THE TORQUE-ANGULAR VELOCITY RELATIONSHIP IN HUMAN MUSCULAR CONTRACTION

by

David John Sanderson

B.Sc. (Kinesiology) Simon Fraser University, 1972

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (KINESIOLOGY) in the Department of Kinesiology

© DAVID JOHN SANDERSON 1975
SIMON FRASER UNIVERSITY
AUGUST 1975

All rights reserved. This thesis may not be reproduced in whole or in part, by photocopy or other means without permission of the author.
APPROVAL

NAME: David John Sanderson

DEGREE: Master of Science (Kinesiology)

TITLE OF THESIS: The torque-angular velocity relationship in human muscular contraction

EXAMINING COMMITTEE:

Chairman: Dr. N.M.G. Bhakthan

Dr. A.E. Chapman
Senior Supervisor

Dr. A.J. Davison

Dr. E.W. Banister

Dr. G. Bojadziev

Dr. T.W. Calvert

Dr. J.B. Morrison
External Examiner
Associate Professor
Kinesiology Department
Simon Fraser University

Date Approved: [Date]
PARTIAL COPYRIGHT LICENSE

I hereby grant to Simon Fraser University the right to lend my thesis or dissertation (the title of which is shown below) to users of the Simon Fraser University Library, and to make partial or single copies only for such users or in response to a request from the library of any other university, or other educational institution, on its own behalf or for one of its users. I further agree that permission for multiple copying of this thesis for scholarly purposes may be granted by me or the Dean of Graduate Studies. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Title of Thesis/Dissertation:

The torque-angular velocity relationship in human muscular contraction

Author:

D. SANDERSON

(date) 24 1975

(signature)
This study proposed examination of the characteristics of an assumed model of muscular contraction for intact human muscles. This model comprises three components: a contractile component (CC), an elastic component in series with the contractile component (SEC) and an elastic component in parallel with the other two components (PEC). It has been shown on isolated muscle preparations that there is a difference in the force-velocity curve ascribable to the method used in the determination of that curve. This observation stimulated the present investigation.

The same apparatus was used for two separate experiments to determine the torque-angular velocity relationship of the elbow flexors over a range of excursion of the elbow-joint. Experiment 1 used the method described by MacPherson (1953) for isolated muscles and adapted it to intact human muscular contraction. This method, based on non-linear differential equations, was successfully adapted to the present experimental situation. However, the experimental results exposed some curious events. A necessary condition for the completion of the analysis was that the rise in torque in an isometric contraction be quicker than when there was an added series compliance. While other research has shown that this condition can be satisfied on isolated preparations the exact opposite event was recorded repeatedly here. Possible anatomical and physiological explanations were discussed but it was concluded that further research was required.
Experiment 2 dealt with the development of the torque-angular velocity curve from dynamic contractions. To obtain points on the torque-angular velocity curve when the velocity was zero, some isometric contractions were completed at five elbow positions from 0.5 radians to 2.0 radians where 0.0 radians was full extension. There appeared to be a variation in the torque-angular velocity curve as a consequence of the position of the elbow-joint. This variation arose out of the interaction of two components; the effect of the change in length of the muscle in reducing the production of torque at long lengths, and the modifications to the angle of pull of the tendon on the radius as a consequence of the joint anatomy.

The compliance of the SEC was determined from the torque-angular velocity curve derived from dynamic contractions and the rise of torque during an isometric contraction. The compliance-torque curve appeared similar to curves shown in other studies. The shape of the compliance-torque curve was similar regardless of the angle of the elbow-joint. This implied that the characteristics of the SEC did not change with elbow position.
# TABLE OF CONTENTS

**ABSTRACT**

**LIST OF TABLES**

**LIST OF FIGURES**

## CHAPTER

### I  INTRODUCTION

### II  RELATED LITERATURE

- Historical development
- Characteristics of isolated muscle
- Characteristics of intact muscle
- Statement of Problem

### III  MATERIALS, METHODS and PROCEDURES

**Materials**

**Methods**

- a) The apparatus used for the measurement of torque, displacement, and acceleration
- b) The dynamometer used for the transduction of torque, displacement, and acceleration
  - i) Transduction of torque
  - ii) Transduction of displacement
  - iii) Transduction of acceleration
- c) Calibration of transducers
  - i) Static properties
  - ii) Dynamic properties
- d) Filtering the output from the transducers
- e) Permanent recording of the output from the transducers
  - i) The frequency modulated (FM) tape-recorder
  - ii) Analogue to digital conversion
  - iii) Recording oscillograph

**Procedures**

- a) Procedures-Experiment 1
  - i) Work-session 1
  - ii) Work-session 2
  - iii) Work-session 3
- b) Procedures - Experiment 2

### IV  METHOD OF ANALYSIS

- a) Calibration during the experiment
  - i) Calibration constants
  - ii) Determination of the moment of inertia of the forearm
  - iii) Estimation of the gravitational effect on the lever with the cast and forearm attached
b) Experiment 1 - Determination of the torque-angular velocity relationship from two isometric contractions
   i) MacPherson's method 61
   ii) Modification to fit rotational system 65
   iii) Data manipulation 69

c) Experiment 2 - Determination of the torque-angular velocity relationship from dynamic contractions
   i) Data manipulation 71
   ii) Determination of the time-constant of the rise in torque 73
   iii) Determination of the compliance of the SEC 74

V ACCURACY OF RESULTS 76

VI RESULTS 78

VII DISCUSSION 115
   a) Experiment 1 115
   b) Experiment 2 121

VIII CONCLUSIONS 129

IX SUMMARY 131

BIBLIOGRAPHY 135

APPENDIXES 138
LIST OF TABLES

TABLE 1: Time constants for the rise in torque during isometric contractions for subjects AC and HW.

LIST OF FIGURES

FIGURE 1: The length-tension curve for isolated frog muscle.

FIGURE 2: The force-velocity-length curve for isolated rat gracilus anticus muscle.

FIGURE 3: The linear horizontal equivalent model used to describe elbow flexion for intact human muscle.

FIGURE 4: The apparatus used in the present study.

FIGURE 5: This spring provided a compliant connection between the two half shafts.

FIGURE 6: This shows the two halves of the cast used to prevent wrist flexion during contraction.

FIGURE 7: This is a schematic of the dynamometer used in the experiment.

FIGURE 8: This is the circuit diagram for each of the transducers.

FIGURE 9: This is the main amplifying unit.

FIGURE 10: This is a drawing of the system described by MacPherson (1953).

FIGURE 11: This is a drawing of the system described in figure 10 as modified to suit the present study.

FIGURE 12: The rise in torque in two contractions, one with the added compliance and the other without the added compliance.

FIGURE 13: The torque-angle curve for subject AC.

FIGURE 14: The torque-angle curve for subject HW.

FIGURE 15: The torque-angular velocity curves for different sessions and at different joint angles for subject AC.

FIGURE 16: The torque-angular velocity curves determined by drawing a smooth line through the points displayed in figure 15.
FIGURE 17: The torque-angular velocity curves for different sessions and at different joint angles for subject HW.

FIGURE 18: The torque-angular velocity curves determined by drawing a smooth line through the points displayed in figure 17.

FIGURE 19: The compliance-torque curves for different sessions and at different joint angles for subject AC.

FIGURE 20: The compliance-torque curves for different sessions and at different joint angles for subject HW.
INTRODUCTION

A great deal of the knowledge concerning muscular contraction has been determined from experiments with isolated muscle preparations. These preparations were desirable because variables such as muscle length and activation could be carefully controlled. While these studies were used to examine the mechanisms of contraction in frog muscles the results could be applied to intact human muscles. In this manner a composite picture of muscular activity could be obtained.

Many investigators have used conceptual models to describe the physiological events surrounding muscular contraction. A conceptual model has been devised which describes quite satisfactorily the phenomena associated with muscular contraction. Rigorous application of this model to describe more complex systems, e.g. intact human muscular contraction, has presented some problems. For example, Wilkie (1950) used a conceptual model to describe flexor activity in human subjects. Chapman (1973) has shown that Wilkie's conclusions were particular to one elbow position only and that there were changes in some other factors which prevented the extrapolation from Wilkie's data to other elbow positions. A model which is applicable to one set of conditions only is not as useful as one which describes activity under a wide range of conditions.

A major problem associated with precise determination of the characteristics of intact muscle is attributable to the complexity introduced by considering the muscle as part of a
much larger complex system. It is difficult to quantify, and in some cases qualify, the involvement of extraneous factors so as to take their affect into account. This is especially evident when one has to consider the conscious subjective control of the human subject over his actions.

The present experiments examine the dependancy of the torque-angular velocity curve for human muscular contraction on the technique used to derive that curve. The characteristics of the CC depend upon whether the experimental conditions required isometric contractions or whether the conditions required dynamic contractions (Parmley, Yeatman and Sonnenblick, 1970). If the behaviour of an isolated muscle depends upon the type of resistance encountered then one can only wonder at what constitutes the real characteristics of each component. Isometric and dynamic contractions will be employed in this study to derive the torque-angular velocity curve which should provide a means of comparing the characteristics of the muscle under different experimental conditions.

The following section outlines some of the historical development of research in this area. This section is followed by the description of an experiment designed to investigate some of the areas associated with human muscular contraction. The implications of these findings are discussed in the final sections.
Related Literature

Historical Development

In an attempt to understand the mechanisms of gross muscular activity, investigators have used mechanical analogues. They attempted to design mechanical models that adequately described the many characteristics of this physiological activity. Early studies relied upon observations on the mechanical output of a muscle. Later, measures of the heat released during a contraction were used as indicators of any internal changes resulting in that mechanical output.

The observation that a muscle moved lighter loads at a higher velocity than it moved heavier loads initiated considerable research into the subject of the mechanical features of muscular contraction. Early investigators (Fick, 1882; Blix, 1893) represented the muscle as a spring moving through a viscous medium and they observed that a tetanized muscle did less work if allowed to shorten quickly against a small mass. This observation was considered indicative of the supposition that when shortening much of the muscular energy was degraded into heat when overcoming the internal or viscous resistance. This internal resistance was greater the more rapid the movement (Fick, 1893).

Laulaine (1905) was among the first to recognize explicitly that in human muscular movement the efficiency (work/total energy used) varied with the speed of contraction.
The existence of such a relationship invited studies into the possibility of a relationship between shortening speed and force exerted. Surprisingly, this line of investigation was not undertaken until Hill (1922) reintroduced the idea of 'muscle viscosity' to account for the decrease in force with an increase in the speed of shortening observed during experiments on the elbow flexors. He showed that the work done increased rapidly at first during a single contraction and then more slowly becoming asymptotic with time reaching a theoretical maximum. This observation identified the amount of energy degraded to heat with viscous resistance within the muscle. The amount of energy dissipated in overcoming the frictional resistance was proportional to the speed of the contraction (Lupton, 1922).

Gasser and Hill (1924) repeated Hill's earlier work to examine whether there could have been any reciprocal innervation that would have distorted Hill's studies (i.e. the results might have been the consequence of nervous activity rather than muscle activity alone). They were able to confirm Hill's conclusions, however, using isolated frog muscles. They concluded that "...the phenomena investigated are not due primarily to an intervention of the nervous system, but to some fundamental character of the muscle fibre itself." (Gasser and Hill, 1924). The question of whether the relationship was the consequence of a viscosity factor remained to be determined.

In 1927 Levin and Wyman studied quick stretches and releases in contracting muscle. They observed that the tension
never responded instantaneously to the stretch or release. Secondly, the classically proposed linear relationship between force and velocity of the theoretical viscous model was found instead to be a non-linear one.

To account for these differences Levin and Wyman suggested some modifications to the single spring model previously postulated. They proposed adding an undamped spring in series with the damped spring. This latter model satisfactorily described their data.

The investigations of Boukeart, Capellen and de Blende (1930) also confirmed the modifications of Levin and Wyman. The conclusions they reached from studies on isolated frog muscle, were that "...there was no doubt that the muscle behaves as a viscous elastic system of the damped undamped two spring type." (Boukeart et al., 1930). The investigations during this era supported the viscous hypothesis which was considered applicable to a wide variety of muscles from dogfish (Hursh, 1938) to tortoises (Wyman, 1926). However, Penn in cooperation with Marsh produced some controversial findings that demanded modification of the viscous model (Penn and Marsh, 1935).

Penn and Marsh (1935) examined the muscular force at different speeds of shortening using isolated frog and cat muscles by studying the mechanical properties of muscle deprived of any participation by possible non-viscous elastic elements. This was done by observing the speed of shortening under different isotonic loads varying from zero to the maximum
which could be lifted.

