysed on their own they did show a positive trend of reduction but this reduction was not significant at the $p = 0.10$ probability level.

Table 7.9 Results of the start/finish analysis (long term)

Parameter	Torque range ($Nm \times 10^{-3}$	Mid. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
$\bar{y}$	8.15	0.20	2.22
S_y	50.7	1.10	5.24
$S_{\bar{y}}$	16.03	0.35	1.65
t	0.51	0.57	1.34
D of f	9	9	9

The result of this long term analysis was similar to that for the treatment group of wax plus ultrasound in that none of the joint stiffness parameters showed a significant change from the start to the finish of the therapy period. However, there was a positive trend of overall stiffness reduction which was quite the reverse of the trend exhibited by the wax + pus treatment group.

7.11 Hot wax alone

7.11.1 Qualitative analysis of some typical results

Patient fourteen

The results presented in figure 7.12 are from an 84 year old, right handed, female who was suffering from O.A. in both hands and experiencing a great deal of pain in both wrists. Subjectively, the range of movement of the MCP joints in flexion appeared to be satisfactory but some limitations were evident when attempting to extend the fingers beyond the neutral position.

This set of results was characteristic of the group as a whole. The short term effects are highly inconsistent and in many cases the stiffness parameters appear to have increased quite substantially. In the long term it appears that no significant change has occurred in any of the joint parameters.

Patient nineteen

Figure 7.13 shows the results from a 57 year old, left handed, female. Patient 19 had been suffering from R.A. for a number of years. At the start of the treatment period the patient complained of 'stiff 'fingers, particularly in extension but remarked later in the treatment sessions that this symptom was very much reduced.

It can be seen that all the stiffness parameters are extremely low. A result of this type was not uncommon among amongst patients, even those, who like patient 19, remarked on the increased stiffness of their joints. The low value of the parameters imply joint laxity rather than stiffness and this would tend to suggest that what this patient described as 'stiffness 'could be better described as an inability or reluctance to move her joints.

There appear to be no distinguishable short or long term effects on joint stiffness following application of the hot wax treatment.

Figure 7.12 Stiffness pre/post treatment: Patient fourteen:WAX

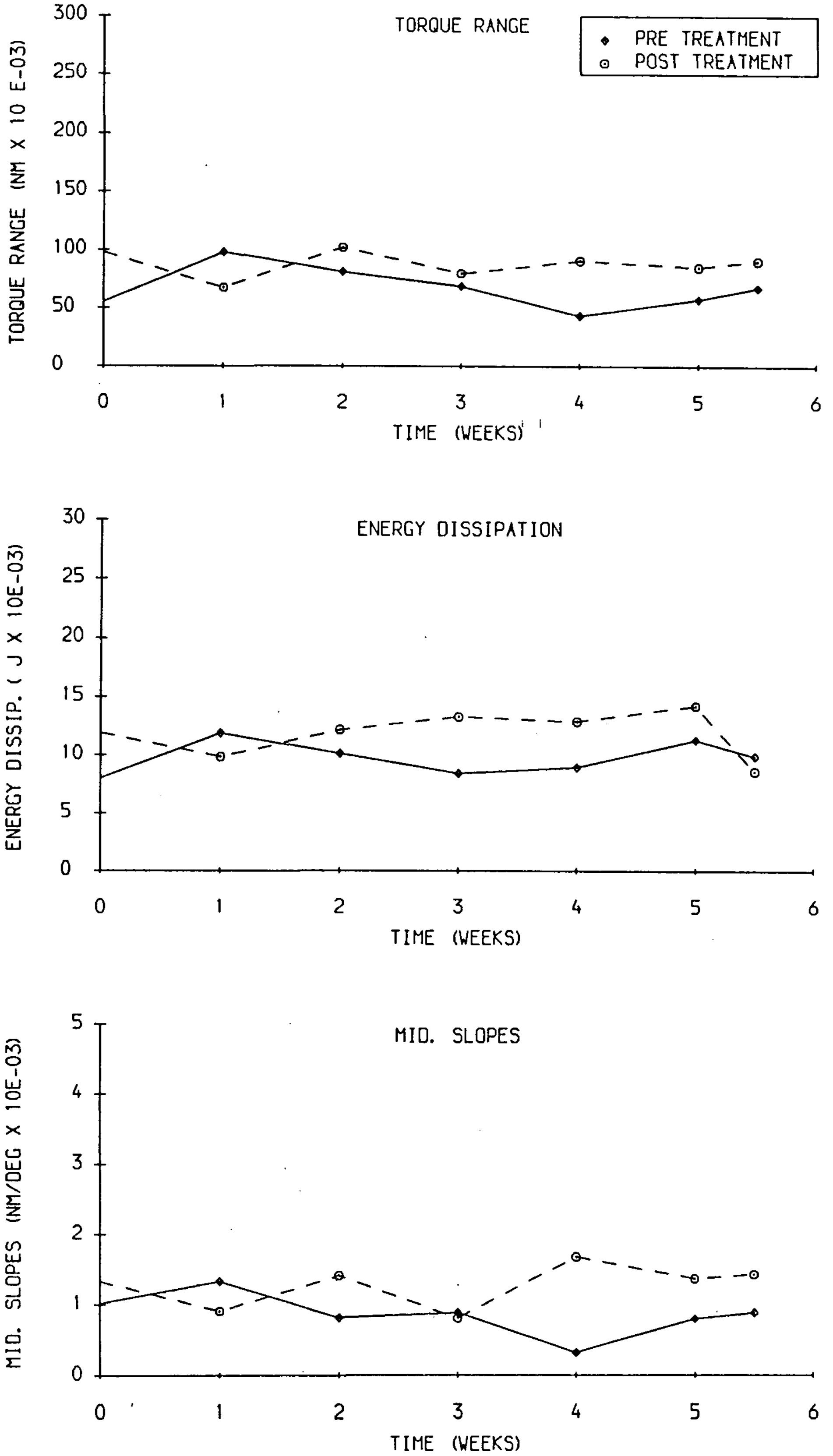


Figure 7.13 Stiffness pre/post treatment: Patient nineteen:WAX

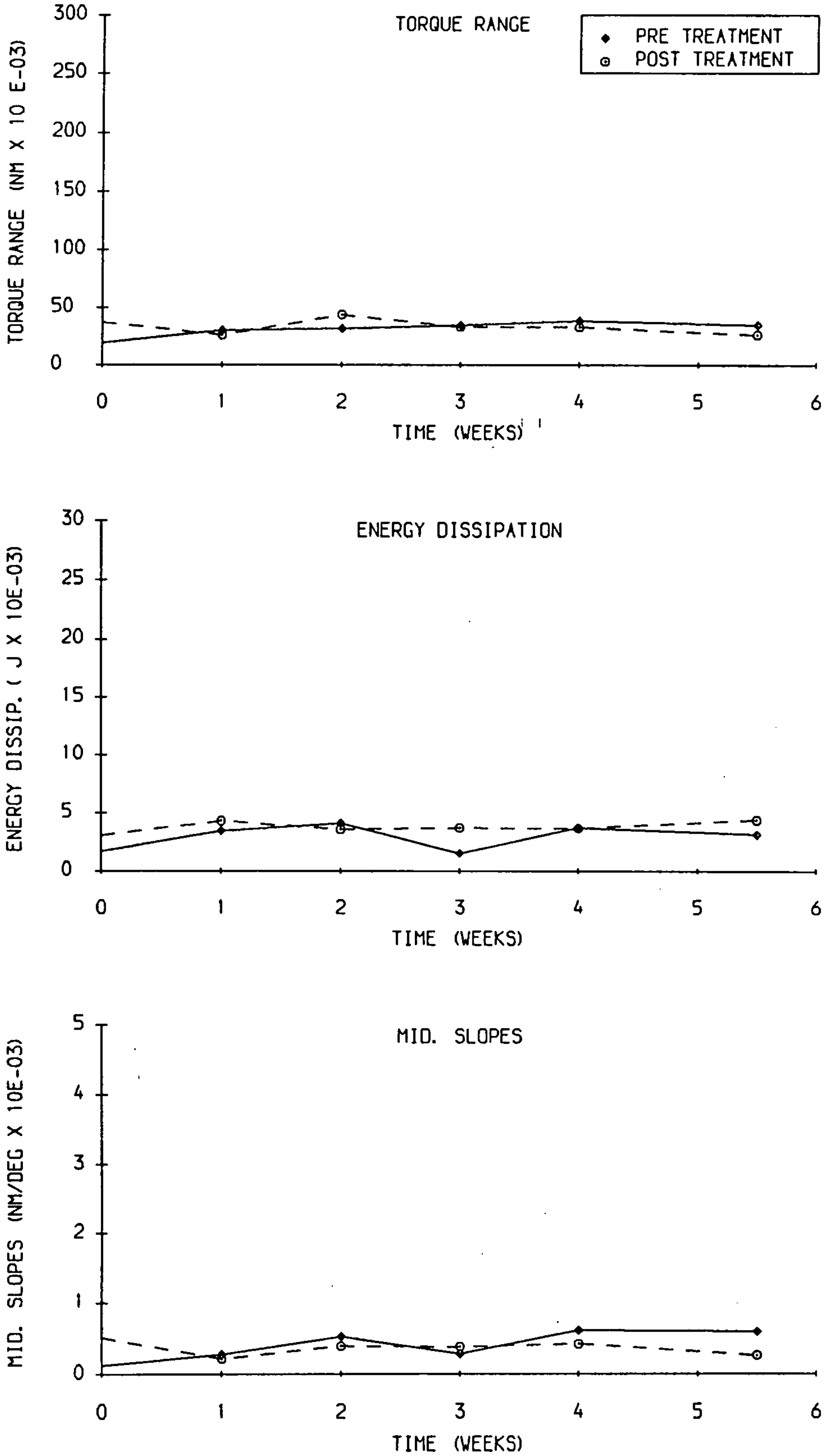


Table 7.10 Results of short term pre/post analysis

Treatment group : Wax alone

No. of subjects = 10

No. of pre/post pairs = 65

No. of pairs considered for the analysis = 60

Parameter	Torque range ($Nm \times 10^{-3}$	Mid. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
$\bar{y}$	-9.3	-0.085	-0.61
S_y	47.0	0.514	2.60
$S_{\bar{y}}$	6.06	0.066	0.335
t	-1.53	-1.27	-1.81
D of f	59	59	59

Comparison of the calculated t-values with those from statistical tables reveals a rather interesting short term result. The energy dissipation parameter was negatively significant at the $p = 0.10$ level and the torque range parameter almost showed negative significance at the same level. From this it may be concluded that hot wax treatment alone appears to increase certain joint stiffness parameters in the short term.