They found that the force-velocity characteristics of the isolated contractile element did not follow the equation derived by Hill (1922). They re-expressed the relationship referring to a coefficient of tension loss, rather than a coefficient of viscosity, as being a major factor in determining the force-velocity characteristics of a muscle. This claim was supported by the observation of the non-linearity of the force-velocity relationship. "...this exponential relation was concerned in some way with the process of developing extra energy for the work of shortening and that a muscle cannot properly be treated as a simple mechanical system."

Three years later Hill (1935) developed the force-velocity relationship in the course of experiments examining the heat production of isolated frog muscle. This curve was similar to that of Penn and Marsh (1935) but obeyed a simpler and more convenient relationship:

\[( P + a )V = ( Po - P )b \]

where \( P \) is the force, \( V \) the velocity of shortening, and \( Po \) the isometric maximum force developed. The values for \( a \) and \( b \) were chosen to give the best fit of the equation to a series of observed values of \( V \) and \( P \) and the constants 'b' and 'a' have the dimensions of velocity and force respectively.

This study dealt the final blow to the viscosity hypothesis which had held scientists captive for so long. "The fact that a muscle shortens more slowly under greater force was
due, not to 'viscosity' but as Penn has claimed, to the manner in which energy liberation was regulated. A large force causes a low energy rate, which results in a low speed." (Hill 1938). The muscle was still described as a two-component system with an undamped elastic element and a contractile element in series. The characteristic equation for the force-velocity relationship described the activity of the contractile element.

The characteristic equation (1) and model suffered some limitations in that they were essentially empirical and made no statements about the mechanisms underlying the properties of the contractile component. They did describe accurately the phenomenological relationships and in doing so provided a convenient mechanism by which one could study muscle action. There have been other equations derived to describe the force-velocity relationship (Penn and Marsh, 1935; Polissar, 1952; Abbott and Wilkie, 1953) but they were in no fundamental conflict with Hill's derivation. Later studies confirmed the applicability of Hill's characteristic force-velocity relationship to several muscle types without excluding the other possible equations (Katz, 1939; Abbott and Lowy, 1952; Ritchie, 1954).

Characteristics of isolated muscle

The force-velocity relationship adequately describes the activity of the contractile component (CC) of skeletal muscle. However, there are other structures which also contribute to
the mechanical output of the muscle. Investigations into the properties of length and tension of a muscle began as early as 1893 (Blix). Studies conducted through the following years produced some conflicting results concerning the length-tension relationship and its anatomical basis. Ramsey and Street (1940) attributed these conflicts primarily to differences in experimental technique and, as a consequence, to the magnitude of the resting tension.

To settle these differences Ramsey and Street (1940) examined the isometric length-tension diagram of isolated frog semi-tendonous muscle fibres. The length-tension curve that they developed comprised three subcomponents, one being the sum of the other two. The curve r in figure 1 represented the passive length-tension relationship developed for isolated muscle. The muscle was stretched in stages and tension recorded at each increment of stretch. Having noted this curve the next step was to identify the anatomical correlates. The investigators developed a technique that allowed them to destroy the muscle fibres alone without altering the external sarcolemma. Isolated sarcolemma from such a preparation possessed a curve for the passive stretch identical to intact muscle indicating that the sarcolemma was responsible for the passive length-tension curve for whole muscle while the contractile material contributed nothing to this tension.

The active tension curve a in figure 1 was obtained by setting the initial muscle length and stimulating the muscle tetanically. The relationship between force and length in this
FIGURE 1: The length-tension curve for isolated frog muscle where:
curve $\gamma'$ - passive stretch of the muscle
curve $a$ - maximally activated muscle
curve $d$ - the difference between curves $\gamma'$ and $a$

adapted from Wilkie, 1968.
case appeared independent of the sarcolemma tension and seemed to act in parallel to the passive tension. This active curve was actually the consequence of the interaction of two components, the active contractile component (CC) and the passive parallel elastic component (PEC). It is evident from figure 1 that the PEC contributes to the overall tension only after a specific length has been obtained. This 'threshold length' is a characteristic of each individual muscle. If the passive contribution (curve r) was subtracted from the active curve (a) there remained a bell shaped curve. It was thought that this curve represented the true length-tension curve for the contractile component (curve d).

A wide variety of muscles have been investigated in this manner (see Close, 1972). Technical limitations delayed the determination of the real length-tension curve of the contractile component. These limitations were overcome in 1966 when Gordon, Huxley and Julian (1966) examined the effect of changes in length of a single sarcomere on the force developed over a range of lengths of 110% of the resting length Lo. The investigators found a length-tension relationship that was similar to that of Ramsey et al. (1940).

The contractile component has two characteristics that describe its activity. These are the force-velocity relationship and the isometric length-tension relationship. It was pertinent, therefore, to observe whether there was any interplay between these which would affect the development of force or the shortening of the muscle.
Hill (1950) stated that "...the experimental relation between speed of shortening and load could be expressed by a family of curves, each for a given muscle length over a considerable range ... it was given mathematically by the single characteristic equation...".

Using frog sartorius muscle Abbott and Wilkie (1953) examined the relationship between the velocity of shortening and muscle length to verify whether Hill's characteristic equation fitted at other muscle lengths. They found that if the isometric maximum force for that muscle length was used as Po then the equation fitted very well. In other words, there was a range of force-velocity curves each a characteristic of some value of Po which could be attributed to the resting muscle length.

Bahler, Fales and Zierler (1968) examined the interrelationship of force, velocity and muscle length "...of the contractile component of tetanically stimulated intact mammalian skeletal muscle, the rat gracilis anticus.". The results were displayed as a three dimensional representation of the family of force-velocity curves with respect to muscle length (figure 2). It may be seen that the instantaneous length through which the muscle shortened affected both the velocity of shortening and the force developed.

The development of the length-tension relationship, the force-velocity relationship and the interrelationship of all these factors on isolated preparations has been considered. The next issue requiring investigation was whether the same relationships held for intact human muscles.
FIGURE 2: The force-velocity-length curve for isolated rat gracilus anticus muscle

adapted from Bahler, Fales and Zierler, 1968
Characteristics of intact muscle

The problems of determining the characteristics of intact
human muscles are numerous due to the concern for the well
being of the subject. Ralston, Inman, Strait, and Shaffrath
(1947) attempted to find the length-tension relationship for
intact human muscles. Their subjects were veterans with
amputated forearms. Experimentally they were fitted cineplastic
tunnels connected to a tension recording device so that the
muscle tension at different lengths could be examined.

These data showed a relationship similar to that proposed
by Ramsey and Street (1940). However, there were some problems
in correlating the two studies because in the study of Ralston
et al. (1947) the muscles were not 'normal' muscles in the
ordinary sense. They were not attached to the forearm as they
would be in the intact subject and it was not clear where these
data of Ralston et al. (1947) lay on the total length-tension
curve of normal subjects. Also, the maximum tensions recorded
were quite low when compared to other studies (Wilkie, 1950).
That there was at least a similarity in the two curves
(isolated and intact) was encouraging since it indicated a
possibility of comparable length-tension relationships for
intact human muscles.

Another approach to studying the applicability of the
length-tension curve derived by Ralston et al. (1940) to intact
human muscles has been outlined by Stolov and Weilepp (1965).
They cited six anatomical elements possibly contributing to the
passive length-tension curve. These were: 1. the outer connective tissue sheath; 2. the perimysium and endomysium; 3. the sarcolemma; 4. the individual fibre contents; 5. the tendons at origin and insertion; and 6. adhesions to neighbouring structures. Although the exact contribution of each of these factors remained unknown the authors suggested that each must be taken into consideration when examining the PEC and its contribution to the tension developed.

Dern, Levine and Blair (1947) attempted to define the force-velocity relationship in human muscles about the elbow joint. However, their results were not described by the characteristic equation. The authors documented some antagonistic muscular activity and suggested that this was one source of discrepancy. Lack of consideration for the acceleration of the arm would have led to further error. The authors did not suggest that the characteristic equation was in fundamental error, only that further study of its general applicability was required.

Wilkie (1950) proposed the first significant attempt to apply the model to intact human muscles. He developed a force-velocity relationship for a two-component (CC plus SEC) single equivalent muscle, parallel to the upper arm, acting at the hand (figure 3). This model represented the combined effect of all the elbow flexor muscles. Its force-velocity relationship was accurately described by the characteristic equation, after justifiable corrections for the acceleration of the inertia of the forearm.
FIGURE 3: The linear horizontal equivalent model used by Wilkie (1950) to describe elbow flexion.

- **F** - horizontal force recorded
- **L** - torque produced
- **θ** - elbow angle
- **CC** - contractile component
- **SEC** - series elastic component

adapted from Wilkie, 1950.
However, attempts to generalize from Wilkie's model to the range of movement from a horizontal position to complete flexion of the elbow met with difficulty. Chapman (1973) has shown wide variation in horizontal force developed through a range of flexion of the elbow (30% of the greatest isometric force). Wilkie showed a 20% variation over 90 degrees of flexion. On the basis of these observations, it would seem that the single equivalent horizontal muscle may be a fair representation of a muscle over a small range of lengths only. Between elbow-angles of 0 degrees and 20 degrees (long muscle lengths), changes in force take place which are far too great to be compatible with those predicted from the relationship between isometric tension and length of a 'real' muscle. Chapman (1973) suggested that a geometrical correction may have to be applied as the tendons of the biceps brachii and brachialis pass over the capitulum and trachlea of the humerus respectively. This factor would alter the angle of pull of the tendons and in doing so alter the torque developed about the elbow-joint.

The examination presented thus far has centered on the CC. There is also a SEC which affects the transmission of the force developed by the CC to the insertion of the muscle. The presence of such a component has been evident from some of the earliest studies (Levin and Wyman, 1927). These authors considered the SEC as an undamped spring in series with the contractile component and as such the SEC modified the rate of change of the external tension recorded as well as the velocity of movement.
While the SEC has been shown to be a passive element throughout contraction (Wilkie, 1956) it does introduce peaking and oscillation in the velocity-time curve during flexion of the forearm (Wilkie, 1950). Accurate determination of the velocity of shortening of the CC is dependant upon the determination of the velocity of movement at the hand as a function of both the changing length of the SEC and the velocity of movement of the CC. If the velocity of shortening of the CC is rapid then the velocity of flexion of the hand will be different by an amount equivalent to the velocity of movement of the SEC.

The location of the SEC has not been conclusively determined. It seems likely that some resides in the tendons (Wilkie, 1950) and connective tissue. It has also been suggested that some can be attributed to the contractile material itself. In any case, it is not possible to remove the SEC from intact muscles and therefore some vigilance will have to be maintained on the effect of the changing length of the SEC.

One factor which affects studies of intact human muscles is the degree of voluntary muscular activation. This problem was most troublesome when repeatable maximal voluntary contractions are required. In isolated muscle preparations the activation of the muscle would be very carefully regulated. In human muscles this regulation is not quite as simple. Factors such as frequency of stimulation and the number of active motor units affect the rise of force (Bahler et al., 1968). There is
also the possibility of interaction of antagonistic units resulting in reflex control (Dern et al., 1947). In studies dealing with intact human muscles these factors must be taken into account and corrected for where possible. Few investigators have made repetitive studies to confirm the achievement of repeated maximal activation or whether it has been achieved even once.

Electromyography (EMG), as a technique to explore the events occurring within a muscle, has received much attention. Use of surface electrodes provides a simple non-invasive technique for monitoring internal electrical activity. However, there are a number of problems associated with the quantification of the EMG signal (Ralston, 1961) and consequently there has not been any successful attempt at relating the EMG signal, be it unprocessed or quantified in some fashion, to the events leading to activation of the muscle. The purpose of this thesis is not in any way to attempt to devise such a relationship nor will any attempt be made to use EMG.

The problems of determining the effect of active state on the rise in force cannot be ignored. Jewell and Wilkie (1958) have shown that the theoretical rise in force derived from isotonic force-velocity relationships was quicker than recorded experimentally. Parmley, Yeatman and Sonnenblick (1970) have derived force-velocity relationships from isotonic and isometric contractions. Their results show that there was a consistent difference in the two curves. Both groups of
investigators argued that this anomaly could be attributed to differences in the active state of the muscle.