Table 7.11 Results of the Start/finish analysis (long term)

Parameter	Torque range ($Nm \times 10^{-3}$	Mid. sl. ($\frac{Nm}{deg} \times 10^{-3}$)	Energy dissip. ($J \times 10^{-3}$)
$\bar{y}$	-13.19	0.009	1.12
S_y	30.96	0.62	4.31
$S_{\bar{y}}$	9.79	0.20	1.36
t	1.34	0.05	0.82
D of f	9	9	9

None of the values of t was significant thus showing that the application of hot wax had no significant effect, either positively or negatively, after the total period of treatment was concluded.

7.12 Active and passive exercise

All of the patients attending the clinic were encouraged to perform various forms of exercise in their own time, each day. This exercise was supplemented by courses of exercise therapy whilst visiting the clinic. In some ways the results from those patients receiving no other type of therapy apart from exercise provide background information upon which the characteristics from the other treatment groups must be superimposed.

7.12.1 Qualitative assessment of some typical results

Patient one

Fig 7.14 shows the results of patient one who came into the clinic for a further period of therapy approximately 10 months after the period of wax plus ultrasound treatment. As such this data represents a very good basis for comparison of the two treatment groups as the variations due to age, disease type and hand dominance are completely eliminated.

If comparison is made with fig. 7.4 then the contrast between the two therapeutic techniques is dramatic. The pre-treatment state of the joint was similar for both cases but the subsequent pre/post, short term variation for the exercise results seems to be very inconsistent. In the long term, once again, the therapy appears to have produced no significant change in any of the stiffness parameters.

Patient thirty eight

The results presented in fig. 7.15 are from a 53 year old, right handed, male suffering from R.A.. Patient 38 had very large hands and was the only subject tested who could not be accommodated in the arthrograph with the cushioning in place beneath the hand. Although the results show no long or short term trends they are of interest because of the very high stiffness levels reflected in all of the parameters. Tissue bulk surrounding the joint was not measured in any of the experiments but it seems clear in this case that the contribution of bulk in the areas surrounding the joint was a major cause of the very high readings, particularly for energy dissipation and mid-position slope.

The trend in the other treatment groups was that major short term reductions were evident when the pre-treatment levels were high. For the patients in the exercise group, of which patient 38 is a good example, this did not seem to be the case. Figure 7.15 shows that there were no significant short or long term changes in any of the stiffness parameters due to the exercise therapy.

Figure 7.14 Stiffness pre/post treatment: Patient One : EX

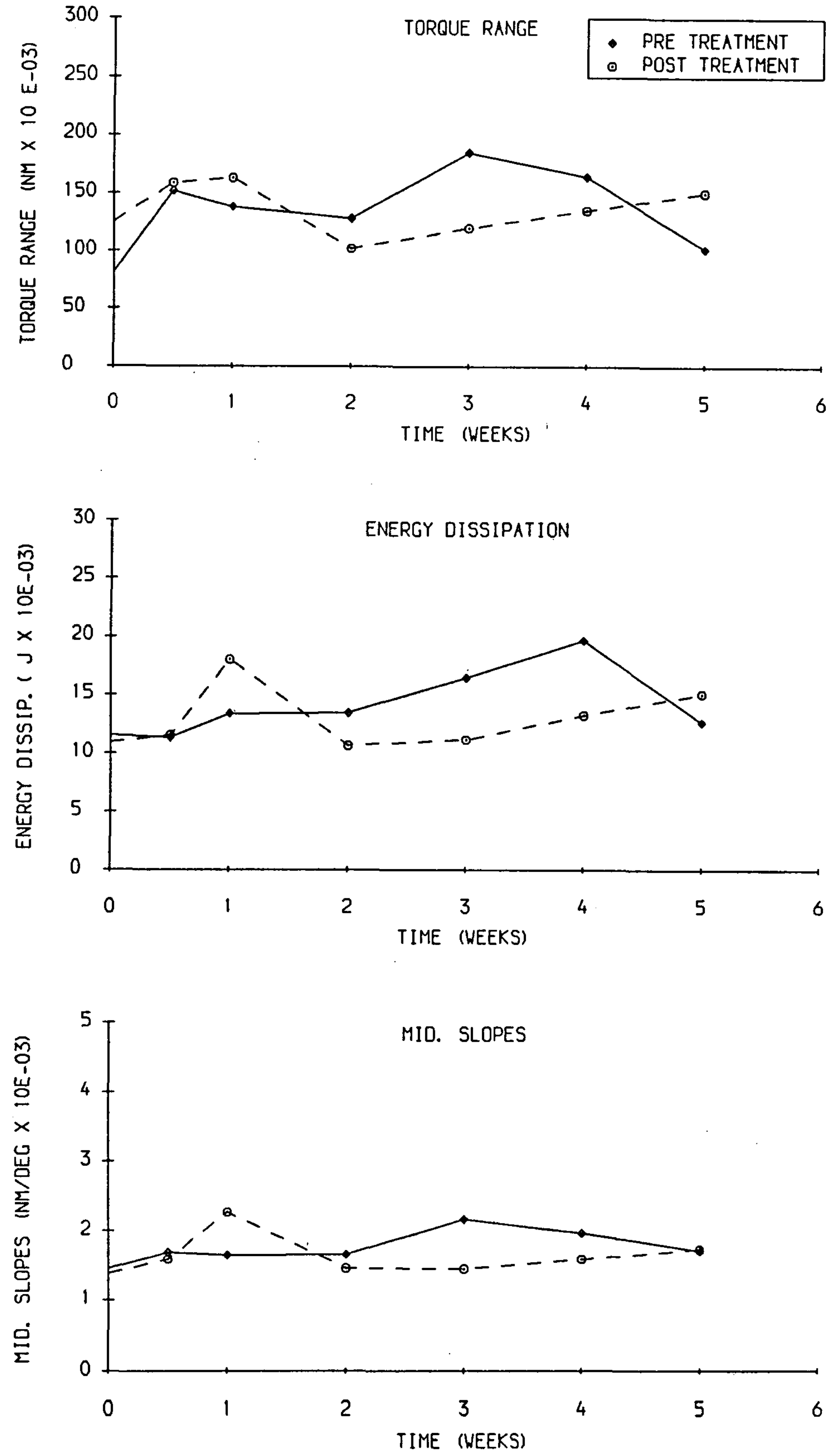
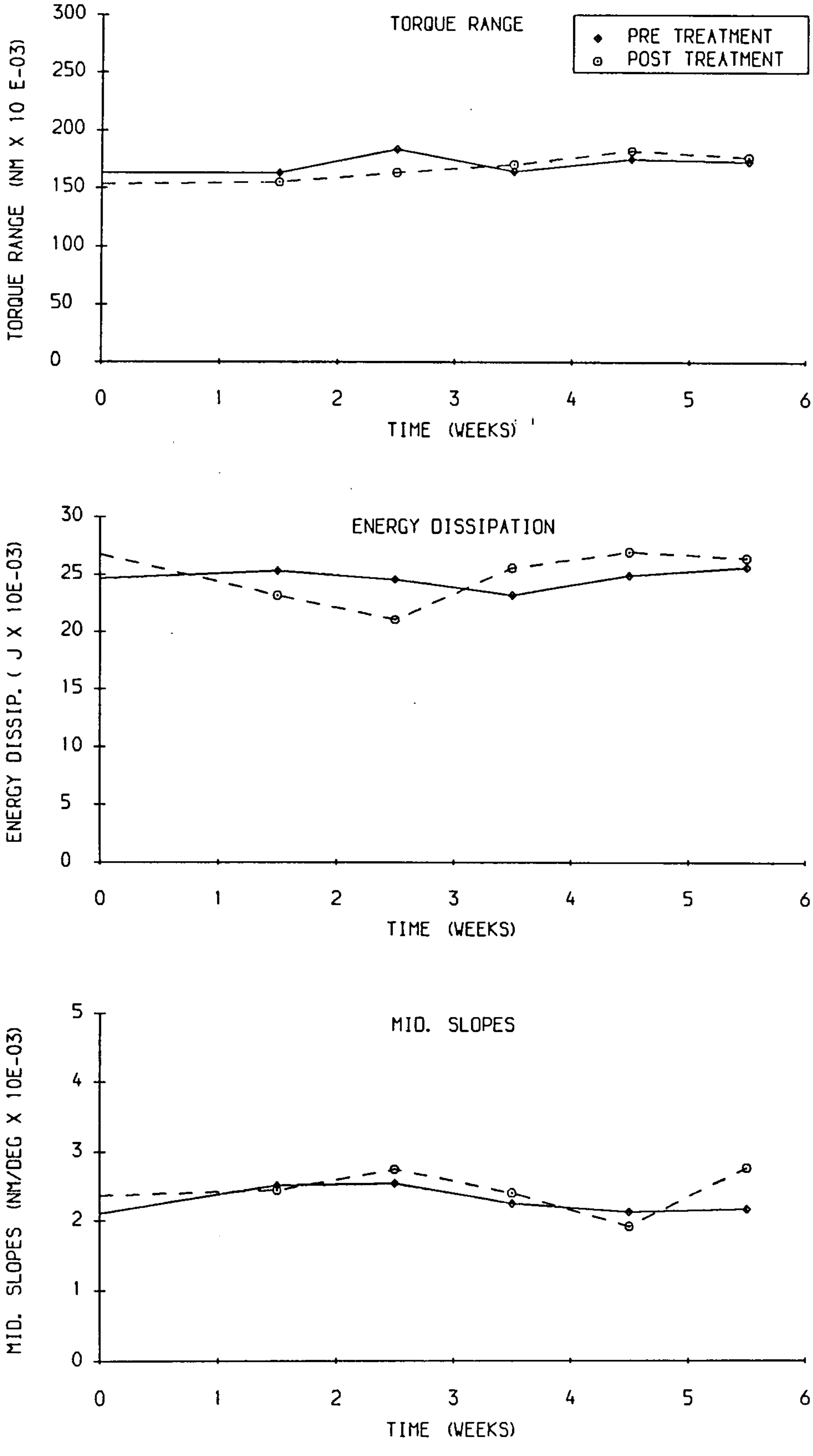


Figure 7.15 Stiffness pre/post treatment: Patient thirty eight: EX



Patient thirty seven

Finally, to provide a contrast to the majority of patients involved in these experiments, the results of a patient receiving therapy for a trauma injury will be considered. The results presented in fig. 7.16 are from a 50 year old, right handed, male patient who was receiving therapy to increase a highly restricted range of motion following major skin grafts.

The initial level of all the parameters was very high reflecting the 'tightness 'of the tissue surrounding the joints and the restrictions on the flexor and extensor mechanisms of the fingers. Exercise therapy in this instance seems to have had a beneficial effect in reducing the stiffness of the joint in both the short and long term. The reduction in the energy dissipation parameter and the mid. slopes was substantial.

Although these particular data were a 'one off 'they do reflect the general impression, gained over a number of months, of the success of active and passive exercise in improving the function of hands that had been subjected to serious injuries.

Figure 7.16 Stiffness pre/post treatment: Patient thirty seven : EX

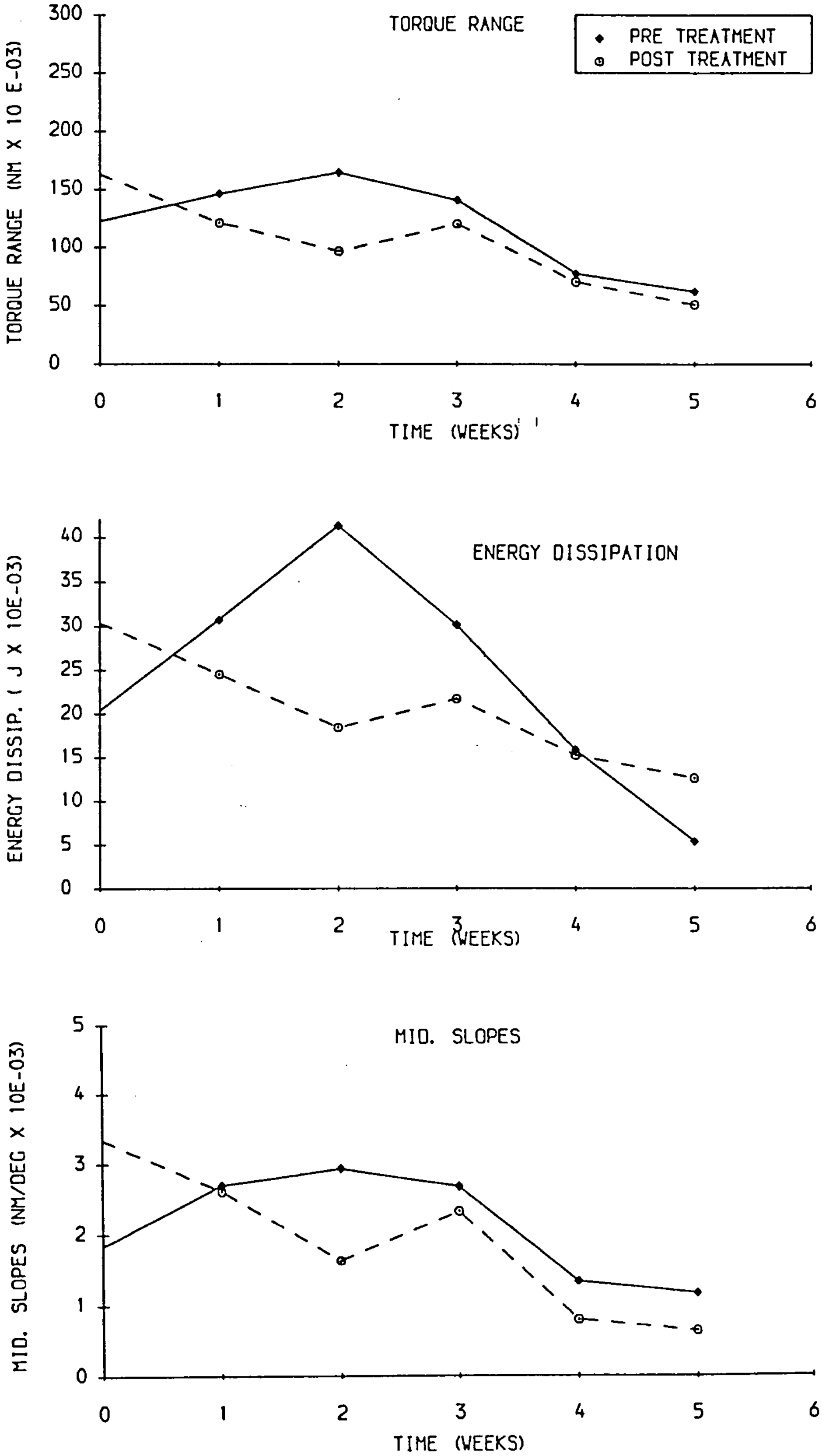


Table 7.12 Results of short term pre/post analysis

Treatment group : Exercise alone

No. of subjects = 6

No. of pre/post pairs = 34

No. of pairs considered for the analysis = 30

Parameter	Torque range $(Nm \times 10^{-3}$	Mid. sl. $(\frac{Nm}{deg} \times 10^{-3})$	Energy dissip. $(J \times 10^{-3})$
$\bar{y}$	3.09	-0.448	0.50
S_y	26.0	2.79	5.60
$S_{\bar{y}}$	4.73	0.50	1.02
t	0.64	-0.88	0.49
D of f	29	29	29

For twenty nine degrees of freedom, statistical tables for Student t give the following values :-

D of f	$p = 0.10$	$p = 0.05$	$p = 0.01$	$p = 0.001$
29	1.69	2.04	2.76	3.66

Unsurprisingly considering the individual results, the statistical analysis of the short term effects of the exercise treatment group showed that there was no significant reduction in any of the parameters. As exercise therapy was common to all treatment groups then this result suggests that the important factor in producing the significant, short term changes, already demonstrated, must have been the other forms of treatment themselves.

Table 7.13 Results of start/finish analysis (long term)

Parameter	Torque range $(Nm \times 10^{-3}$	Mid. sl. $(\frac{Nm}{deg} \times 10^{-3})$	Energy dissip. $(J \times 10^{-3})$
$\bar{y}$	-19.9	-0.24	-0.68
S_y	41.6	0.45	4.83
$S_{\bar{y}}$	13.16	0.14	1.53
t	1.51	1.71	0.44
D of f	5	5	5

For nine degrees of freedom statistical tables for Student t gives the following values :-

D of f	$p = 0.10$	$p = 0.05$	$p = 0.01$	$p = 0.001$
5	2.01	2.57	4.03	6.85

Once again, the long term effects of the treatment, when analysed statistically, proved to be not significant. It must be noted, however, that the size of the exercise group was two thirds of the size of the other groups and consequently the comparisons between this group and the others must be treated with a degree of caution.

7.13 Discussion of results

Analysis has shown that none of the physiotherapeutic treatments considered caused a significant long term change in any of the joint stiffness parameters. However, the parameters of torque range and energy dissipation were reduced, highly significantly, but temporarily, by a single application of the wax plus ultrasound therapy. Ultrasound alone, wax alone and exercise alone did not cause a significant reduction in any of the parameters in the short term. Indeed, the application of hot wax led to a significant short term increase in dissipated energy.

The striking short term reduction in stiffness caused by the wax plus ultrasound combination cannot therefore simply be explained by predominantly beneficial effects of either wax or ultrasound individually. It appears that there must have been some form of synergistic effect when the two treatments were combined. Further consideration of the action of the individual treatments may help to explain why such an effect occurred.

7.13.1 The effect of heat on joint stiffness

Wax therapy causes heating of the skin surrounding the joint and some of the underlying tissues. Both Wright and Johns (1960a) and Backlund and Tiselius (1967) investigated the effects of localised temperature changes on MCP joint stiffness. Although subject numbers were small (two subjects in each case) both workers observed that raising the temperature of the skin at the surface of the joint caused a decrease in elastic stiffness and lowering of the temperature an increase in elastic stiffness. Lowering of the skin temperature appeared to produce the most marked changes.

In contrast, Yung et al (1981) in a larger scale study found that the application of ice packs to the MCP joint did not cause any significant change in elastic stiffness or energy dissipation in either healthy or diseased joints. Furthermore, hot wax therapy, applied in the same manner as in this study, did not cause any significant changes in elastic stiffness or energy dissipation.

The results of Yung et al for wax therapy are supported by the short term results presented in this text. If the numbers of subjects tested is considered, the weight of the evidence suggests that the raising of the temperature of the skin local to the joint does not cause a significant change in joint stiffness. The phrase 'significant change 'is perhaps the key to explaining the conflicting results of Wright and Johns and Backlund and Tiselius. From the individual results presented in section 7.11 it can be seen that on some occasions hot wax therapy did lead to a reduction in some stiffness parameters. A single observation at these times would have suggested that wax therapy reduced stiffness. In general this was clearly not the case.

The depth of penetration of heat applied at the skin's surface to the underlying tissues is limited by the rate at which the circulation is able to disperse the heat. Some evidence of the effects of heating deeper placed structures is provided by the short wave diathermy experiments of Yung et al.

The capacitance method of short wave diathermy causes an alternating electric field to be set up in the joint which in turn causes ions present in the tissues of the joint to oscillate. Some of the kinetic energy acquired by the ions is dissipated as heat when they collide with tissue molecules.

This therapy can therefore produce heating of the deeper placed structures of the joint. Yung et al showed that the amount of energy dissipated in diseased MCP joints was significantly reduced by short wave diathermy.

The heat produced at any point is determined by the resistance of the tissues at that point. The greater the fluid content of the tissues the greater the heating effect. Tissue swelling, due to accumulation of fluid, is likely to be present in some diseased joints, particularly if the disease is in an active phase. This could help to explain why reductions in dissipated energy were observed in diseased joints but not in healthy joints on application of short wave diathermy.

It could be argued that short wave diathermy would increase the temperature of synovial fluid and thus reduce its viscosity and consequently its lubricating effect. However, even if this was the case, it has already been shown in chapter three that synovial fluid does not have a significant role in the overall stiffness measurement.

The implication of the evidence thus far is that heating of the tissues and fluids composing diseased joints can lead to changes in their stiffness characteristics but only if the heat is able to be applied at a deep level. Application of hot wax therapy does not seem to be capable of producing a sufficient depth of penetration.

7.13.2 The effect of ultrasound on joint stiffness

Quantitative information about the effect of ultrasound therapy on joint stiffness is restricted to the work presented here and the short term studies of Yung et al. In both studies the ultrasound was applied in the same manner but the results differ slightly.

The individual results presented in section 7.10 demonstrated that ultrasound did cause a reduction in all joint stiffness parameters in some patients. However, the reduction was limited to the early treatment sessions and did not reach significance for the group as a whole. Yung et al found that ultrasound produced a significant reduction ($p < 0.025$) in energy dissipation in diseased joints but not in resistive torques measured at 20 degrees from the equilibrium position. The resistive torques did however show a trend of decreased stiffness.

There seems to be clear evidence that ultrasound therapy causes some temporary reduction in the energy dissipated in diseased joints. The reason why this energy reduction should be more significant in one study than another is not immediately clear.

It should be noted that the results of Yung et al were based on one treatment session per patient whereas the short term results of this study were based upon the average of many treatment sessions. In addition there is no way of knowing whether the stiffness of the joints prior to treatment was the same in both studies, due to the disparity in measurement techniques.

From inspection of all individual results there was some evidence to suggest that major reductions in stiffness parameters were more likely for joints with initially high stiffness levels. It could have been that the patients in Yung's study were initially stiffer in general than those of the present study, thus leading to more significant reductions.

The mechanism by which ultrasound can affect joint stiffness in not clear but some facts are known about its effects on biological tissue.