Pringle (1959) postulated a different view of the active state to explain these observations. Rather than hypothesize an active state as being unaffected by quick stretches or quick releases "...one might postulate a property called, say activation, which was increased by tension and which controls velocity of shortening at a given tension." Using this definition Pringle was able to describe the origin of the differences between isotonic and isometric derivations of the force-velocity relationship. The force-velocity relationship now represented the combined action of tension and activation and the observations of Jewell et al. (1958) and Parmley et al. (1970) could be explained. Whether this view is in greater harmony with the underlying mechano-electrical-chemical events than the traditional view, postulated by Hill (1949), remains presently undetermined.

Since this thesis is concerned with the rate of rise in force measured under isometric conditions the above comments of Jewell et al. (1958) and Parmley et al. (1970) are important. If such dramatic differences were shown in isolated preparations, equally pronounced variations may well be observed in intact preparations. Obviously, extreme vigilance will have to be maintained on all factors affecting the rise in force.
Parrley et al. (1970) have shown that the force-velocity curve calculated from isometric contractions of isolated preparations was different from that derived from the same preparations using dynamic contractions. It would be interesting to see whether the same observations would be made on intact human muscles. To complete this task required the development of two techniques, one using isometric contractions and one using dynamic contractions. While these techniques are discussed extensively in the section titled Method of Analysis they will be outlined briefly here.

To derive a force-velocity curve from isometric contractions MacPherson (1953) devised a technique that relied on the development of force under two conditions. In the first condition the muscle contracted isometrically against a force transducer and the rise in force was recorded. A compliant structure (a spring) was then fixed between the muscle and the transducer and the muscle was stimulated again. In both conditions the stimulation produced a maximal isometric contraction but the rise in force in the second instance was slower than in the first instance. The magnitude of the compliance had to be large enough to permit the separation of the two force-time curves but not so large as to permit gross changes of the muscle length. MacPherson assumed only that the velocity of shortening was a function of the force developed. With this assumption he was able to use the differential of the
rise in force in the two contractions and through a series of mathematical manipulations determine the velocity of shortening of the contractile component. This method is very desirable as it permits the determination of the force-velocity curve of the contractile component from two contractions unaffected by the series elastic component. The SEC modifies the velocity of shortening of the CC as it transmits that velocity to the insertion of the muscle. If this effect can be bypassed then the determination of the force-velocity curve of the CC is very much simplified.

The method of developing a force-velocity curve for human muscles from dynamic contractions is not quite as straightforward as when it is developed isometrically. The rotation of the elbow, the interaction of the series elastic component in the modification of the velocity of shortening of adjoining structures and the interaction of the subject's conscious awareness of the required muscular activity all affect the force recorded. Before one can isolate the force developed and velocity of shortening produced by the contractile component alone, the magnitude of the involvement of the interfering factors must be assessed and subsequently removed. Ideally, for the determination of the velocity of shortening of the CC the rate of change of torque must be zero. At this point the velocity of the hand is the same as the velocity of shortening of the CC. However, this restricts the selection of points for the development of a torque-angular velocity curve and it may be desirable to select a range of torques where the change is
small enough to introduce a negligible error in the calculation of the velocity of shortening of the CC. This possibility will be explored in the section titled 'Method of Analysis'.

Once the two methods for development of the torque-angular velocity curve are developed the study proposes to examine the following:

1. Is there a difference in the torque-angular velocity curve derived from isometric contractions when compared to a torque-angular velocity curve derived from dynamic contractions?

2. Through the range of excursion of the elbow-joint is there sufficient lengthening of the CC to change the force produced by the muscle?

3. Do the properties of the series elastic component change during a maximal contraction at different joint positions?

4. Does Wilkie's single equivalent model adequately describe the characteristics of human muscular contraction?
MATERIALS

There were two groups of subjects in this study. The members of each group were healthy male university personell and their ages, weights and statures were listed in Appendix 1. All subjects were right handed and although some exercised regularly none were engaged in progressive resistance exercises. In group one there were nine subjects and in group two there were two subjects.
METHODS

a) The apparatus used for the measurement of torque, displacement and acceleration

The apparatus (figure 4) essentially comprised the rear axle of an automobile which was supported with its outer casing rigidly fixed in a wooden tressle and aligned parallel to the sagittal axis of the subject. The two half-shafts, complete with bearings, remained within the casing of the axle and as the differential had been removed, the two opposing ends of the half shafts were joined with a mild steel collar. To the collar was attached a spring which could be so arranged to provide a compliant connection between the two half shafts (figure 5). At one end of this apparatus were located the torque, acceleration and displacement transducers and the mechanism for aligning the subject with the apparatus. The subject was seated in an adjustable chair with the right arm elevated so that the upper arm was horizontal in the coronal plane. There was a vertical support for the elbow as well as a chest support to stabilize the subject's position. To maintain this position safety belts were passed around the subject's chest and thighs and attached to the apparatus.

At the other end of the apparatus was located a board that was used to fix the position of the axles for the isometric pulls as well as provide a convenient place to hang the weights for the dynamic pulls.
FIGURE 4: The apparatus used in the present study.  
(see text for a complete description)
FIGURE 5: This spring provided a compliant connection between the two half shafts.
FIGURE 6: This shows the two halves of the cast used to prevent wrist flexion during contraction.
FIGURE 7: This illustrates a schematic of the dynamometer used in the experiment. The various transducers were attached to this dynamometer. The dimensions of the beam (in cms) are as follows:

<table>
<thead>
<tr>
<th>Letter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1.78</td>
</tr>
<tr>
<td>b</td>
<td>50.0</td>
</tr>
<tr>
<td>c</td>
<td>7.86</td>
</tr>
<tr>
<td>d</td>
<td>10.87</td>
</tr>
<tr>
<td>e</td>
<td>10.62</td>
</tr>
<tr>
<td>f</td>
<td>6.58</td>
</tr>
<tr>
<td>g</td>
<td>3.54</td>
</tr>
<tr>
<td>h</td>
<td>6.03</td>
</tr>
<tr>
<td>i</td>
<td>5.56</td>
</tr>
<tr>
<td>j</td>
<td>41.12</td>
</tr>
<tr>
<td>k</td>
<td>35.09</td>
</tr>
<tr>
<td>l</td>
<td>10.2</td>
</tr>
<tr>
<td>m</td>
<td>2.0</td>
</tr>
<tr>
<td>n</td>
<td>0.95</td>
</tr>
<tr>
<td>o</td>
<td>3.02</td>
</tr>
<tr>
<td>p</td>
<td>0.48</td>
</tr>
<tr>
<td>q</td>
<td>0.55</td>
</tr>
</tbody>
</table>
To limit the flexion of the forearm a fibreglass cast was taped to the subject's forearm. This cast consisted of two sides and extended from the fingertips to the elbow. It did not limit elbow flexion but it did prevent wrist flexion. On the palmer side and located in the centre of the palm a block of wood was fixed with a threaded bolt which could be attached to the beam (figure 6).

b) The dynamometer for the transduction of torque, displacement and acceleration

The dynamometer (figure 7) was required to register torque, displacement and acceleration with reference to the axis of rotation of the elbow joint. In order to keep compliant connections to a minimum, a beam, to which the forearm cast could be bolted, was chosen as the basic unit of the dynamometer. This beam or lever had to be constructed in such a manner that it allowed the individual transducers to operate without interference. While rigidity was important a certain amount of bend was necessary to ensure an output from the strain gauge transducers. This criterion was determined by the characteristics of the strain gauges which had a linear range of resistance in response to strain between zero and 1/1000 of their unstrained length. To meet these specifications a beam was chosen that would bend no more than .00125 radians at its outer end (40cm from the axis of rotation).
i) Transduction of torque

This transduction was completed by four strain gauges (type WA-06-2508G-120, manufactured by Micro Measurements, Mich.) attached to the beam, their long axes coincidental to the long axis of the beam, 10 cms from the centre of the axle. The four strain gauges were wired together as the active arms of a Wheatstone bridge (figure 8). The use of four gauges minimized the effect of temperature (all four would be affected thereby increasing the stability) and allowed for greater resolution of the applied torque as two of the gauges were subject to strain while the other two were subject to compression.

ii) Transduction of displacement

The transducer for recording displacement was a wire wound potentiometer with a resistance which varied from 0 ohms to 10 kilohms (type 151-585313, manufactured by IRC, St. Petersburg). The axle of this potentiometer was fixed to the centre of the half shaft closest to the subject. The transduction of the angular displacement of the beam from the horizontal depended upon the linear relationship between angular displacement of the shaft and the electrical resistance of the potentiometer.
FIGURE 8: The circuit of the Wheatstone Bridge (R1 to R4) along with the power supply (2.5v) and the balancing resistor (R6) used for the transducers of torque and angular acceleration. The bridge used for the transduction of torque involved R1 and R3 in compression and R2 and R4 in tension or vice versa depending upon the direction of the torque. The bridge used for the transduction of acceleration involved R2 in compression and R4 in tension or vice versa depending upon the direction of the acceleration while R1 and R3 remained fixed in value. The nominal values for the resistors (in ohms) are as follows:

<table>
<thead>
<tr>
<th>Torque</th>
<th>acceleration</th>
<th>both</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1-R4 = 120 variable</td>
<td>R1 and R3 = 120 fixed</td>
<td>R6 = 10K</td>
</tr>
<tr>
<td>R5 = 0</td>
<td>R2 and R4 = 120 variable</td>
<td>R7 = 10K</td>
</tr>
<tr>
<td></td>
<td>R5 = 1K</td>
<td>R8 = 10K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R9 = 1M</td>
</tr>
</tbody>
</table>
FIGURE 9: This shows the main amplifying unit.
iii) The transduction of acceleration

This was performed by a miniature accelerometer (type BLA2, manufactured by Pye Dyn., London) mounted on a rigid clip fixed to the outer end of the beam. The sensitive axis of the accelerometer was oriented with the sensitive axis of the beam. A small inertia affected the output of the strain gauges within the accelerometer when the transducer was subject to acceleration. These two strain gauges were coupled with two fixed resistors within the amplifier to form a Wheatstone bridge circuit.

The power supply to each transducer and amplification of its output voltage was controlled by separate strain gauge amplifiers (type AD6) mounted in a single integrated unit (type TE4, manufactured by Teca, White Plains, N.Y.). See figure 9.

c) Calibration of the transducers

i) Static properties

To assess the bidirectionality of the torque transducer a series of weights were hung from the slot when the lever was horizontal on either side of the vertical. A plot of the relationship between the known applied torques and the calculated torques, based on the output of this transducer, showed that the torque transducer exhibited a linear response bidirectionally. There was no measureable variation from this
response. The applied torques covered the range of force expected for even the strongest of subjects.

Since the accelerometer and torque transducer were subject to the effects of gravity the output for the full range of positions was expected to be proportional to the cosine of the angle of the beam. This angle was determined by aligning the displacement transducer so that at angle 0 (lever horizontal) the output voltage was 0 and the output voltage was fullscale (1.25 V) at the angle 180 degrees. By knowing the angle and recording the output from the other two transducers a plot of and torque transducers followed a cosine curve.

ii) Dynamic properties

The dynamic properties of the transducers were assessed as follows:

1. The angle measured from the output voltage of the displacement transducer was compared with the angle determined by rapidly rotating the lever as it was illuminated with a stroboscopic light and photographed. There was no detectable difference between the results obtained from the two methods of determination of the angle.

2. The frequency response of the torque transducer was determined by examining its output following a step input. The output of the transducer was exponential in form with a time-constant of 10 msecs indicating that it would faithfully
reproduce the signals slower than this. The time constant for an isometric pull has been estimated to be near 50 msec which is well within the capabilities of the apparatus.

3. The response of the accelerometer was assessed by oscillating the lever from the opposite end of the apparatus. A bolt was fixed to the slot in the beam so that a larger output from the torque transducer could be achieved. Because the inertia of the bolt and beam was constant the ratio of the torque to the acceleration should also have been constant. A variation of 2% was observed in the response of these transducers. This variation was attributed to the frequency response of each transducer. This was not a serious deficiency since the signals were filtered prior to analysis or storage as described below. Hence, the signals were attenuated to the same level.

d) Filtering the output of the transducers

Electronic filtering of the output from each transducer permitted the removal of nonphysiological disturbances, such as the natural frequency of the beam (36Hz.), and matching the frequency response of the accelerometer and torque transducer. The output from the accelerometer contained the highest frequency components and hence, the unfiltered output from this transducer was recorded and subsequently played back through an adjustable analogue filter. The bandwidth or frequency response was determined by narrowing the width until the signal
was attenuated 3db. The recordings demonstrated that the signal became attenuated below frequencies of 12Hz (-3db). The cutoff frequency was chosen to be 15Hz (-3db) to maintain a margin of safety.

e) Permanent recording of the output from the transducers

i) The frequency modulated (FM) tape-recorder

An FM tape recorder (type 3096A, manufactured by Hewlett Packard, Colorado USA) was used to store the output from the transducers. This recorder has four separate channels each with an input and output amplifier. Each amplifier has a gain control which allowed the user to maintain the input and output voltages within the linear response range of the amplifiers (full scale 0-2.5 V). The tape used was low noise Phillips Instrumentation tape (manufactured in Vancouver Canada) .635 cm in width. The record and playback speed was 38.1 cm/sec. The centre frequency of modulation was 27KHz and the signal to noise ratio was 48db.