The velocity of ultrasound in one kind of soft tissue is very much the same as that in another but can vary distinctly in other strucures which compose the joint. Consider the following data taken from Wells (1969):

Structure	Mean velocity m/sec
Fat	1450
Human soft tissue	1540
Blood	1570
Muscle	1585

The velocity of sound depends upon the elasticity of the substance, its density, its temperature and also its physiological condition (Wells 1969).

Thus if the elasticity or density of the soft tissues composing the joint is different between healthy and diseased joints a difference in the effectiveness of ultrasound on diseased and healthy joints may be expected.

When sound passes through a substance, the resulting deformations oscillate at a rapid rate. When applied to human tissue this periodic tension and compression is thought to have an effect similar to massage. The reduction in stiffness following numerous successive oscillations of the joint has been noted (section 5.5) and it could be that ultrasound is causing reductions in stiffness in a similar manner.

7.13.3 The possible action of hot wax and ultrasound

One possible explanation of the significant reductions in stiffness resulting from the combination of wax and ultrasound lies in the fact that the wax was consistently administered before the ultrasound.

The absorption rate of ultrasound by a body depends upon the temperature of the body. It has been shown that in some tissues the rate of absorption increases as the temperature of them increases (Dunn (1962) cited by Wells (1969)). The hot wax therapy, although not effective in itself, may sufficiently raise the temperature of the tissues surrounding the joint so that the absorption rate of the subsequent ultrasound therapy is increased. Furthermore, changes in tissue temperature may lead to changes in elastic modulus. Thus the frequency of oscillation of the tissues, due to the ultrasound, may be altered. Both of these factors may explain why the combination of wax plus ultrasound was so effective in reducing stiffness in the short term even though the individual treatments themselves were not so effective.

From the discussions on the relative contributions of different structures to the stiffness measurement, presented in chapter 3. (section 3.8), it seems likely that any gross changes in the elastic stiffness or energy dissipation must be due to changes in the tissues comprising the joint capsule or the muscles or both. Both hot wax and ultrasound therapies were applied locally to the joint and thus it seems unlikely that the muscles of the forearm, which are moved passively during flexion/extension, could have been affected. This implies that the hot wax and ultrasound combination caused changes in the viscoelastic properties of the joint capsule and the tissues surrounding it.

7.14 Long term effects of physiotherapeutic treatment

Joint stiffness was shown not to be changed significantly in the long term by any of the modes of physiotherapy considered. Even the highly significant short term reductions in stiffness parameter, caused by the wax plus ultrasound combination have been shown to be of a temporary nature.

Physiotherapy is a very common form of therapy to be recommended for treatment of arthritic complaints but it appears from this study that one course of treatment does not have any beneficial effects on joint stiffness. However, to suggest that physiotherapy serves no purpose, on the present evidence, would be foolish for a number of reasons :

1) The present study is the only one which has considered long term effects and thus further experimentation is required to confirm the findings presented here.

2) Joint stiffness is but one aspect of arthritic disease, and alleviation of it may not be of paramount importance. For example, relief of pain and development of musculature may be more important to the general well being of a patient.

3) The individual attention which a physiotherapist gives to a patient is probably very important psychologically and may lead to a patient being able to manage the effects of arthritic disease more effectively.

4) The temporary reductions in joint stiffness, resulting from some forms of therapy, must be better than no stiffness reduction at all.

CHAPTER EIGHT

GENERAL CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

8.1 The measurement systems

The new arthrographic system was used extensively and proved to be reliable, easy to use and sufficiently accurate to quantify changes in MCP joint stiffness. Pilot studies showed that the parameters of mid-slope, energy dissipation and torque range were within acceptable limits of repeatability. The equilibrium position of the joint has been shown to be important when attempting to compare the stiffness of different joints. A new, semi-automated, experimental procedure was developed which used the equilibrium position as the datum for the stiffness measurements. Results of good consistency were obtained with this new procedure. The use of a microcomputer to control the arthrographic system made it possible to perform the measurements with a minimum of effort and enabled results to be analysed automatically.

The grip machine enabled the forces developed during a power grip to be analysed. Measurement was made of the force contributions of individual digits and the maximum total gripping force. The machine was portable and extremely easy to use. However, the repeatability of consecutive measurements was disappointing but perhaps not surprising for an active test reliant upon subject effort. Insufficient data was collected with the grip machine to be completely sure of its effectiveness in clinical studies but initial results were encouraging.

8.2 Circadian variation

A circadian variation of stiffness has been observed in the joints of arthritic subjects. In general, changes in one stiffness parameter were reflected by similar changes in the other two. Joint stiffness was elevated in the early morning and for some subjects the degree of change was profound. No significant circadian variation was observed in the joint stiffness of healthy subjects.

When results were combined the variations present on an individual basis were not observed. This finding was attributed to differences in the timing of stiffness peaks from one individual to another.

A circadian variation of grip strength was observed in arthritic subjects. Grip strength reached a minimum value between 2.00 and 4.00 a.m. in the majority of subjects. No consistent relationship was found between changes in joint stiffness and changes in grip strength.

8.3 Effects of Physiotherapy

The effects of several forms of physiotherapy on the joint stiffness of arthritic subjects has been compared in the short and long terms. The combination of hot wax baths and ultrasonic therapy effected temporary reductions in all stiffness parameters. The reductions in energy dissipation and torque range were highly significant ($p < 0.05$ and $p < 0.001$ respectively). No significant reductions were found for hot wax or ultrasound alone. A mechanism to explain the synergistic action of the two treatments has been suggested.

Active and passive exercise did not cause any significant changes in joint stiffness.

When the joint stiffness before the start of a course of treatment was compared with that at the end (minimum period five weeks) no significant change was found for any of the treatments considered.

8.4 Suggestions for further work

8.4.1 Systems development

Both systems fulfilled the vast majority of their design criteria but some deficiencies were noted during their use 'in the field '.

The awkwardness of taking the arthrographic system to the test subject, rather than vice versa, was particularly apparent during the circadian experiments. There is a case for attempting to reduce the bulk of the system even further. Happily, the advent of extremely powerful laptop computers should mean that this could be accomplished with relative ease. If such a task were undertaken it is suggested that the print device should be dispensed with and all experimental data stored on hard disc and backed up on floppy disc. Alternatively, the data could be transmitted directly to any other processing or output device via a modem.

The fact that the arthrograph could only test the MCP joint of the index finger was also a limiting factor. For some arthritic subjects, with no MCP joint involvement of the index finger, it was clear that the other MCP joints were affected. If the arthrograph was used to provide corroborative evidence of the effectiveness of say, a certain drug therapy, measurement of only one joint would restrict the conclusions that could be made. Some thought was given to this problem during the development of the torque transducer. Whilst a multiple joint transducer design did seem possible, although quite elaborate, it was felt that great care would be needed during interpretation of results. The MCP joint of the index finger is reasonably independent of the other joints and measurement of its stiffness can be quoted with a degree of confidence. Consideration of the anatomy of the other joints reveals that it is likely that stiffness measurements of one joint would be affected by the stiffness of the surrounding joints. However, if this factor was taken into account, a multiple joint transducer should enable some interesting comparative studies to be made.

In Chapter Three it was shown that joint stiffness parameters are dependent on a number of factors in the experimental procedure. These included, frequency of oscillation, amplitude of oscillation and position of oscillation. Further detailed studies of the way in which joint stiffness characteristics change with varying experimental parameters could be of considerable use. For example, it could be that particular frequencies of oscillation would magnify the differences between the stiffness of diseased and healthy joints. It is suggested that rheological studies, particularly those which compare diseased and healthy joints, could lead to the development of a more effective measurement system.

The major design flaw of the grip machine was the selection of the miniature dot-matrix printer as the output device. This printer proved to be too noisy during the circadian study and also required a fairly large amount of current which meant that battery powered operation of the machine was not suitable. This printer could be replaced by a 'pen trace 'device or a thermal printer. Alternatively, the printer could be dispensed with completely and the results stored for subsequent analysis. Digital displays could also be used to give an immediate indication of the important grip parameters such as maximum total grip force.

8.4.2 Further clinical research

There is an amount of controversy as to whether arthritic joints are in fact stiffer than healthy joints. It has been suggested in this text that the joints of those patients with active disease are stiffer than healthy joints, particularly if the disease is in its early stages. There seems to be good evidence to suggest that the joints of those patients who have been suffering from the disease for a long period of time are no stiffer, or in some cases less stiff, than healthy joints. A useful further study would be to compare the joint stiffness in carefully selected groups of subjects. For example, one group could be newly diagnosed arthritic subjects, another group could be long time sufferers and yet another could be those subjects in whom the disease was in its active phase.

The circadian studies, presented here, suggested that stiffness does vary significantly in some subjects throughout the course of a day. Further circadian studies over a full twenty four hour period are needed to confirm this suggestion. In addition, further circadian studies of healthy joints should also be undertaken, in view of the paucity of data in this area and the conflicting experimental results.

The investigation of the effect of physiotherapy on joint stiffness suggested that local application of heat, in the form of wax baths, and ultrasound acted in combination to reduce joint stiffness in the short term. A more detailed study of these two treatments may explain why this phenomenon occurred. A first step to check on the theory presented in Chapter Seven could be to administer the ultrasound therapy before the hot wax treatment.

As the long term physiotherapy results were judged in isolation, another similar study would be useful to confirm or deny these findings.

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APPENDIX ONE

Contents.

A.1 Calculation of acceptable frequency/amplitude combinations for the arthrograph drive

At certain frequencies and amplitudes the inertial torque of the index finger would approach the magnitude of the resistive torque at the MCP joint. The aim of the following calculations was to determine what combinations of frequency and amplitude would not compromise the resolution of the torque transducer.

The symbols used in the calculation are defined as follows:

θ - Angular displacement of the joint.

A - The amplitude of the forcing displacement.

ω - Angular velocity

t - time

T - inertial torque.

I - moment of inertia of the index finger.

For a sinusoidal displacement the maximum angular acceleration, $\ddot{\theta}_{max}$ is given by :-

$$\ddot{\theta}_{max} = A\omega^2 \qquad 1$$

The angular acceleration of the joint gives rise to an inertial torque, T, which is governed by the equation of motion

$$T = I\ddot{\theta}$$

Furthermore, the maximum inertial torque will clearly occur when the angular acceleration is a maximum.

Hence,

$$T_{max} = I\ddot{\theta}_{max} \qquad 2$$

In order to estimate the moment of inertia, I, the finger will be considered as a cylinder filled with water. Approximate dimensions are ; length = 0.10 M, radius 0.01 M.

For a cylinder of length L, rotated about its base,

$$I = \rho A\frac{L^3}{3}$$

where ρ = density of water = 1000 $\frac{kg}{M^3}$ and $A = \pi r^2 = \pi(0.01)^2$ and L = the length of the index finger = 0.1M.

Substituting these values gives,

$$I = 1 \times 10^{-4} KgM^2$$

Now, the torque resolution required is 0.001 NM so to avoid compromising this resolution it is reasonable to assume a maximum allowable inertial torque of 0.0005 NM.

Substituting the values for I and T into equation (2) gives,

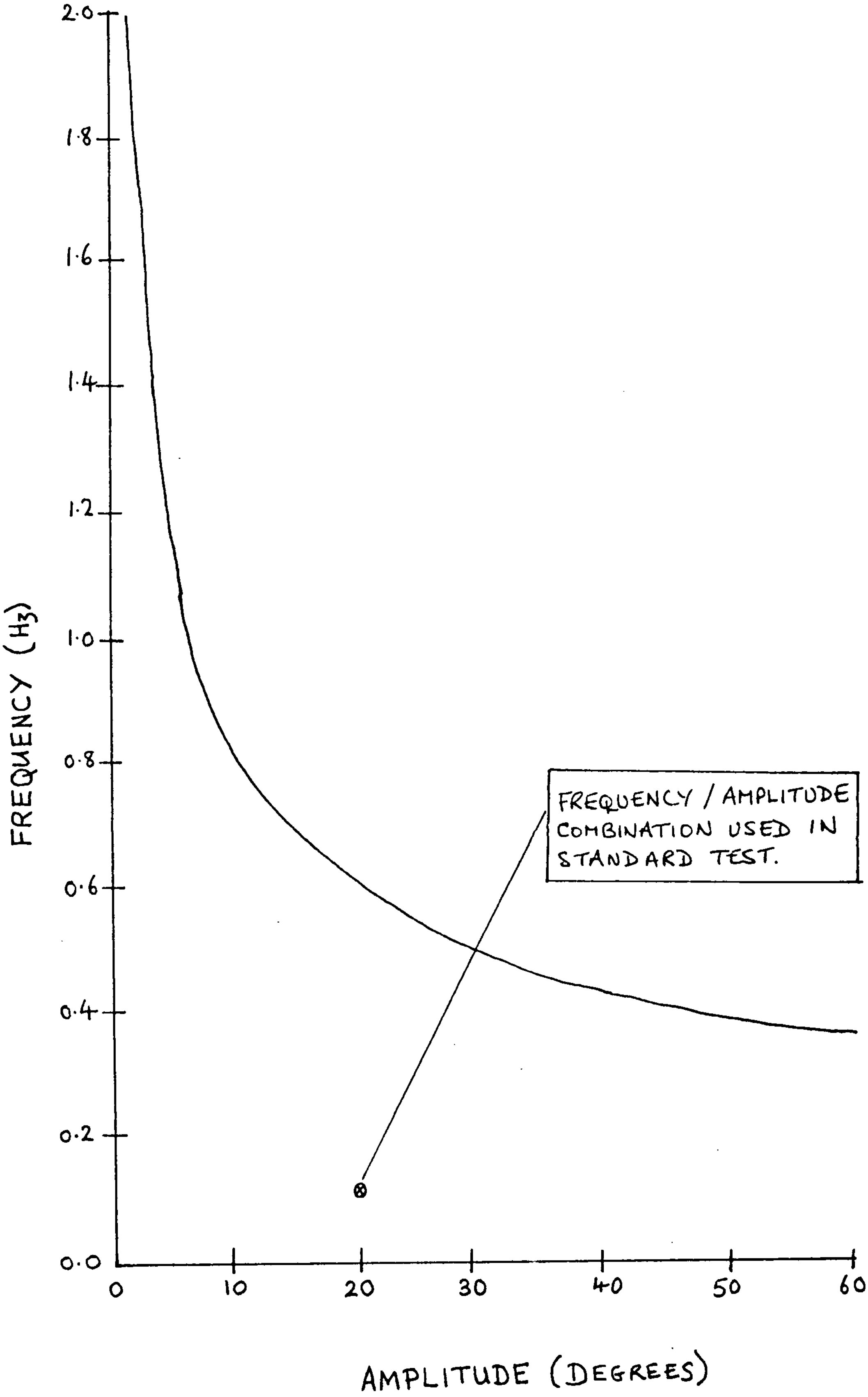
$$\ddot{\theta}_{max} = \frac{0.0005}{1 \times 10^{-}4} = 5rad/sec^2$$

From equation (1) there are a variety of angular velocity/ amplitude combinations that will satisfy the inequality,

$$A\omega^2 < 5rad/sec^2$$

Noting that $\omega = 2\pi f$, where f is the frequency of oscillation, a plot was made of the acceptable frequency/amplitude combinations. This plot is shown in figure A.1. The position of the frequency/amplitude combination used in the standard arthrographic test is clearly indicated.

Figure A.1 Acceptable frequency/amplitude combinations for the arthrograph drive



A.2 Alternative torque transducer designs

In the course of designing the torque transducer a number of different designs were considered. Particular emphasis was placed on the elimination of the effect of point of loading on the measured torque.

A.2.1 Suggestion One - a difference cantilever

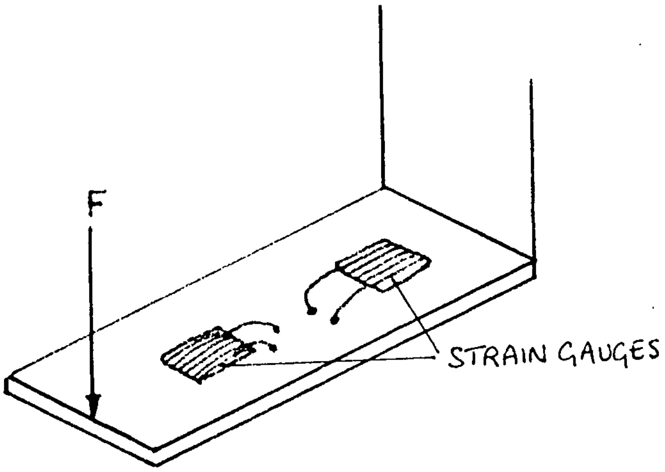
The principle of the difference cantilever is that the difference between two bending moments is considered as the indication of the applied force. The advantage of this design over one which measures only one bending moment is that for the same force, applied at different points along the length of the cantilever, the same differencee in bending moment will be measured. This situation is shown in fig. A2, case 1.

However, if two equal resistive torques are considered, which have different reactive loading positions along the cantilever length, the applied forces will not be the same. This situation is shown in fig. A2, case 2. For this case, the measured difference in bending moments for the same resistive torque at the joint will not be the same. Hence, this transducer design was not suitable.

A.2.2 Suggestion two - measurement of shear force

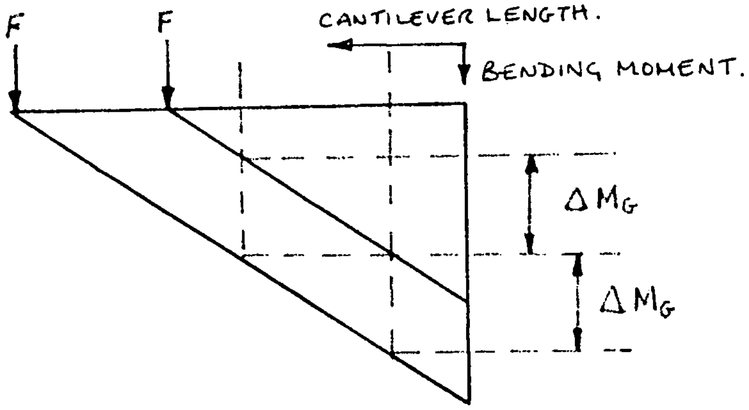
A second suggestion was to measure the shear force in the cantilever rather than the bending moment. The shear force diagram for forces applied at different points along the length of the cantilever is shown in fig. A3. Shear force is constant regardless of the position of the applied force. However, using exactly the same arguments as in suggestion one, the shear force for equal resistive torques, with different points of loading, will not be the same. Hence, this suggestion was not suitable either.

A2 Bending moment diagrams for difference cantilever



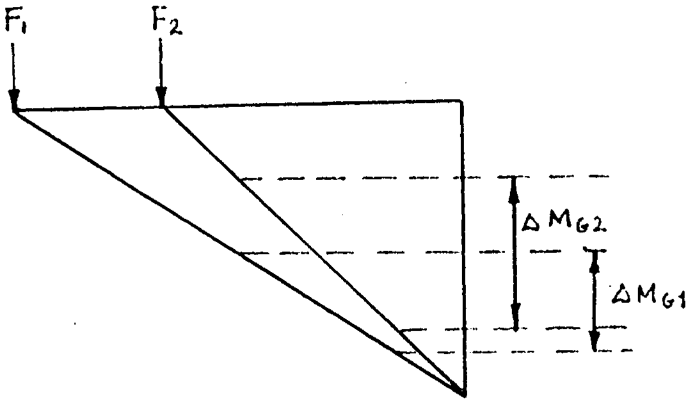
PHYSICAL LAYOUT

BENDING MOMENT DIAGRAMS



CASE 1

SAME FORCE, F, APPLIED AT DIFFERENT POINTS.



CASE 2

DIFFERENT FORCES, F1, F2, APPLIED AT DIFFERENT POINTS.

A.2.3 Suggestion three - Torque tube transducer

A torque tube transducer was used successfully by Thompson (1978) in his design for the horizontal knee arthrograph. It was thought that a similar transducer may have been suitable for the horizontal MCP arthrograph.

The basic principle of such a transducer is that the resistive torque at the joint causes twisting of a cylindrical tube. By measuring the change in shear strain due to the twist, the resistive torque at the joint can be determined. Strain gauges, aligned along the axis of maximum shear (45 degrees to the longitudinal axis) and connected to suitable amplification circuitry, provide an electrical analogue of the shear strain.

A critical element of the torque tube transducer is the thickness of the tube wall. Changes in wall thickness cause changes in the magnitude of shear strain at the outer tube surface. A calculation was performed to estimate the dimensions of a torque tube transducer suitable for the measurement of resistive torques at the MCP joint.

Reference should be made to fig. A.4.

The symbols used in the following calculation are defined as follows :

T - applied torque about the tube axis.

J - Polar second moment of area.

τ - shear stress

R - radial distance from the tube axis

E - modulus of elasticity of the tube material

ϵ - shear strain

Assumptions

1) A reasonable dimension for the tube outer radius, d_o, could be 20 mm.

2) The required torque resolution is 0.001 NM.

3) The tube material is steel. E for steel is $20 \times 10^{10} N/M^2$.

4) A reasonable minimum strain to measure would be 1 microstrain (1×10^{-6}).