The input signals were filtered to and from the tape recorder through the same filters. This served to remove any high frequency noise generated by the tape-recorder during either the recording or retrieval process.
ii) Analogue to digital conversion

In order to use a computer for the computation it was necessary to transfer the analogue signal on the FM tape recorder to the computer. This was completed by transferring the data through a 10 bit, 10000 samples per second analogue to digital converter (type ADC, manufactured by Digital Equipment Corp., Mass. USA) which was a peripheral unit to a minicomputer with 12K locations of 12 bits each (type PDP-8e, manufactured by Digital Equip. Corp., Mass, USA). All signals were converted at a sampling rate of 200 samples per second. This was chosen as the minimum rate which would accurately reproduce the input signal. A compromise between the ideal sample rate and available storage space within the computer was necessary and therefore a higher sampling rate could not be used as it would result in an overfilling of the storage.

The process of conversion was controlled by machine language (PAL III) while the initialization was controlled by the operator through a conversational language FOCAL. A control switch was used to initiate the acquisition and to reset after completion of one pass. To acquire the data the operator played the output from the tape recorder to an oscilloscope with storage facility (type 1201 A, manufactured by Hewlett Packard, Colorado USA) and then replayed the output with the image remaining on the screen. As the image moved across the screen a second time the operator initiated the A-D with the control switch at the appropriate time.
Storage of the data was completed in digitized form on magnetic tape (type DECTAPE, manufactured by Digital Equip. Corp. Mass USA) through a tape drive system interfaced with the computer.

iii) Recording Oscillograph

A multi-channel oscillograph (type 5-127, manufactured by Bell and Howell, Basingstoke, Eng.) was used to record the rise in torque in a series of isometric contractions. These data were used in the determination of the compliance of the SEC as well as in the determination of the time-constants of the rise in torque. This oscillograph was connected on-line with the transducers eliminating interim storage on the FM tape-recorder.
PROCEDURES

This study comprised two separate experiments. The equipment used was the same but the procedures for each experiment differed greatly and will be discussed separately. The aim of the first experiment was to obtain a torque-angular velocity relationship from isometric contractions while that of the second experiment was determination of the same relationship from dynamic contractions.

A) Procedures - Experiment 1

Subjects attended experimental sessions at their convenience. All subjects attended three such sessions each session being separated from the others by no less than one week. These sessions will be termed work-session 1, 2 and 3.

i) Work-Session 1

The purposes of this session were to locate accurately the subject within the apparatus, to determine the moment of inertia of the forearm and to familiarize the subject with the experimental procedures of the study.

The first step was to attach the cast to the forearm. A light underwrap was used to ease the contact between fibreglass and skin when the cast was attached to the forearm. The wrap was tightly compressed and contributed a negligible amount to
the compliance of the forearm. The cast was placed on the forearm, adjusted to its most comfortable position and securely wrapped with tape in order to prevent wrist flexion without restricting blood flow.

The subject was then placed in the experimental position and the apparatus adjusted to make the axis of the elbow-joint coincidental with the axle and to position the upper arm horizontally. A safety strap from an automobile was placed around the chest and another around the thighs to eliminate gross changes in the experimental position. To check the location of the elbow-joint a pencil was attached to the cast and the subject was instructed to flex the elbow-joint so that an arc was drawn on paper placed vertically in the frontal plane of the subject.

This procedure was repeated several times and the perpendicular bisectors of two chords drawn on these arcs intersected at the location of the axis of rotation of the elbow-joint. Any necessary adjustment was made to the elbow and chest supports to align the axis of rotation of the elbow with the axle. The individual position of supports for the chest and elbow were noted so that they could be replicated in all further experiments.

With the subject fixed in the apparatus the next step was to determine the moment of inertia of the limb. The method described in Chap. IV, a(ii) was used. When this was complete the subject practiced some trial contractions with careful observation by the investigator and subsequent
suggestions for improvement should they be required. The subject was not informed about the aim of the study. However, the importance of maximal activation was stressed.

ii) Work-Session 2

In this session data needed to derive the torque-angular velocity relationship was collected. Upon arrival the subject was placed in the apparatus according to previous measurements taken during work-session 1. On all occasions the subject was instructed to produce maximal voluntary contractions about the elbow joint as rapidly as possible. The verbal stimulus from the investigator was the command 'pull'.

Five starting positions were chosen for the development of the torque-angular velocity curve. These were 0.5, 0.8, 1.0, 1.5, and 2.0 radians where 0.0 radians represented full extension of the elbow. The beam was set at the required position by a chain attached at the other end of the axle. At each position the subject made eight separate pulls. The first, third, fifth and seventh pulls were completely isometric. There was no added compliance and the investigator ensured that the resisting chain had no slack. The second, fourth, sixth and eighth pulls were not completely isometric in that they were made against the spring, which was now part of the system. The spring uncoiled by an amount related to the tension exerted and the compliance of the spring.

The data were collected on an FM tape-recorder. The subject
was allowed to rotate his arm freely between each contraction to ease any stress induced by the contraction. Each pull lasted no more than 1.5 seconds.

Upon completion of all the pulls the calibration for the effect of gravity (Chap. IV, a (iii)) was completed. The subject was removed from the apparatus and the calibration (Chap. IV, a(i)) of the transducers was completed.

iii) Work-Session 3

This session was a repeat of work-session 2 and served to provide a check on the repeatability of the previously collected data. The intersessional time-interval was no less than one week.

After all the data from each work-session had been collected on a tape-recorder it was transferred to a computer DECTAPE in preparation for analysis. Analysis of the original data showed that it did not exhibit the expected form. The rise of torque during a compliant pull was faster than in a non-compliant pull. As the converse of this observation was a necessary condition of the analysis an unidentified phenomenon was judged to have been contributing to the difference between rise-time of the compliant and non-compliant pulls. Consequently, a new approach to the deduction of the torque-angular velocity curve was required.

Wilkie (1950) was able to elicit a response from intact human muscles similar to that reported by MacPherson (1953).
Wilkie's subjects were presented with more contractions to complete than in the present study. Therefore the unusual results obtained here may have been due to a lack of practice or skill in recruiting muscular activity as rapidly as possible on all occasions. It was thought that perhaps a period of training was required. Consequently two subjects were chosen and performed a series of experimental sessions from which their data was analysed progressively. There was no trend in the data that indicated an effect which could be associated with practise. The subjects did make some comments on how they felt during each type of contraction. Both said that they felt more satisfied with the compliant pull than with the non-compliant pull and attributed this feeling to the fact that they had accomplished something by making the beam move a considerable amount. In the case of the non-compliant pull the extent of movement was so small that there was little feedback to the subject in terms of how that person had done.

On the basis of these comments it seemed that there was perhaps some form of physiological feedback that affected the performance of the subjects. With this in mind it seemed reasonable to try a session during which the subjects would not be informed of the nature of the contraction that would be required. The motions the investigator went through during a recording session were standardized so as not to provide any hints. The only comment during this session was the command to pull.
In spite of the attempts to mask the apparatus the data were at variance with the intention of the study. It was decided at this stage to abandon this approach and concentrate on the second part of the study.

It should be noted that the response of the apparatus was checked to ensure that the problem was not a function of the apparatus. To do this the investigator attached a weight (12.15 Kg) by a rope to the lever in the horizontal position. Initially the investigator supported the weight so the rope was slack but released the weight applying a sudden input to the lever. This procedure was completed under both experimental conditions. The rise of torque in the contraction with the added compliance was slower than without the added compliance. The apparatus was not the source of the variation in the data with that reported elsewhere.

B) Procedures—Experiment 2

As before this group came at their convenience and since the dynamic contractions were not as demanding as isometric came as frequently as once a day. One subject came only six times but the other subject was able to attend seven sessions. A session similar to work-session 1 in experiment 1 was completed before the actual data collection began. The subject was carefully fitted into the apparatus and the moment of inertia of the limb was determined.
The method of determining the torque-angular velocity curve from dynamic contractions required the subject to contract against a variety of opposing loads. The opposing loads were a series of weights that could be fixed to any one of three positions on the board at the end of the apparatus opposite the subject. The board was fixed off centre to the axle. Two of the holes in the board were on one side of the axle and one on the other side. Using different weights and hole position produced a range of torques that the subject had to overcome. To enable achievement of high velocities of movement the investigator aided movement by rapidly rotating the board in the direction of flexion.

It was decided to determine torque-angular velocity curves for five elbow positions, 0.5, 0.8, 1.0, 1.5, and 2.0 radians, where 0.0 radians represents full extension of the elbow-joint. To complete the torque-angular velocity curves it was necessary to record the isometric torques for each of these positions. A torque-angle curve was developed by requesting the subject to contract isometrically four times during each experimental session. To maintain the position of the beam during an isometric contraction a chain was used to fix the board to the floor. The investigator ensured that there was no slack in the chain during the contraction.

The experimental situations were the same for the first four sessions for subject one and first three for subject two. Upon arrival the subject was fixed within the apparatus in accordance with the measures noted during the trial session.
During these experimental sessions the first and last two contractions were isometric while the remaining eighteen were dynamic. A dynamic contraction required that the investigator fully extend the relaxed right arm of the subject. At the command 'PULL' the subject maximally activated the flexors of the elbow and flexed his arm as quickly as possible. The flexion was arrested by a mechanism of rope that prevented the subject hitting himself. For each weight and hole position two pulls were completed. The other four pulls were completed, two of which were done when there was no load on the board and the other two were done while the investigator assisted the rotation. The latter four provided torques that were low with high velocities.

In the remaining three sessions the contractions were isometric only. This data was used in the determination of the compliance of the SEC during an isometric contraction and in the calculation of the time-constant of the rise in torque. In the first two of these sessions the subject pulled once at each of the five elbow positions described above. A third session was completed during which the subjects completed three pulls at each of these elbow positions.

The data to be used in the determination of the torque-angular velocity curve were collected on the FM tape-recorder. The data to be used for the calculation of the compliance of the SEC and the time-constant of the rise in torque during an isometric contraction were collected onto the recording oscillograph.
The primary aim of this study was to derive a torque-angular velocity relationship for human muscular contraction. Two different methods have been developed to achieve this aim. Since joint-angle reflects muscle-length then the interrelationship of three variables could be studied. During the experimental process calibration was performed to facilitate quantification of the relationships in absolute units.

a) Calibration during the experiments

i) Calibration constants

To determine absolute units for the data it was necessary to use a calibration procedure that would convert the output voltage from the transducers to absolute units. The procedure was as follows (see DACAL.SV in Appendix 2). The lever was placed in five different positions. In the first position the lever was placed vertical and in the other positions the lever was placed horizontal alternating from side to side of the vertical. These positions were numbered sequentially from one to five.

In position one the lever was vertical and there was no torque recorded by the strain gauges. The output from this position was biased to 50% of full scale to facilitate
recording biphasic signals. To calculate the torque factor a known torque was applied in positions four and five. The torque 'seen' by the transducer when the lever was horizontal with no load, positions 2 and 3, was that torque attributable to the effect of gravity on the lever. The difference in output between position four and two and position five and three was the consequence of the known applied torques. Calculation of two torque factors served to check the linearity of the response of the transducer in the early stages of the experiment.

Once the investigator was satisfied with the response characteristics of the torque transducer the bias level was shifted to a value slightly higher than zero volts. This shift, concomitant with an increase in the gain of the amplifier, permitted an increase in the resolution of the data collected from this transducer.