The equation relating shear stress to the tube dimensions for a thin walled cylinder is given by,

$$\tau = \frac{RT}{J}$$

for the shear stress at the outer surface,

$R = \frac{d_o}{2}$, $J = \frac{\pi}{32} \times (d_o{}^4 - d_i{}^4)$

Thus,

$$\tau = T \times \frac{d_o}{2} \times \frac{32}{\pi} \times \frac{1}{(d_o{}^4 - d_i{}^4)}$$

Now,

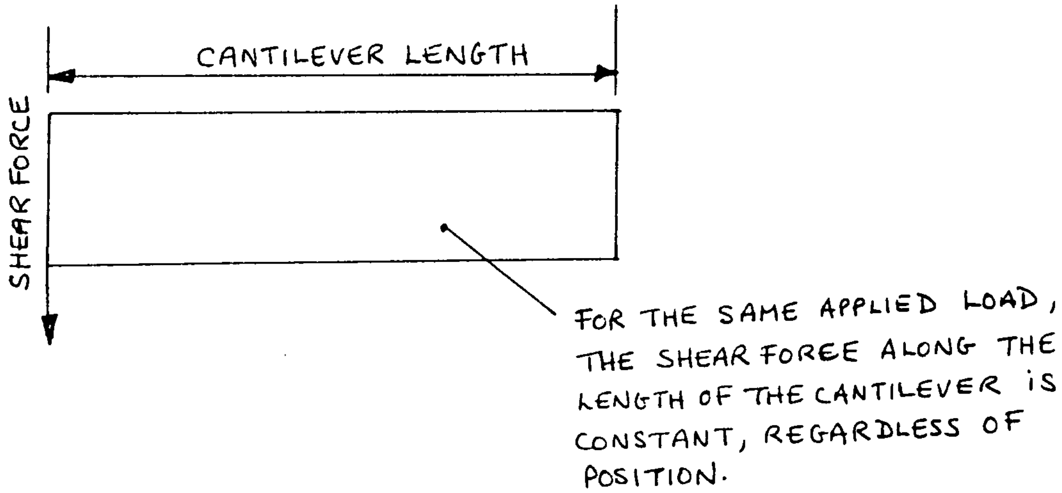
$$\tau = E\epsilon$$

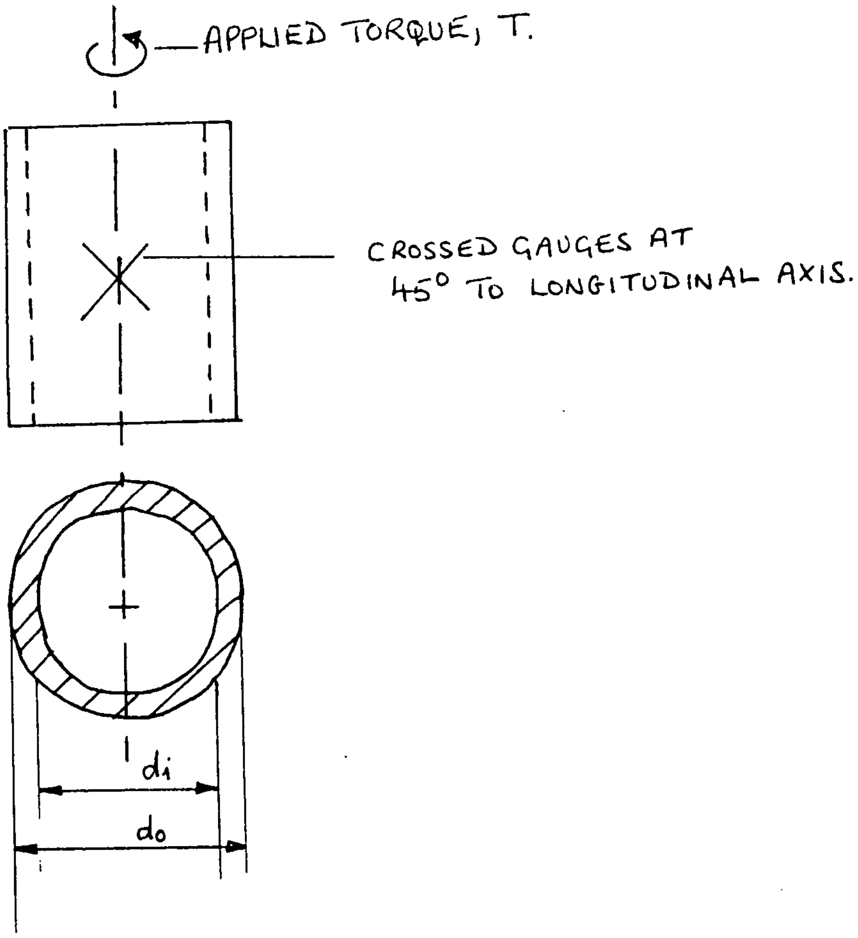
Substituting the minimum torque resolution for T, E for steel, 1 microstrain for ϵ and 20 mm for d_o, then,

$$d_i = 19.98mm$$

Therefore the thickness of the torque tube wall to produce the required resolution was estimated as 0.02 mm. It was thought that the manufacture of such a tube would present problems and that the ruggedness of the tube would be questionable. Consequently, this suggestion for the torque transducer was rejected.

Figure A3 Transducer suggestions Two and Three





APPENDIX TWO

Contents

6800 assembler listing of the grip machine control programme.

Full assembler listing of the grip strength machine control programme.(JB 15/7/86)

```
Line #      Source Statement
______      ________________

  1.2       DDRA EQU $3000
  2.        DDRB EQU $3002
  3.        CRA EQU $3001
  4.        CRB EQU $3003
  5.        TEMP EQU $0009
  6.        TEMP1 EQU $000A
  7.        TEMP2 EQU $000B
  8.        TEMP3 EQU $000C
  9.        TEMP4 EQU $000D
 10.        TEMP5 EQU $000E
 11.        TEMP6 EQU $000F
 12.        TEMP7 EQU $0010
 13.        TEMP8 EQU $0011
 14.        TEMP9 EQU $0012
 15.        TEMPA EQU $0013
 16.        TEMPB EQU $0014
 17.        TEMPC EQU $0015
 18.        TEMPD EQU $0016
 19.        TEMPE EQU $0017
 20.        TEMPF EQU $0018
 21.        TEMPO EQU $0019
 22.        TEMPG EQU $001A
 23.        DT0 EQU $1000
 24.        DT1 EQU $1001
 25.        DT2 EQU $1002
 26.        DT3 EQU $1003
 27.        DTC8 EQU $10C8
 28.        DT44 EQU $1044
 29.        DT64 EQU $1064
 30.        DT84 EQU $1084
 31         DTA8 EQU $10A8
 32         DTC7 EQU $10C7
 33         DTD3 EQU $10D3
 34.        DTDF EQU $10DF
 35.        DTD5 EQU $10D5
 36.        DTD8 EQU $10D8
 37.        DTDE EQU $10DE
 38.        DTD4 EQU $10D4
 39.        DT20 EQU $1020
 40.        DTD9 EQU $10D9
 41.        DTDA EQU $10DA
 42.        DTDD EQU $10DD
 43.        DTD6 EQU $10D6
 44.        DTD7 EQU $10D7
 45.        DTCC EQU $10CC
 46.        DTDC EQU $10DC
 47.        DTDB EQU $10DB
 48.        DTCD EQU $10CD
 49.        HSUM EQU $0000
 50.        LSUM EQU $0001
```

```
 51.      HMAX EQU $0002
 52.      LMAX EQU $0003
 53.      NUMB EQU $0004
 54.      MAXI EQU $0005
 55.      MAXM EQU $0006

Line #    Source Statement
______    ________________

 56.      MAXR EQU $0007
 57.      MAXL EQU $0008
 58.      TAB1 EQU $FB00
 59.      TAB14 EQU $FB14
 60.      TAB28 EQU $FB28
 61.      TAB3C EQU $FB3C
 62.      TAB50 EQU $FB50
 63.      TAB64 EQU $FB64
 64.      TAB78 EQU $FB86
 65.      TAB86 EQU $FB86
 66.      TAB94 EQU $FB94
 67.      TABA2 EQU $FBA2
 68.      TABB0 EQU $FBB0
 69.      TABBF EQU $FBBF
 70.      RAM0 EQU $2000
 71.      RAM1 EQU $2001
 72.      RAM2 EQU $2002
 73.      RAM3 EQU $2003
 74.       ORG $F000
 75.       LDS #$0030
 76.       LDX #DT0
 77.      START LDAA RAM0
 78.       CMPA #$01
 79.       BHI INPT
 80.       LDAA RAM1
 81.       CMPA #$01
 82.       BHI INPT
 83.       LDAA RAM2
 84.       CMPA #$01
 85.       BHI INPT
 86.       LDAA RAM3
 87.       CMPA #$01
 88.       BHI INPT
 89.       BRA START
 90.      INPT CLC
 91.       LDAA RAM0 ;READ INDEX FINGER
 92.       STAA $00,X ;STORE IN RAM
 93.       INX
 94.       CLC
 95.       LDAA RAM1 ;READ MIDDLE FINGER
 96.       STAA $00,X
 97.       INX
 98.       CLC
 99.       LDAA RAM2 ; READ RING FINGER
100.       STAA $00,X
101.       INX
102.       CLC
103.       LDAA RAM3 ; READ LITTLE FINGER
104.       STAA $00,X
105.       INX
106.       CPX #DTC8 ;4X50 READINGS ?
```

```
107.     BEQ CALC
108.     LDAA #$4E
109.    DEL LDAB #$FF ;DELAY BETWEEN READINGS
110.    DELY DECB
```

```
Line #     Source Statement
------     ----------------

111.     BNE DELY
112.     DECA
113.     BNE DEL
114.     BRA INPT ;GO BACK FOR NEXT
115.    CALC LDX #DT0 ;INIT RAM LOCATIONS
116.     CLRB
117.     STAB HMAX ;HBYTE OF MAX SUM
118.     STAB LMAX ;LBYTE OF MAX SUM
119.     STAB NUMB ;NUMBER OF TOTALS CALCULATED
120.    NEXT CLRB ;CLEARB FOR NUMBER OF NUMBERS ADDED
121.     STAB HSUM ; HBYTE STORE OF SUM
122.     STAB LSUM ;LBYTE STORE OF SUM
123.    ADFR CLC
124.     LDAA $00,X ;PICK OUT READING IN A GROUP OF FOUR
125.     ADDA LSUM ;ADD TO LOBYTE OF RUNNING SUM
126.     STAA LSUM
127.     LDAA #$00
128.     ADCA HSUM ;ADD CARRY TO HBYTE OF SUM
129.     STAA HSUM
130.     INCB ;KEEP TRACK OF NUMBERS ADDED
131.     INX
132.     CMPB #$03 ;HAVE WE GOT FOUR NUMBERS
133.     BLS ADFR ;IF NOT GO BACK
134.     LDAA HSUM
135.     CMPA HMAX ;CF. HBYTE OF RUNNING MAX. BRANCH IF  SMALLER
136.     BMI CONT
137.     BEQ CHCK ;BRANCH IF EQUAL
138.     STAA HMAX ;UPDATE HBYTE OF MAX.
139.     LDAA LSUM
140.    UPDT STAA LMAX
141.     BRA CONT
142.    CHCK LDAA LSUM ;IS LOBYTE OF NEW TOTAL LARGER
143.     CMPA LMAX ;THAN THAT OF RUNNING MAX.
144.     BHI UPDT
145.    CONT LDAA NUMB
146.     CMPA #$32
147.     BEQ ON ;BRANCH IF EQUAL TO FIFTY
148.     BRA NEXT ;BRANCH BACK TO CALCULATE NEXT TOTAL
149.    ON CLRB
150.     STAB MAXI ; RUNNING MAX INDEX STORE
151.     LDX #DT0
152.    DO1 LDAA $00,X ;LOOK FOR MAX READING FROM INDEX
153.     INX
154.     INX
155.     INX
156.     INX
157.     CMPA MAXI ;CF RUNNING MAX
158.     BLS GBK ;BRANCH IF LESS THAN MAX.
159.     STAA MAXI ;UPDATE IF NOT
160.    GBK INCB ;KEEP TRACK OF NO. OF NUMBERS COMPARED
161.     CMPB #$32
162.     BEQ DO2A ;BRANCH IF EQUAL TO FIFTY
```

```
 BRA DO1 ;OTHERWISE GO BACK FOR NEXT NUMBER
DO2A CLRB
 STAB MAXM ;RUNNING MAX. MIDDLE

Line #     Source Statement

 LDX #DT1
DO2 LDAA $00,X ;LOOK AT MIDDLE FINGER
 INX
 INX
 INX
 INX
 CMPA MAXM
 BLS GBK1
 STAA MAXM
GBK1 INCB
 CMPB #$32
 BEQ DO3A
 BRA DO2
DO3A CLRB
 STAB MAXR ;RUNNING MAX. RING STORED HERE
 LDX #DT2
DO3 LDAA $00,X ;LOOK AT RING FINGER
 INX
 INX
 INX
 INX
 CMPA MAXR
 BLS GBK2
 STAA MAXR
GBK2 INCB
 CMPB #$32
 BEQ DO4A
 BRA DO3
DO4A CLRB
 STAB MAXL ;RUNNING MAX. LITTLE STORED HERE
 LDX #DT3
DO4 LDAA $00,X
 INX
 INX
 INX
 INX
 CMPA MAXL
 BLS GBK3
 STAA MAXL
GBK3 INCB
 CMPB #$32
 BEQ CONFIG ;BRANCH TO CONFIGURATION OF PIA
 BRA DO4
CONFIG CLR CRA ;CLEAR CRA ACCESSING DDRA
 LDAA #$FF
 STAA DDRA ;SET DDRA FOR OUTPUTS
 CLR CRB ;CLEAR CRB ACCESSING DDRB
 CLR DDRB ;SET DDRB FOR INPUTS
 LDAA #$04 ;SET BIT2 OF CRA TO ACCESS DRA
 STAA CRA
 LDAB #$00
BLANK LDAA #$20
 STAA TEMP
```

```
 JSR OUTPT
 INCB
```