To calculate the accelerometer factors (in radians per sec, per sec.) the differences in output between position two and one and position three and one were determined. The accelerometer recorded zero acceleration when the lever was vertical. At each of the horizontal positions the accelerometer recorded one g or 9.81 m/sec/sec of tangential acceleration. The relationship between tangential acceleration 'TA' and angular acceleration 'AA' is:

\[ TA = AA \times \frac{R}{2} \]

where 'R' was the distance between the axis of rotation and the accelerometer. This equation was solved for the angular
acceleration which was then divided by the output from positions 1 and 2. A second accelerometer factor was determined using the output from positions one and three. The effect of gravity on the accelerometer was assessed by calculating the difference between the output from position two and three and dividing by 2.

The displacement or position of the lever was considered in radians. Full extension of the elbow was considered to occur at 0.0 radians. The relationship between radians and degrees was described as 180 degrees being equivalent to 3.1416 radians. From this relationship the radian factor was determined. The difference in the output from positions two and three (lever horizontal on opposite sides of the vertical) was equivalent to a displacement of 3.1416 radians or 180 degrees. The radian factor (radians/unit) was determined by dividing 3.1416 radians by the differences in the output from the lever when horizontal on opposite sides.

To maintain a safety margin in case of drift within the amplifiers a small voltage above zero was included in the determination of the radian factor. To adjust the levels to absolute zero a radian remainder (units) was determined by calculating the differences between the output when the lever was horizontal for full extension and real zero volts. This radian remainder was subtracted from the calculated positions to assure the calculation of angle in absolute units.
ii) Determination of the moment of inertia of the forearm

The strain gauges were fixed to the lever between the axle and the slot where the cast was attached. A consequence of this arrangement was that the torque recorded by the strain gauges only reproduced the torque developed by the muscle when the mass lying between the elbow-joint and strain gauges was not accelerating. Under conditions of acceleration of this mass the torque recorded was less than the torque developed by an amount equal to the torque required to accelerate the mass. The torque recorded was that torque available to bend the lever and the added compliance.

If an impulse was applied to the axles from the opposite end of the apparatus then the torque recorded is that torque which accelerates the mass distal to the strain gauges. Consequently, this torque can be used to determine the inertia of the forearm and casts. This recorded torque is equal to the acceleration of the inertia of the forearm and cast multiplied by the inertia.

The technique developed required the investigator to apply a rapid positive and negative torque to the subject's forearm via the axles linking each end of the apparatus while the subject was at rest. The applied impulse was of short duration in order to exclude involuntary activity by the subject and of small displacement to exclude the effects of gravity. The accuracy of this technique was determined by fixing known inertias to the beam and performing the experiment. There was
little difference between the computed values and the known values of inertia.

Four trials were used and the mean of value of these four estimations was chosen as the final value. This data and the calibration data was acquired directly by the computer. A program (see NEWMIS.SV in Appendix 2) determined the absolute values of torque and acceleration from which the value of inertia was determined. The final values were typed on paper and the mean value calculated.

iii) Estimation of the gravitational effects on the lever with the subjects arm and cast attached

The effect of gravity on the lever was seen to modify the output of the transducers with respect to angular position. It was necessary to remove this effect when determining the absolute values of torque. For this reason, the output of the torque transducer was measured for eighteen different angular positions with the subject in the experimental position. A program (see GRAV.SV in Appendix 2) printed out the associated positions and torques and then submitted the eighteen pairs to a polynomial curve-fitting program (see CURFIT.SV in Appendix 2) which predicted torque at any given angle by a polynomial equation. This equation could then be subtracted from the obtained values of torque to remove the effect due to gravity.
b) Experiment 1 - Determination of the torque-angular velocity relationship from two isometric contractions

MacPherson (1953) devised a technique which allowed the derivation of the force-velocity relationship of the CC unaffected by the SEC. The method essentially comprised the muscle contracting isometrically at one time and then contracting again with a compliant connection between the muscle and the recording transducers. By examining the differences between the force-time curves in the two conditions he was able to derive the force-velocity relationship. This method is outlined below as well as the modifications necessary for a situation with intact human muscle.

i) MacPherson's Method

In developing this method of analysis MacPherson assumed that the force developed by the CC varied only with the velocity of shortening. Given two conditions of force which rose to the same isometric level with little or no change in length, any point of force on these curves indicated equal velocities of shortening of the CC. To create two different conditions MacPherson inserted a compliance between the muscle and the recording transducers. This compliant connection could be either isolated from the experiment, allowing for an isometric contraction, or included, which produced a slower rate of rise of force. From the two different rates of rise of
FIGURE 10: This is a drawing of the system described by MacPherson.

a) this describes the situation without the added compliance.
b) this represents the situation with the added as a part of the total system

P = the force developed by the CC
F = the force recorded by the transducers
x = the lengthening of the SEC
y = the lengthening of the added compliance
SEC added compliance CC.

a.

b.
force he chose equal values of force and, therefore, equal calculated velocities. Figure 10a illustrates the experimental conditions and the following is the mathematical manipulation required to achieve the final results. When the contraction is totally isometric,

\[
\frac{dP}{dt|0} = \frac{dx}{dt|0} \cdot \frac{dx}{dP|0}
\]  \tag{3}

and

\[
\frac{dx}{dt|0} = \frac{dP}{dt|0} \cdot \frac{dx}{dP|0}
\]  \tag{4}

where \(\frac{dx}{dt}\) is the velocity of the CC. The subscript '0' denotes the condition without the added compliance. Figure 10b shows the situation with the added compliance. Now,

\[
\frac{dP}{dt|c} = \frac{dP}{dL(x+y)|c} \cdot \frac{d(x+y)}{dP|c}
\]  \tag{5}

This reduces to

\[
\frac{d(x+y)}{dt|c} = \frac{dP}{dt|c} \cdot \frac{d(x+y)}{dP|c}
\]  \tag{6}

Now velocity of the CC is \(\frac{d(x+y)}{dt|c}\) where the subscript 'c' denotes the condition with the added compliance. Since, at any instant velocity depends upon the force then for any equal values of \(P\) the velocities could be equated. Thus, equating equations 4 and 6:

\[
\frac{dP}{dt|0} - \frac{dx}{dP|0} = \frac{dP}{dt|c} - \frac{d(x+y)}{dP|c}
\]  \tag{7}
The value of $\frac{dx}{dP}$ is the compliance of the SEC and can be substituted into equation 4 which is solved for the velocity of shortening of the CC.

ii) Modifications to fit rotational system

This above analysis was developed for linear systems and before it was used on rotational systems (human movement) some modifications were made. The measurements were made in angular terms, such as moment of inertia, angular velocity etc. Secondly, it was not possible to couple an added compliance directly to the SEC of intact human muscles. There was an inertia between the SEC and the added compliance, namely the arm, casts and beam. During contraction with the added compliance this inertia was accelerated and, hence, the torque recorded was less than the torque developed by an amount equal to that required to accelerate the arm, casts and beam. If $P$ was the torque developed by the CC and $T$ was the torque recorded then:

$$P = T + I\dot{\theta}$$

where $I\dot{\theta}$ was the torque required to accelerate the inertia.

This manipulation was completed prior to the application of MacPherson's analysis. Once $T$ was corrected very little
FIGURE 11: This is a drawing of the system described in figure 10 as modified to suit the needs of the present study.

a) this describes the situation without the added compliance.

b) this represents the situation with the added as a part of the total system

\[ P = \text{the torque developed by the CC} \]
\[ T = \text{the torque recorded by the transducer} \]
\[ \theta_1 = \text{the angular displacement of the SEC} \]
\[ \theta_2 = \text{the angular displacement of the added compliance} \]
\[ I = \text{the inertia of the forearm, cast and outer portion of the lever} \]
The modification of the original analysis was required. The following presents the modified analysis (see figure 11).

\[
\frac{dP}{dt} = \frac{dP}{d\theta} \cdot \frac{d\theta}{dt}
\]

(10)

and

\[
\frac{d\theta}{dt} = \frac{dP}{dt} \cdot \frac{d\theta}{dP}
\]

(11)

With the added compliance

\[
\frac{dP}{dt} = \left( \frac{dP}{d(\theta_1 + \theta_2)} \right) \cdot \frac{d(\theta_1 + \theta_2)}{dt}
\]

(12)

and

\[
\frac{d(\theta_1 + \theta_2)}{dt} = \left( \frac{dP}{dt} \right) \cdot \frac{d(\theta_1 + \theta_2)}{dP}
\]

(13)

Equation of the angular velocities and reduction gives;

\[
\frac{d\theta}{dP} = \left( \frac{d\theta}{dt} \cdot \frac{dP}{d\theta} \right)
\]

(14)

\[
\frac{d\theta}{dP} = \left( \frac{d\theta}{dt} \cdot \frac{dP}{d\theta} \right)
\]

The value for the compliance of the SEC, \(d\theta/dP\), was substituted into equation 11 which was solved for the velocity of shortening of the CC. This technique allowed one to arrive at a torque-angular velocity relationship for the contractile component as well as check on changes in the compliance of the SEC. When the analysis was done at a series of different muscle lengths one was able examine the effect of changes in length on the torque-angular velocity relationship for intact human muscle.
iii) Data manipulation

When the operator was ready to begin the final computation the data set was transferred from the DECTAPE to core memory. The program used to manipulate the data was catalogued as DAVEP2.SV and a listing and typical printout is shown in Appendix 2.

The program initially required the operator to enter the calibration constants, coefficients for the correction of torque due to gravity and the moment of inertia of the forearm and cast. These values were used in the computation of absolute units from arbitrary computer units. To make use of the full capabilities of the computer the calculated values were scaled by the use of multiplication constants. When data was digitized the range in values was 0 to 1024 units but the computer has the capacity to deal with numbers ranging from 0 to 4096 units. In the case of displacement, the largest possible value was 3.142 radians. Hence, this number was multiplied by 1000 to increase the resolution. When the results were printed out the multiplier became the divisor and 3142 was returned to 3.142. Additive constants were also used to make all numbers positive.

Because of the discrete increments in the data resulting from the digital conversion a method of digital smoothing was employed to smooth these increments. A method described by Lanczos (1956) was employed. This method entailed the averaging of five successive points and depositing them where the third point in the array was located. The next series of points to be
averaged included this third, now smoothed, point. The process of smoothing included three points that had been smoothed and two, as yet, unprocessed points.

Upon completion of these steps a subroutine within the program displayed the data on an oscilloscope interfaced with the computer. In this fashion a visual check was maintained on the program as it processed the data. When this step was complete the actual analysis was begun. The program determined the numerator for equation 14. This reduced to the velocity at the hand and its determination was done by differentiating the array of displacement. This step was completed and the array of velocity was stored in the location previously held by acceleration. The array of acceleration was not required after the array of torque had been corrected for acceleration of the mass discussed above. The velocity was scaled but not smoothed as one had no means of assessing what was signal and what may have been noise.

It should be pointed out that there were two methods employed to calculate the velocity of movement of the hand during the compliant pull. One method assumed that there was no movement during the isometric contraction and therefore any movement in the compliant contraction was attributed to the spring. The other method was not to assume zero movement in the first pull and to calculate the difference in velocities as a result of movement in both pulls. In this fashion the velocity that arose strictly from the added compliance was determined. Using two methods provided some further information that may have been useful.
The next step required the determination of the denominator in equation 14. The denominator consisted of two components, the differentials of the rise in torque from two contractions. The values for these differentials were determined, their difference calculated and divided into the numerator. The value was deposited in core for later acquisition. This step was completed for the array of torque values already processed and stored in core. If the difference between the differentials was zero or negative execution of the program was stopped.

Having calculated the solution to equation 14 and the values stored as an array in the memory the program initiated the calculation of the velocity from equation 9. These values were also deposited for later acquisition. The plotting subroutine was employed upon completion to permit visual inspection of the results.

A separate program, PLOTDA.SV, was loaded to plot the final results on hard copy. This program picked up the arrays of velocity, torque, and compliance and plotted them on a plotter which was a peripheral device to the PDP-8e.

c) Experiment-2 The determination of the torque-angular velocity relationship from dynamic contractions

The data required for this analysis was the torque developed at any time during a dynamic contraction and the
velocity at that same instant in time. To determine the velocity it was necessary to differentiate the output from the displacement transducer. This was the velocity at the hand and how accurately it was a measure of the velocity of the contractile component depended upon how quickly the torque was changing. Under conditions of high rate of change of torque the SEC was either lengthening or shortening and this change in length in the SEC affected the velocity recorded at the hand. When the rate of change of torque was low then the SEC was stable and the velocity at the hand accurately reproduced the velocity of shortening of the contractile component.