Line # Source Statement

```
 CMPB #$14
 BNE BLANK
 JSR PAUSE
 LDAB #$00
BLANK1 LDAA #$20
 STAA TEMP
 JSR OUTPT
 INCB
 CMPB #$14
 BNE BLANK1
 JSR PAUSE
 LDX #TAB1
OUT1 LDAA $00,X
 STAA TEMP
 JSR OUTPT ;OUTPUT NEWTONS
 INX
 CPX #TAB14
 BNE OUT1
 JSR PAUSE ;PAUSE OF 750ms FOR PRINT OP.
 LDAA MAXI ;LOAD MAX INDEX VALUE
 CMPA #$46 ;SEE IF ANY FINGER EXCEEDS 70N
 BHI FULL : TO DETERMINE SCALE
 LDAA MAXM ;LOAD MAX MIDDLE
 CMPA #$46
 BHI FULL
 LDAA MAXR ;LOAD MAX RING
 CMPA #$46
 BHI FULL
 LDAA MAXL ;LOAD MAX LITTLE
 CMPA #$46
 BHI FULL
 LDAA #$04
 STAA TEMP1 ;SET TEMP1 TO 4 FOR SCALE
 JMP GOON
FULL LDAA #$0F
 STAA TEMP1 ;SET TEMP1 TO 0C FOR LOW RES. SCALE
 LDX #TAB14
OUT2 LDAA $00,X ;LABEL AXIS FOR SMALL SCALE
 STAA TEMP
 JSR OUTPT
 INX
 CPX #TAB28
 BNE OUT2
 JSR PAUSE
 LDAB #$00
 JMP AXIS
GOON LDX #TAB28 ;LABEL AXIS FOR LARGE SCALE
OUT3 LDAA $00,X
 STAA TEMP
 JSR OUTPT
 INX
 CPX #TAB3C
 BNE OUT3
 JSR PAUSE
```

```
  LDAB #$00

Line #    Source Statement
______    ________________

AXIS LDAA #$2D
  STAA TEMP
  JSR OUTPT ; OUTPUT "______________"
  INCB
  CMPB #$14
  BNE AXIS
  JSR PAUSE
GOON1 LDX #DT0 ;FIRST READING
MORE CLRA
  STAA TEMP2 ;LOC FOR INDEX POSITION
  STAA TEMP3 ;LOC FOR MID POSITION
  STAA TEMP4 ;LOC FOR RING POSITION
  STAA TEMP5 ;LOC FOR LITTLE POSITION
  STAA TEMP6 ;COMPARISON
  STAA TEMP7 ;CURRENT POSITION
WHERE LDAA $00,X
  CMPA TEMP6
  BLS STAR
  LDAB TEMP7
  INCB
  STAB TEMP7
  LDAB TEMP1 ;HOW MANY TIMES TO INCREMENT
  LDAA TEMP6
LOOP INCA
  DECB
  BNE LOOP
  STAA TEMP6
  JMP WHERE ;LOOK TO NEXT POSITION
STAR LDAB TEMP7
  STAB TEMP2
  INX
  CLRA
  STAA TEMP6 ;PREPARE FOR NEXT
  STAA TEMP7
WHER2 LDAA $00,X
  CMPA TEMP6
  BLS CROSS
  LDAB TEMP7
  INCB
  STAB TEMP7
  LDAB TEMP1
  LDAA TEMP6
LOOP1 INCA
  DECB
  BNE LOOP1
  STAA TEMP6
  JMP WHER2
CROSS LDAB TEMP7
  STAB TEMP3 ;POSITION OF CROSS
  INX
  CLRA
  STAA TEMP6
  STAA TEMP7
WHER3 LDAA $00,X
  CMPA TEMP6
```