An attempt was made to assess the affects of the rate of change of torque on the stretch of the SEC. Subject 2 had been a subject in another experiment the aim of which was to estimate a linear compliance for the SEC. That experiment had determined this value to be .004 Nm/radian. With this estimate it was possible to correct the observed velocities to take into account changes in length of the SEC. However, this method of correction produced an overcorrection when the torques were low and an undercorrection when the torques were high. It was decided not to persue this thought as those points which were affected, and consequently further displaced from the bulk of the data, could be ignored.

The analysis program printed the values of torque, angle, and angular velocity for the whole contraction. Since five positions were chosen as suitable for the development of the torque-angular velocity curve the operator had to select the points from the printout.
i) Data manipulation

This program was catalogued as DFV-SV and a listing is contained in Appendix 2. The program initially required the operator to load the calibration factors, moment of inertia and coefficients for the correction of gravity prior to beginning the analysis. With these constants the program determined the absolute values for each of acceleration, torque and displacement, smoothed these by the 5 point moving average technique and stored them. The array of torque was corrected last because the array of acceleration was required to correct for acceleration of the limb. Velocity was calculated from the array of displacement and then stored in the location previously held by acceleration. When the program was finished the analysis and it punched the data on hard copy for the operator. A display program was built into the overall program and all the values were displayed for visual examination as the program progressed.

ii) Determination of the time constant of the rise in torque

Houk (1963) linearized the relationships of force-velocity for the CC and the length-tension for the SEC and developed a transfer function that described the rate of rise in force. This description was exponential in nature and followed closely the rise in force determined experimentally. Chapman (1973)
also used this determination of linear properties of components of the model to examine some effects of length on the model. Since the rate of rise in force could be described as an exponential it was possible to determine the time constant of the rise in force. This determination permitted the examination of the rate of activation of the muscle.

This rise in torque in the present study was considered to be nearly exponential in nature and the following analysis applied to determine the time-constant of the rise in torque. The initial slow rising portion of the curve was ignored as being due to the compression of the soft tissue (Chapman, 1973). The curve was extrapolated to the zero level. The time constant of an exponential curve was defined as that time required to attain 63% of the maximum value. The maximum value for the isometric contractions obtained in this study were determined and then the time required to attain 63% of this value. These data were examined to see whether the change in elbow-position affected the rise in torque.

iii) Determination of the compliance of the SEC

The rate of rise in torque during an isometric contraction is dependent upon the torque-angular velocity relationship of the CC and length-tension curve of the SEC. Knowing the force-velocity curve and the rate of change of force during an isometric contraction one was able to determine the compliance of the sec.
The torque-angular velocity curve was determined from the dynamic contractions. To facilitate the derivation of the compliance of the SEC a smooth line was drawn through the middle of the points on a torque-angular velocity curve. The calculation of the compliance was done by hand and therefore an equation defining the torque-angular velocity curve was considered unnecessary.

The data collected from the isometric contractions were displayed on the paper recording oscilloscope at a paper speed of 16 cm/sec. The calibration data was displayed in the same fashion. The investigator selected points on the rise in torque curve on this recording and determined the absolute torque. A geometrical tangent was drawn to the curve at these points and the value of rate of rise in torque determined in Nm/sec. The relationship between rise in torque and velocity of shortening is dependant upon the extension of the SEC (determined by its stiffness) and the velocity of shortening of the CC (see equation 3). This relationship was used to calculate the compliance of the SEC (the inverse of the stiffness of the SEC).

The points on the rise in torque curve were transferred to the torque-angular velocity curve determined in experiment 2 and the velocities for that torque recorded. Multiplying the velocity by the inverse of the rate of rise in torque produced the compliance at that point during the contraction. The compliance data was displayed as a function of torque.
ACCURACY OF RESULTS

There were a number of factors which could have affected the outcome of the experimental results. A primary source arises from the conscious awareness of the subject.

The method of aligning the subject with the apparatus was made carefully consistent with each session. As was stated earlier the position of each support was recorded and the supports returned to that same position each time the subject was in the experiment. The application of the casts was also kept exactly the same so that the necessary consistency of fit was maintained. During the experiment the subject was instructed to look straight ahead at a blank wall and not to move during the contractions. The chest and thigh supports and safety straps maintained the experimental position throughout the experiment.

With these precautions the investigator was assured that the subject was in the same position each time he was aligned with the apparatus. The only area where the investigator had no control was the area of activation of the muscle. Repeatable maximum activation was a necessity of the experimental technique. There has not been a method designed that will permit the estimation of activation in intact muscles. The investigator had to rely on the subject appreciating the importance of consistent activation and attempting to respond appropriately. It was possibly this item which led to the discrepancies observed during experiment 1.
The response characteristics of the transducers has been described fully elsewhere and it was evident that they were within the requirements of this study. No detectable difference could be assessed in the static or dynamic response over a number of trials. Filtering to 15 Hz provided a wide margin for response of each transducer as well as matching the upper limit of the frequency response of each transducer.

The filtering of the signal from the tape recorder removed most of the noise inherent in that form of recording. Further digital smoothing removed any noise resulting from the digitization of the analogue input signal from the tape-recorder.

On this basis, then, there does not appear to be any major source of error in the experimental procedure.
RESULTS

This section presents the data as they were collected during the study. These data are presented primarily in graphical form. The implications of the data will be discussed in the following section.

As described in the section titled 'Method of Analysis', the success of MacPherson's technique relied on the rise of torque in the non-compliant pull being quicker than the rise in torque in the compliant pull. However, in this study this condition was not met. Figure 12 illustrates the rise in torque for a typical pair of contractions. It is evident that the rise in torque in the non-compliant pull is slower through a large range of the contraction. This pair were chosen as they were a typical example of the data observed during the experiment regardless of attempts to gather data similar to that reported by MacPherson (1953). On the basis of this inability to obtain appropriate data this experiment was abandoned. The remainder of the data presented here was derived from experiment 2 using dynamic contractions.

Figures 13 and 14 present the points describing the torque-angle relationship for each of the subjects in group 2. The variation in isometric torque with elbow position indicate that at least one point on the torque-angular velocity curve is dependant upon joint position. To determine the isometric torque for each of the experimental positions a smooth line was drawn through the points in figures 13 and 14. The value of
torque was determined at the intersection of this line with a line drawn from the appropriate elbow position.

Figures 15a to 15e and 17a to 17e present the intersessional data describing the relationship between torque developed and angular velocity for each subject at each of the five experimental positions. It is evident from the scatter of the points that the data from each session overlaps the others. The overlapping of the intersessional data permitted the drawing of a line through these points that would permit comparison of a mean of each curve for each elbow position (Figures 16 and 18). An assessment of the compliance of the SEC and the use of that assessment to correct the torque-angular velocity curves did not alter the curves to any extent (see Method of Analysis).

The compliance of the SEC was determined from the rise in isometric torque and is presented as a function of torque in figures 19a-e and 20a-e for each elbow position. Trials 1 and 2 were obtained on different days while trial 3 was completed at one session. Trial 3 contains 3 contractions for each position of the elbow-joint.

Table 1 presents the time-constants for the rise in torque during an isometric contraction. These data were computed from the data collected as described in Chap. IV, c(ii).
FIGURE 12: The rise in torque in two contractions, one with the added compliance and one without the added compliance.
ISOMETRIC

WITH ADDED COMPLIANCE

TORQUE (COMPUTER UNITS) $\times 10^1$

TIME (MSECS)

0.00 41.00 82.00 123.00 164.00 205.00

0.00 70.00 140.00 210.00 280.00 350.00
FIGURE 13: The torque-angle curve for subject AC.
FIGURE 14: The torque-angle curve for subject HW.
FIGURE 15: The torque-angular velocity curve for different sessions and at different joint angles for subject AC.

a) torque-angular velocity curve at 0.5 radians
b) torque-angular velocity curve at 0.8 radians
c) torque-angular velocity curve at 1.0 radians
d) torque-angular velocity curve at 1.5 radians
e) torque-angular velocity curve at 2.0 radians
T/AV AC1 AT .5 RAD
T/AV AC2 AT .5 RAD
T/AV AC4 AT .5 RAD
T/AV SMOOTH .5 RAD

TORQUE (NM.)

VELOCITY (RAD/SEC.)
T/AV ACO AT .8 RADS
T/AV AC1 AT .8 RADS
T/AV AC4 AT .8 RADS
T/AV SMOOTH AC
T/AV AC0 AT 1.0 RADS
T/AV AC1 AT 1.0 RADS
T/AV AC2 AT 1.0 RADS
T/AV AC4 AT 1.0 RADS
T/AV SMOOTH AC
T/AV ACO AT 1.5 RADS
T/AV AC1 AT 1.5 RADS
T/AV AC2 AT 1.5 RADS
T/AV AC4 AT 1.5 RADS
T/AV SMOOTH AC
- T/RV T/RV RCl FIT 2.0 RRDS
- T/RV T/RV RC2 BT 2.0 RROS
- T/RV T/RV BCY RT 2.0 RROS
- T/RV SHCJCJTH 2.0 AROS

Diagram:

- Chart: Torque (in lb) vs. Velocity (rads/sec)
- Data points for various cases labeled as: T/AV ACO AT 2.0 RADS, T/AV AC1 AT 2.0 RADS, T/AV AC2 AT 2.0 RADS, T/AV AC4 AT 2.0 RADS, T/AV SMOOTH 2.0 RADS.
FIGURE 16: The torque-angular velocity curves determined by drawing a smooth line through the points displayed in figure 15.
FIGURE 17: The torque-angular velocity curve for different sessions and at different joint angles for subject HW.

a) torque-angular velocity curve at 0.5 radians
b) torque-angular velocity curve at 0.8 radians
c) torque-angular velocity curve at 1.0 radians
d) torque-angular velocity curve at 1.5 radians
e) torque-angular velocity curve at 2.0 radians
T/AV HW3 AT .5 RADS
T/AV HW4 AT .5 RADS
T/AV HW5 AT .5 RADS
T/AV HW SMOOTH AT .5
T/AV HW3 at .8 RADS
T/AV HW4 at .8 RADS
T/AV HW5 at .8 RADS
T/AV SMOOTH .8 RADS
T/AV HW3 AT 1.0 RADS
T/AV HW4 AT 1.0 RADS
T/AV HW5 AT 1.0 RADS
T/AV HW SMOOTH AT 1.0

TORQUE (NM.)

VELOCITY (RADS./SEC.)

0.00 3.00 6.00 9.00 12.00 15.00
T.Av HW3 1.5 RADS
T.Av HW4 AT 1.5 RADS
T.Av HW5 AT 1.5 RADS
T.Av HW SMOOTH AT 1.5
FIGURE 18: The torque-angular velocity curve determined by drawing a smooth line through the points displayed in figure 17.
FIGURE 19: The compliance-torque curve for different sessions and at different joint angles for subject AC.

a) compliance-torque curve at 0.5 radians
b) compliance-torque curve at 0.8 radians
c) compliance-torque curve at 1.0 radians
d) compliance-torque curve at 1.5 radians
e) compliance-torque curve at 2.0 radians
AC1 1.0 RADS
AC2 1.0 RADS
AC3 1.0 RADS
AC2 2.0 RAD
AC3 2.0 RAD

COMPL. (RAD/NM x 10^{-3})

TORQUE (NM)
FIGURE 20: The compliance-torque curve for different sessions and at different joint angles for subject HW.

a) compliance-torque curve at 0.5 radians
b) compliance-torque curve at 0.8 radians
c) compliance-torque curve at 1.0 radians
d) compliance-torque curve at 1.5 radians
e) compliance-torque curve at 2.0 radians
HW1 0.5 RADS
HW2 0.5 RADS
HW3 0.5 RADS
<table>
<thead>
<tr>
<th>position</th>
<th>trial</th>
<th>.5</th>
<th>.8</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106</td>
<td>77</td>
<td>160</td>
<td>115</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>72</td>
<td>88</td>
<td>82</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>65</td>
<td>60</td>
<td>62</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>75</td>
<td>60</td>
<td>57</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>65</td>
<td>65</td>
<td>35</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

Table 1a: time-constants for rise in isometric torque subject AC (in msecs.)

<table>
<thead>
<tr>
<th>position</th>
<th>trial</th>
<th>.5</th>
<th>.8</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55</td>
<td>65</td>
<td>45</td>
<td>30</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>85</td>
<td>66</td>
<td>100</td>
<td>36</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>63</td>
<td>56</td>
<td>48</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>62</td>
<td>58</td>
<td>72</td>
<td>48</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>68</td>
<td>96</td>
<td>35</td>
<td>44</td>
<td></td>
</tr>
</tbody>
</table>

Table 1b: time-constants for rise in isometric torque subject HW (in msecs.)
A) Experiment 1

One of the initial aims of this project was to adapt MacPherson's method for determination of the force-velocity curve of the CC to intact human muscles. The method outlined by MacPherson (1953) was developed on isolated preparations and its simplicity made it a desirable method for use in other types of preparations. However, the method was found to be inadequate for use in intact human muscles in that it produced results that were inconsistent with those derived from isolated preparations.

Torque developed by the CC is a function of at least three factors; the velocity of shortening (Hill, 1938), the activation of the CC (Bahler et al., 1968) and the initial length of the CC (Bahler et al., 1968). To examine the relationship between torque developed and velocity of shortening extraneous factors must be held constant. Failure to maintain them constant presents problems in the interpretation of the effect of velocity of shortening alone on force developed by the CC. In experiments on isolated preparations, such as MacPherson's, the length of the muscle can be maintained fairly easily as can the activation. In human preparations these factors are more difficult to control and it is likely that at least one of these variables, velocity of shortening, activation or initial length, was not staying constant in the present study.
During the present experiment the subjects were informed of the importance of activation and were requested to activate maximally each time as fast as they could. Although the subjects reported that they felt that they had done so throughout the experiment, activation was not well controlled as is evident from Table 1. Because of this difficulty examination was made of the possibility that variations in activation were the source of the problem.

Wilkie (1950) was able to obtain results similar to those described by MacPherson (1953) and did so on intact human muscles. Wilkie's data was obtained after a number of trials and it seemed possible that there was a training effect. To examine this hypothesis two subjects were chosen to perform a number of contractions. The subjects were aware of the need for consistent activation and tried very hard to achieve that. However, there was no change in the data that would support the claim that a period of training was beneficial. The later results were as variable as those produced earlier in this study.

To explore further the possible sources of variation in activation it was thought that pre-knowledge of the type of pull required affected the ability of the subject to contract maximally. This hypothesis was based on the comments of the subjects who reported that they felt better after completing a compliant pull rather that a non-compliant pull. While these feelings of accomplishment could only be realized after the contraction was well underway there may have been some
involvement, perhaps unconscious, prior to the contraction itself. The problem of testing this hypothesis was solved by masking the apparatus in such a manner that the subjects would not know which type of contraction would ensue. The investigator standardized his movements and only gave the command 'pull'. The subject stayed relaxed throughout the time between each pull. If there was some interference by the nervous system on the basis of the subjects knowledge then this interference should have been removed. Upon the command to pull the subject pulled against the lever as quickly as possible. The data was similar to that produced previously in that the faster rising torque was obtained from the non-compliant pull.

Clearly the expectation of the type of resistance to be encountered was not the factor that affected the results. Since elbow position reflected muscle length, and because there was some rotation of the elbow during a contraction, it was possible that the change in length of the muscle was affecting the development of force.

Upon an applied torque of 80Nm the added series compliance permitted a rotation of the axle and lever of .16 radians. If this rotation was too large then the CC might have shortened to a different position on its tension-length curve. To test this hypothesis the starting position of the compliant contraction was varied with respect to the non-compliant pull. First the contractions were completed in an area of small change in torque with respect to angle of the joint on the torque-angle curve (figure 13 and 14). The starting position
for the non-compliant pull was then maintained at 1.0 radians. The starting position of the non-compliant pull was set at one of three locations. For example, with a developed torque of 80 Nm the starting position of one of the compliant pulls was set .16 radians before the starting position of the non-compliant pull. In this contraction the two pulls finished at the same position. Another pair of contractions were obtained by starting the compliant pull .08 radians before the non-compliant pull. The third pair were obtained when the starting positions were the same. However, the procedure described did not produce data which differed from that described initially. It seems that the range of length of the CC in these contractions was insufficient to affect the rate of development of torque.

As the present data are not substantially influenced by either changes in activation or changes in elbow-angle, the inconsistency with the data of Wilkie (1950) is even more inexplicable. His study examined the force-velocity curve of a single equivalent horizontal muscle in linear terms. The added compliance he used was almost 3 times as large as that used in the present study. Wilkie justified this selection on the grounds that the horizontal force developed by his single equivalent model was fairly constant over a wide range of elbow flexion. The use of a highly compliant structure as the added compliance ensured that his results followed a format similar to MacPherson's data. The present study has shown how large is the variation in torque with respect to joint-angle so that
gross changes in length of the muscle may render the use of MacPherson's technique invalid.

It is evident that the variation of the data presented here from the expected form arises from the subject rather than from the apparatus. The origin of the mechanism of response is not obvious. A possible candidate is the central nervous system. Feelings of satisfaction reported by the subjects arise from higher orders of the CNS which enhances the possibility that this system is somehow involved. However, response from the CNS requires time and the contraction would most likely be over by the time the CNS had responded. In other words, the contraction would have to be complete before one could feel satisfied with it. Even if satisfaction was based on prior experience the contraction would be well on the way before the subject could be aware of how he might feel about it. This possibility is ruled out, of course, because of the time factor involved. Also, when the subjects were unaware of what type of contraction was to be required they reacted in the same manner as when they were aware of what was coming next.

Activation of lower orders of the nervous system (e.g. the spinal reflex loop) also require time and consideration of these mechanisms will not be of import here. It seems highly likely that some reflex activity resulted in the sharp change in the rate of rise in torque part way through the contraction with the added compliance (figure 12).

There is an interaction between the muscles and the tendon and muscle receptors. Guyton (1971) stated that the muscle
spindles can respond in a fraction of a millisecond. If their response was quick enough this organ may have had an effect on the rise in torque. The selection of the starting point for the analysis was done by searching for a change in the resting torque that was larger than the noise. When the change was larger than this level the program initiated and began the analysis. If this point was poorly chosen then perhaps some reflex activity might have been missed. This is unlikely because before the spindles can react there has to be tension developed and once there was tension it would be recorded by the transducer. The threshold level in output for the torque transducer was quite small and the likelihood of missing some activity is very small.

Similar considerations exclude explanations based on the studies of Gollnick, Piehl and Saltin (1974). They have suggested that there is some selective recruitment of different fibre types depending upon the type of contraction. While this is interesting the mechanism of selection of fibre types undoubtedly relies on activation of some reflex system. There may be a new factor, as yet unknown, that is having a significant effect on the rise in torque during isometric contractions. This factor is neither neuromuscular nor mechanical in origin but rather muscular only. Speculation regarding a feedback system involving the golgi tendon organ, the muscle spindles and the muscle itself which bypasses the CNS are implausible since they would imply an intramuscular synapse which would permit almost instantaneous reaction between the effectors and affectors.
A number of authors have suggested that there is some other factor which affects the tension produced in contracting muscle (Pringle, 1959; Hill, 1970). These authors suggest that the presence of tension augments the active state. It may be possible, then, for the type of resistance to affect the rise of active state. This sort of mechanism would explain the findings here although the reason for such a mechanism is not clear.

B) Experiment 2

The initial aim of the whole study was to investigate the dependence of the torque-angular velocity curve on its method of determination. The first experiment did not produce the expected results, the second experiment assumed the task of the determination of the torque-angular velocity relationship at different joint-angles.

There are some noticeable deficiencies in the data as exemplified in figures 15a, 15e, 17a and 17e. In figures 15e and 17e there is a definite absence of points in some portions of the torque-angular velocity curves. This lack of points was the result of some inadequacies in the experimental design. Consequently, a line drawn through these points, including the isometric point, passes through an area where there are no guidelines for the selection of its path. The smooth lines were drawn on the basis of observations made in other studies and on the assumption that human striated muscle acts in a similar
fashion. This step is, perhaps, of questionable validity for as was pointed out earlier there are differences in the force-velocity curves when determined by different techniques.

In figures 15a and 17a the smooth curve rises almost too sharply to be consistent with other data. The point where velocity of shortening was zero was determined from isometric contractions whereas the other points on the torque-angular velocity curve were determined from dynamic contractions. One is led to speculate that there may be totally different responses of the muscle to different types of loading (Pringle, 1970), that is, a different force-velocity curve for dynamic contractions and a different curve for isometric contractions. These curves may have the same shape but will vary in absolute value.

The determination of the velocity of shortening of the CC from data collected at the elbow-joint is subject to error when the rate of change of torque is not zero. This is because the SEC also changes length during an isometric contraction. The velocity of movement at the elbow-joint is the sum of the velocity of shortening of the CC and the rate of change of length of the SEC. A method for estimating the error in velocity of shortening had to be devised. If the rate of change of force is multiplied by the compliance of the SEC then the result is the velocity of change in length of the SEC. This figure can then be added to or subtracted from the velocity recorded at the hand thereby correcting the angular velocity at the hand to yield the velocity of shortening of the CC.
To perform this correction an estimation of the compliance of the SEC was required. Wilkie (1950) determined the compliance of the SEC for a number of subjects. The most compliant of those provided by Wilkie was approximately 0.03 radians/Nm. This value was multiplied by the rate of change in torque to give a value of velocity. The range of correction values determined in this manner was from .001 rad./sec. to .19 rad./sec. These values were not sufficient to alter the shape of the curves presented in figures 16 and 18 and so it is assumed that the curves do represent the relationship between torque and angular velocity.

There are some differences in the torque-angular velocity curve with elbow angle that indicate similar characteristics to isolated muscles as reported by Bahler et al. (1968). The differences in the torque-angular velocity curves with joint angle are most obvious upon comparison of data collected at 0.5 radians with that collected at 1.5 radians. There seem to be two possible explanations for these differences. There may be a lengthening of the CC to an extent where the torque generated was less at the more acute angles. This effect has been reported on isolated preparations by Bahler et al. (1968) and the extent of the effect of lengthening the muscle on the production of torque by the CC depends upon the force-length curve of the CC. A second explanation may be found in the structure of the elbow-joint. Chapman (1973) reported that the shape of the articular surface of the humerus affects the angle of pull of the tendons of the flexors in a fashion that
increased the torque at longer muscle lengths. Both of these possibilities will be discussed here.

To examine the extension of the flexor muscles over a range of joint angles used in this study, measurements were made on a skeleton of the distance between the short head of biceps brachii and its insertion in the radius. An excursion of the elbow joint from 0.5 radians to 1.5 radians represents a variation in the length of 21%. During passive extension this stretch would be absorbed primarily by the contractile material for it would not resist stretch, as would the tendons and thus, the figure of 21% is small. Noble (personal communication) has conducted some measurements on a single cadaver and reported a change in length of the muscle mass of the biceps of up to 60% of the resting length. This range was evident on flexion of the elbow from full extension to flexion of 2.4 radians. While this range is larger than the range used in the present study it illustrates the range of change in length achieved by flexion of the elbow. These measurements suggest that there is a sufficient range of movement in elbow flexion to induce changes in the output of torque by the CC. The magnitude of this change depends upon the shape of the force-length curve of the CC for intact human muscles which has yet to be defined.

Wilkie (1950) conducted a study to develop a force-velocity curve for a horizontally equivalent muscle acting at the hand parallel to the upper arm. He reported that the horizontal force at the hand was relatively constant over a range of elbow flexion. Chapman (1973) reported that the
horizontal force remained constant over a smaller range of flexion and that as the arm became more extended the force rose in a fashion unlike a real muscle. The force rose as a function of the sine of the angle of flexion of the elbow (figure 3). Wilkie assumed that the flexors of the elbow acted parallel to the upper arm and, hence, was appropriate over a small range of elbow flexion only. Chapman (1973) suggested that to calculate the correct horizontal force one had to take into account a geometrical factor. This factor resulted from the tendons of the flexors curling over the humerus when the elbow was extended passed a certain angle. As a result of this the angle of pull of the tendon remained constant for continued extension of the elbow.

Conversion of the data presented in the present study illustrated similar results. The horizontal force at the hand at 0.5 radians was 97 Newtons whereas it was only 84 N at 1.5 rads for subject AC. For subject HW the differences were larger, 150 N at 0.5 rads and 96 N at 1.5 radians.

It is fair to assume that when the elbow is near 90 degrees of flexion that the muscle is near its resting length and the number of cross bridges formed during contraction at this length would be the greatest (Gordon et al. 1966). When the arm is extended then the number of cross bridges formed may be less as the muscle is lengthened. Hence, the torque produced at the extended position should be less than at the ideal flexed position. While it is likely that this occurs the presence of such high horizontal components, as noted here,
indicate that there is some other factor affecting the torque recorded at the hand. The most likely explanation is that the transmission of torque to the hand is affected by the structure of the joint itself (Chapman, 1973). The overall effect is to permit the development of considerable torques at a position which is mechanically inefficient and when there are changes in the ability of the CC to develop torques.