Line # Source Statement

```
 BLS DOT
 LDAB TEMP7
 INCB
 STAB TEMP7
 LDAB TEMP1
 LDAA TEMP6
LOOP2 INCA
 DECB
 BNE LOOP2
 STAA TEMP6
 JMP WHER3
DOT LDAB TEMP7
 STAB TEMP4 ;POSITION OF DOT
 INX
 CLRA
 STAA TEMP6
 STAA TEMP7
WHER4 LDAA $00,X
 CMPA TEMP6
 BLS CIRCLE
 LDAB TEMP7
 INCB
 STAB TEMP7
 LDAB TEMP1
 LDAA TEMP6
LOOP3 INCA
 DECB
 BNE LOOP3
 STAA TEMP6
 JMP WHER4
CIRCLE LDAB TEMP7
 STAB TEMP5
 INX
 LDAA #$20
 CPX #DT20 ;EIGHT GROUPS OF 4
 BNE SKIP3
 LDAA #$31 ;OUTPUT "1"
SKIP3 CPX #DT44
 BNE SKIP4
 LDAA #$32 ;OUTPUT"2"
SKIP4 CPX #DT64
 BNE SKIP5
 LDAA #$33 ;OUTPUT "3"
SKIP5 CPX #DT84
 BNE SKIP6
 LDAA #$43 ;OUPUT "4"
SKIP6 CPX #DTA8
 BNE SKIP7
 LDAA #$35 ;"OUTPUT "5"
SKIP7 CPX #DTC8
 BNE SKIP8
 LDAA #$36 ;OUTPUT "6"
SKIP8 STAA TEMP
 JSR OUTPT ;OUTPUT WHATEVER
 LDAA #$6C
```

```
Line #     Source Statement
------     ----------------

 386.       STAA TEMP
 387.       JSR OUTPT  ;OUTPUT "I"
 388.       LDAB #$01
 389.      PRINT CMPB TEMP2  ;"*" HERE ?
 390.       BEQ SCB1
 391.       CMPB TEMP3  ;"+" HERE ?
 392.       BEQ SCB2
 393.       CMPB TEMP4  ;"." HERE ?
 394.       BEQ SCB3
 395.       CMPB TEMP5  ;"O" HERE ?
 396.       BEQ SCB4
 397.       INCB
 398.       LDAA #$20
 399.       STAA TEMP
 400.       JSR OUTPT
 401.       CMPB #$13  ;TWENTY NO'S (TWO HAVE GONE)
 402.       BEQ SCB6
 403.       BRA PRINT
 404.      SCB1 LDAA #$2A
 405.       STAA TEMP
 406.       JSR OUTPT  ; OUTPUT "*"
 407.       BRA SCB5
 408.      SCB2 LDAA #$2B
 409.       STAA TEMP
 410.       JSR OUTPT  ; OUTPUT "+"
 411.       BRA SCB5
 412.      SCB3 LDAA #$2E
 413.       STAA TEMP
 414.       JSR OUTFT  ; OUTPUT "."
 415.       BRA SCB5
 416.      SCB4 LDAA #$6F
 417.       STAA TEMP
 418.       JSR OUTPT
 419.      SCB5 CMPB #$13  ;CHECK FOR TWENTY NUMBERS
 420.       BEQ SCB6
 421.       INCB
 422.       JMP PRINT
 423.      SCB6 JSR PAUSE
 424.       CPX #DTC8  ;LAST?
 425.       BEQ WRITE
 426.       JMP MORE  ;NEXT SET OF FOUR NUMBERS
 427.      WRITE LDX #TAB3C
 428.      OUT4 LDAA $00,X
 429.       STAA TEMP
 430.       JSR OUTPT
 431.       INX
 432.       CPX #TAB50
 433.       BNE OUT4
 434.       JSR PAUSE
 435.      OUT5 LDAA $00,X  ; WRITE INDEX * .MIDDLE +
 436.       STAA TEMP
 437.       JSR OUTPT
 438.       INX
 439.       CPX #TAB64
 440.       BNE OUT5

Line #     Source Statement
```

```
441.     JSR PAUSE
442.    OUT6 LDAA $00,X
443.     STAA TEMP ; WRITE . RING , O LITTLE
444.     JSR OUTPT
445.     INX
446.     CPX #TAB78
447.     BNE OUT6
448.     JSR PAUSE
449.     LDX #DTD3
450.     LDAB #$20
451.     LDAA #$00
452.    CLEAR STAB $00,X
453.     INX
454.     CPX #DTDF
455.     BNE CLEAR
456.    *CONVERT TO ASCII CHARACTERS
457.     LDAA MAXI ; INDEX MAX.
458.     LDX #DTD5
459.     JSR CONVT
460.     LDAA MAXM ;MIDDLE MAX.
461.     LDX #DTD8
462.     JSR CONVT
463.     LDAA MAXR ;RING MAX.
464.     LDX #DTDB
465.     JSR CONVT
466.     LDAA MAXL ;LITTLE MAX.
467.     LDX #DTDE
468.     JSR CONVT
469.     LDX #TAB78
470.    RSLT1 LDAA $00,X
471.     STAA TEMP
472.     JSR OUTPT ;PRINT MAX. INDEX
473.     INX
474.     CPX #TAB86
475.     BNE RSLT1
476.     LDAA DTD3
477.     STAA TEMP ;PRINT VALUE
478.     JSR OUTPT
479.     LDAA DTD4
480.     STAA TEMP
481      JSR OUTPT
482.     LDAA DTD5
483.     STAA TEMP
484.     JSR OUTPT
485.     LDAA #$20
486.     STAA TEMP
487.     JSR OUTPT
488.     JSR OUTPT
489.     JSR OUTPT
490.     JSR PAUSE
491.     LDX #TAB86
492.    RSLT2 LDAA $00,X
493.     STAA TEMP
494.     JSR OUTPT
495.     INX

Line #   Source Statement
```

```
496.      CPX #TAB94
497.      BNE RSLT2
498.      LDAA DTD6  ;PRINT VALUE
499.      STAA TEMP
500.      JSR OUTPT
501.      LDAA DTD7
502.      STAA TEMP
503.      JSR OUTPT
504.      LDAA DTD8
505.      STAA TEMP
506.      JSR OUTPT
507.      LDAA #$20
508.      STAA TEMP
509.      JSR OUTPT
510.      JSR OUTPT
511.      JSR OUTPT
512.      JSR PAUSE
513.      LDX #TAB94  ; PRINT RING MAX.
514.    RSLT3 LDAA $00,X
515.      STAA TEMP
516.      JSR OUTPT
517.      INX
518.      CPX #TABA2
519.      BNE RSLT3
520.      LDAA DTD9
521.      STAA TEMP
522.      JSR OUTPT
523.      LDAA DTDA
524.      STAA TEMP
525.      JSR OUTPT
526.      LDAA DTDB
527.      STAA TEMP
528.      JSR OUTPT
529.      LDAA #$20
530.      STAA TEMP
531.      JSR OUTPT
532.      JSR OUTPT
533.      JSR OUTPT
534.      JSR PAUSE
535.      LDX #TABA2  ;PRINT LITTLE MAX.
536.    RSLT4 LDAA $00,X
537.      STAA TEMP
538.      JSR OUTPT
539.      INX
540.      CPX #TABB0
541.      BNE RSLT4
542.      LDAA DTDC  ;PRINT VALUE
543.      STAA TEMP
544.      JSR OUTPT
545.      LDAA DTDD
546.      STAA TEMP
547.      JSR OUTPT
548.      LDAA DTDE
549.      STAA TEMP
550.      JSR OUTPT

Line #    Source Statement
```

```
551.    LDAA #$20
552.    STAA TEMP
553.    JSR OUTPT
554.    JSR OUTPT
555.    JSR OUTPT
556.    JSR PAUSE
557.   *NOW CONVERT MAX. OVERALL TO ASCII
558.    LDX #TABB0 ;PRINT MAX. OVERALL
559.   RSLT5 LDAA $00,X
560.    STAA TEMP
561.    JSR OUTPT
562.    INX
563.    CPX #TABBF
564.    BNE RSLT5
565.    LDAA #$00
566.    STAA TEMP8
567.    STAA TEMP9
568.    STAA TEMPA
569.    STAA TEMPB
570.    LDAA #$20
571.    STAA TEMPC
572.    STAA TEMPD
573.    STAA TEMPE
574.    STAA TEMPF
575.    LDAA HMAX
576.    CMPA #$03
577.    BHI OVLRD
578.    BNE CHOCK1
579.    LDAA #$07
580.    STAA TEMP9
581.    LDAA #$06
582.    STAA TEMPA
583.    LDAA #$08
584.    STAA TEMPB
585.    JMP CHOCK3
586.   CHOCK1 LDAA HMAX
587.    CMPA #$02
588.    BNE CHOCK2
589.    LDAA #$05
590.    STAA TEMP9
591.    LDAA #$01
592.    STAA TEMPA
593.    LDAA #$02
594.    STAA TEMPB
595.    JMP CHOCK3
596.   CHOCK2 LDAA HMAX
597.    CMPA #$01
598.    BNE CHOCK3
599.    LDAA #$02
600.    STAA TEMP9
601.    LDAA #$05
602.    STAA TEMPA
603.    LDAA #$06
604.    STAA TEMPB
605.   CHOCK3 LDAA #$00

Line #     Source Statement
-------    ----------------

606.    STAA TEMP8
```

```
  LDX #TEMPB
  LDAA LMAX
HERE3 LDAB #$00
HERE5 CMPA #$09
  BLS HERE4
  SUBA #$0A
  INCB
  BRA HERE5
HERE4 ADDA $00,X
  CMPA #$09
  BLS THERE1
  SUBA #$0A
  INCB
THERE1 ADDA #$30
  STAA $04,X
  CPX #TEMP+8
  BEQ RITE2
  DEX
  TBA
  BRA HERE3
OVLRD LDAA #$4D
  STAA TEMP
  JSR OUTPT ;PRINT M
  LDAA #$41
  STAA TEMP
  JSR OUTPT
  LDAA #$58
  STAA TEMP
  JSR OUTPT
  LDAA #$2E
  STAA TEMP
  JSR OUTPT
  LDAB #$00
  LDAA #$20
  STAA TEMP
BLANK2 JSR OUTPT
  INCB
  CMPB #$10
  BNE BLANK2
  JSR PAUSE
  BRA END
RITE2 LDAA TEMPC
  STAA TEMP
  JSR OUTPT
  LDAA TEMPD
  STAA TEMP
  JSR OUTPT
  LDAA TEMPE
  STAA TEMP
  JSR OUTPT
  LDAA TEMPF
  STAA TEMP
  JSR OUTPT
  LDAA #$20

Line #    Source Statement
------    ----------------

  STAA TEMP
  JSR OUTPT
```

```
663.      JSR OUTPT
664.      JSR PAUSE
665.      LDAA #$20  ;CODE FOR 8 LINE FEEDS
666.      STAA TEMP
667.      LDAA #$00
668.     BLANK4 LDAB $00
669.     BLANK3 JSR OUTPT
670.      INCB
671.      CMPB #$14
672.      BNE BLANK3
673.      JSR PAUSE
674.      INCA
675.      CMPA #$08
676.      BNE BLANK4
677.      NOP
678.      NOP
679.      NOP
680.      NOP
681.      NOP
682.      NOP
683.      NOP
683.1    END JMP $FC00
684.     *OUTPT SUBROUTINE.THIS SUBROUTINE SENDS THE ASCII
685.     *CHARACTERS STORED IN LOC. TEMP TO THE PRINTER
686.     OUTPT PSHA ;SAVE REGISTERS
687.      PSHB
688.      CLC
689.      LDAA TEMP
690.      ROLA
691.      LDAB #$0B  ;BIT COUNT
692.     OUT STAA DDRA ;OUTPUT THE BIT
693.      STAA TEMPG
694.      LDAB #$80
695.     PAUS DECB ; DELAY FOR 1200 BAUD
696.      BNE PAUS
697.      LDAB TEMPG ;RETRIEVE B
698.      RORA
699.      SEC
700.      DECB ;DECREMENT BIT COUNT
701.      BNE OUT
702.      PULB
703.      PULA
704.      RTS
705.     *PAUSE SUBROUTINE .THIS IS A DELAY OF 750 MS
706.     *NECESSARY FOR CORRECT PRINTER OPERATION
707.     PAUSE PSHA
708.      PSHB
709.      LDAB #$FF
710.     PAUS2 LDAB #$FF
711.     PAUS1 DECB
712.      NOP
713.      NOP
714.      NOP

Line #   Source Statement
------   ----------------

715.      BNE PAUS1
716.      DECA
717.      BNE PAUS2
```

```
 PULB
 PULA
 RTS
*CONVT SUBROUTINE. THIS CONVERTS THE ONE BYTE
*NUMBER STORED IN REGISTER A FROM HEX. TO ASCII
*AND STORES THE RESULTS IN MEMORY LOCS.
*X-2,X-1,X
CONVT LDAB #$00
TEST CMPA #$09
 BLS DONE
 SUBA #$0A
 INCB
 BRA TEST
DONE ADDA #$30 ;CONVERT TO ASCII
 STAA $00,X
 TBA
 CMPA #$00
 BEQ STOP
 DEX
 BRA CONVT
STOP RTS
*WHAT FOLLOWS IS A TABLE OF VALUES FOR
* OUTPUTTING THE LETTERING AND LABELS
* ON THE GRAPH
 ORG $FB00
TBL FCB $20.$20,$20,$20,$20,$20,$20,$4E,$45,$57
 FCB $54.$4F,$4E,$53,$20,$20,$20,$20,$20,$20
 FCB $20,$20,$20,$33,$30,$20,$20,$20.$20,$31
 FCB $32.$30,$20,$20,$20,$20,$20,$32,$34,$30
 FCB $20.$20,$34.$20,$20,$20,$32,$30,$20.$20
 FCB $20,$34,$30.$20,$20,$20,$20,$36,$34,$20
 FCB $53,$45,$43,$53,$20,$20,$20,$20,$20,$20
 FCB $20.$20,$20.$20,$20,$20,$20,$20,$20.$20
 FCB $2A,$69,$6E,$64,$65,$78,$2C,$20.$2B,$6D

Line #      Source Statement
--------    ------------------------

 FCB $69,$64,$64,$6C,$65.$20.$20.$20.$20.$20
 FCB $2E,$72,$69,$6E,$67.$2C,$20.$6[illegible].$6C.$69
 FCB $74,$74,$6C.$65.$20.$20.$20.$20.$20.$20
 FCB $4D.$61,$78.$2E,$20.$69,$6E.$64.$65.$78
 FCB $20.$20.$3D.$20.$4D.$61.$78.$2E.$20.$6D
 FCB $69,$64,$64.$6C.$65.$20.$3D.$20.$4D.$61
 FCB $78,$2E,$20.$72,$69.$6E.$67.$20.$20.$20
 FCB $3D.$20.$4D.$61.$78.$2E.$20.$6C.$69.$74
 FCB $74,$6C,$65,$20.$3D.$20.$4D.$61.$78.$2E
 FCB $20,$4F,$76,$65.$72.$61,$6C.$6C.$3D.$20
 FCB $20,$20
 END
```

CROSS-REFERENCE

CROSS-REFERENCE