The structure of the joint affects the transmission of the torque produced by the CC to the hand. Chapman (1973) has suggested that the ends of the humerus effectively fix the angle of insertion of the tendon thus maintaining a constant moment arm at that point. This action produces apparently high torques when the elbow is extended. This also explains why the horizontal force is so high. An overall effect would be to ensure that there is substantial torque available to lift loads when the elbow is extended.

A preliminary study by this author showed that the torques developed by the arm actually increased when the arm was extended fully. This has been supported recently by the preliminary studies of Noble (unpublished data) and lends further support to the claim of Chapman (1973) that the elbow-joint modifies the torques recorded at the hand. Such a modification is handy, of course, for it permits a person to develop a torque about the elbow-joint at any angle even when the elbow-joint is fully extended. Without this effect the lever arm permitted by the space between the tendon and the point of rotation of the elbow-joint would be so small that the
torques at this position would be small.

A common method for determining the compliance of the SEC is to calculate the force-velocity relationship from isotonic contractions, record the rate of rise in torque during an isometric contraction and, finally, solve equation 3 above. The recent observation of Parmley et al. (1970), however, has shown an error in this technique. There are different force-velocity curves derivable for different types of contractions. Hence, it is not really correct to use the different contractions during the process of calculating the compliance of the SEC.

The error that is introduced, however, is not one of shape but rather one of magnitude. With the exception of the higher velocities of contraction the two force-velocity curves are of the same shape. As long as the determination of the compliance of the SEC is confined to the middle and end areas of the isometric contraction then one can see the changes undergone during that contraction. The estimations for the actual value of the compliance is, of course, subject to the error.

Because of the curious events noted during experiment 1 the compliance of the SEC was determined in the manner just described. The torque-angular velocity curves were determined from dynamic contractions and the torque-time curve recorded during an isometric contraction. The compliance-torque curves were determined from these data.

The data shown here are similar to that reported by Wilkie (1950). The sharp swing upwards is due using the wrong torque-angular velocity curve. It is also noted that the shape
of the curves does not vary with joint angle. This implies that the characteristics of the SEC do not change with joint position. The intersessional variation is most likely due to the variation in activation noted in Table 1.

The characteristics of the SEC are quite important in the determination of the characteristics of intact muscle. There has been some suggestion that the SEC cannot be represented as a simple non-linear spring because its characteristics may change at very high tensions (Hill, 1970). This issue needs much more examination before the SEC is completely understood. A complete picture of the characteristics of human muscle will have to wait until this is complete.
CONCLUSIONS

This study embarked upon an investigation of five areas of human muscular contraction. These areas were described by question in chapter 1. The conclusions of the investigation are presented here.

1. The question of whether there are differences in the torque-angular velocity curve of the CC that are ascribable to the method of determination remains unanswered. This was the consequence of the failure to adapt MacPherson's technique to intact human muscular contraction.

2. There was little doubt that the joint-angle affected the production of torque about the elbow-joint. It was not clear whether the differences in the torque-angular velocity curve with respect to elbow position were due to the anatomy of the elbow-joint per se or whether the excursion of angle was sufficiently large to provoke a lengthening of the CC. If this component was lengthened then it was likely that the torque produced would decrease with lengthening in a fashion similar to that described by Bahler et al. (1968). It was concluded that there is an interaction of the anatomy of the elbow-joint with the torque-angular velocity curve obscuring any lengthening of the CC. It was not possible to assess the effect of lengthening of the CC as that lengthening would depend upon the torque-angle curve of the CC which has yet to be described.
3. The properties of the SEC appear to stay constant regardless of the position of the elbow-joint. This is evident from the figures that show little change in the shape of the curves with joint position. It is not possible to calculate the actual compliance of the SEC because of the error introduced by the method used to determine that value. The similarity of the curves presented here with those presented elsewhere verify the characteristics as reported by Wilkie (1950).

4. Wilkie's single equivalent horizontal model is not applicable to muscular contraction over the full range of joint excursion. The effect of the anatomy of the joint implies the inclusion of another factor in his model. This factor would take into account the changes in the angle of pull of the tendon as the joint angle became more acute.

While not an original question the problems associated with the application of MacPherson's method to intact muscles presented some curious information. The use of MacPherson's technique in the present study did not produce results similar to that reported elsewhere. This inability appeared to be the consequence of some factor hitherto unrevealed. A number of attempts to obtain results similar to other studies were completed but these did not produce results that were any different from those obtained in the first instance.
SUMMARY

This study began with the aim of exploring a number of problems associated with human muscular contraction. Historically the basis of an understanding of muscular contraction has come from experiments dealing with isolated muscles. These preparations permitted control of variables that affected the output of the muscles. The aim of the experimentation was to develop a conceptual model that described the observed characteristics of striated muscle. By 1938 the conceptual model comprised three components that could to some degree be associated with anatomical parts of the muscle. These components were the contractile component, a series elastic component that transmitted the force to its attachments with bones, and a parallel elastic component that provided some resistance to stretch at longer lengths. This model adequately describes the observed characteristics of isolated muscles.

The next task facing researchers was the adaptation of this model to intact human muscular contraction. There is no reason to suspect that human striated muscle has any different characteristics than other muscles. However, there are a number of variables that are more difficult to control in intact muscles than in isolated muscles. Key examples are activation, relationship of the muscle to the joint about which it is acting, and the nature of voluntary control. Since the investigator has to rely on the subject maintaining conscious
control the investigator has to be aware of the moods of the subject and the possible effects of that mood on the outcome of the experiment.

It was thought that for the present study these factors could be sufficiently controlled to permit the collection of the information desired. Apparatus was designed and built to permit the investigation of the properties of the CC and the SEC. These properties were to be explored under conditions of isometric contraction and dynamic contraction. Two techniques were devised for the experiment. The technique devised for isometric contractions was a modified version of one described by MacPherson (1953). To explore the muscle under dynamic contractions a new technique was developed.

With these techniques the investigator proposed examination of the characteristics of the CC and the SEC of human intact human muscles. Some of the data collected provided startling information. It seemed apparent that the muscle could react instantaneously to subtle variations in the resistance to contraction. Studies dealing with isolated muscles do not show this response primarily because they are isolated from the whole system. The phenomenon appears to occur in intact muscles only. In spite of attempts to produce data that did not exhibit these anomalies. The data remained the same as it was when initially collected.

The use of dynamic contractions alone in the determination of the characteristics of intact human muscles presents a limited view. In spite of the limitations the data was
interesting. There was an effect of joint position on the production of force by the CC. This effect was seen as a decrease in the force produced as the angle of the joint became smaller i.e. with further extension of the muscle. The question of major concern here was whether the decrement in force was due to changes in length of the CC or to the interaction of the muscles with the bones of the joint. It was concluded that the joint anatomy plays a large role in determining the output of the muscle. It was difficult to assess the extent of change in length of the CC because is not easy or painless to measure this length. Measurements taken from a skeleton showed that for the range of joint excursion in this study there was a change in the distance between origin and insertion of the biceps in excess of 21%. The actual change in length of the muscle bundle as separate from the tendons would be substantially larger. This range of length implies some changes in the length of the CC but whether the changes were sufficient to provoke a decrease in torque similar to that reported by Bahler et al. (1968) remains undetermined.

The compliance of the SEC was determined from isometric contractions. The relationship of compliance, torque and elbow position imply that the characteristics of the SEC are unaffected by elbow position. No absolute values for compliance were determined because of the problems associated with the use of a dynamic torque-angular velocity curve and an isometric torque time curve. The error is one of magnitude only in the middle portions of the compliance-torque curve. This
portion in the present data was very similar to that reported by Wilkie (1950).

This study has shown that the three component model can be applied to intact human muscle only when some modifications are made. There is a geometrical factor which must be taken into account as this factor can affect the force that is recorded at the hand. Such a correction, of course, would depend on the muscle group being examined. Activation appeared to vary quite substantially from contraction to contraction in spite of assurances by the subject that he was contracting consistently. The area of activation requires much work. The development of a technique of monitoring and quantifying activation would be a great boon in achieving a complete understanding of muscular contraction. Perhaps further study on the EMG will provide a solution. The problem that arose using MacPherson's technique is, perhaps, the most interesting. There do not seem to be any available mechanisms that describe why the anomaly occurred. The area of study dealing with intra-muscular receptors and response of muscle to different loads will obviously have to be examined further.
BIBLIOGRAPHY

Abbott, B.C. and Lowy, J. (1952). Mechanical properties of Mytilus muscle. J. Physiol. 120, 50P.


Noble, B. (1975). Personal communication.


APPENDIX 1

Table 1: The ages, weights and statures of the subjects in groups one and two.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>AGE YEARS</th>
<th>WEIGHT KG.</th>
<th>HEIGHT CM.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUP I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>WS</td>
<td>24</td>
<td>72.7</td>
</tr>
<tr>
<td>2</td>
<td>VG</td>
<td>21</td>
<td>57.3</td>
</tr>
<tr>
<td>3</td>
<td>LM</td>
<td>24</td>
<td>79.1</td>
</tr>
<tr>
<td>4</td>
<td>RR</td>
<td>29</td>
<td>77.3</td>
</tr>
<tr>
<td>5</td>
<td>DK</td>
<td>29</td>
<td>64.5</td>
</tr>
<tr>
<td>6</td>
<td>GM</td>
<td>25</td>
<td>70.5</td>
</tr>
<tr>
<td>7</td>
<td>JS</td>
<td>20</td>
<td>77.7</td>
</tr>
<tr>
<td>8</td>
<td>CA</td>
<td>26</td>
<td>75.0</td>
</tr>
<tr>
<td>9</td>
<td>IM</td>
<td>28</td>
<td>70.9</td>
</tr>
<tr>
<td>GROUP II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>AC</td>
<td>32</td>
<td>79.5</td>
</tr>
<tr>
<td>2</td>
<td>HW</td>
<td>37</td>
<td>90.9</td>
</tr>
</tbody>
</table>
APPENDIX 2

These are the programs used to analyze the data collected during the above experiments. The programs were written in the conversational language FOCAL.

The program ADFOCA.SV was used to acquire the data into the computer memory. The operator responded to each question with a response appropriate to the needs of each particular acquisition.
01.20  F  G=1.5; D 2
01.30  S  RF(1)=3.1416/(R(3)-R(2)) S  RF(2)=3.1416/(R(5)-R(4))
01.32  S  HR(1)=R(2)*RF(1) S  HR(2)=R(4)*RF(2)
01.34  A  "TDHO APPL NM" TA I S  TF(1)=TA/(T(5)-T(3)) S  TF(2)=TA/(T(2)-T(4))
01.36  S  GL(1)=(T(3)-T(1)) S  GL(2)=T(1)-T(2) S  MT=T(1)
01.38  S  D=0.171 S  AF(1)=9.81/(A(2)-A(1)) S  AF(2)=9.81/(A(1)-A(3)) * D
01.40  S  AG=(A(2)-A(3))/2 S  MA=A(1)
01.45  T  %12.0E "RF(1)" "RF(1)" " R/U",!! "RF(2)" "RF(2)" " R/U",!!
01.47  T  "HR(1)" "RR(1)" " R",!! "RR(2)" "RR(2)" " R",!!
01.48  T  "TF(1)" "TF(1)" " U",!! "TF(2)" "TF(2)" " U",!!
01.49  T  "GL(1)" "GL(1)" " U",!! "GL(2)" "GL(2)" " U",!! "AF(1)" "AF(1)" " R PER S2 T"
01.51  T  "AF(2)" "AF(2)" " R PER S2 T",!! "AG" "AG" " U",!! "MA" "MA" " U",!! "MT" "MT" E
01.52  S  ER=EI1 IT %15.0E "ER EMG REMAINDER" "ER",!!
01.53  F  J=2.51 D 4
01.55  S  EF=0 IF J=2;51 S  EF=EF+EF(J)
01.57  T  %15.0E "MEAN EF EMG FACTOR" "EF/4"," MVOLTS/U",!!
01.59  Q

02.20  S  S=01 S  K=8092+100*G1 S  T=9092+100*G1 S  A=8592+100*G1 S  E=9592+100*G1
02.24  F  I=1,100 D 3
02.26  S  H3G=S100 S  S=01 S  K=T I=1,100 D 3
02.28  S  T(G)=S100 S  S=01 S  R=I F I=1,100 D 3
02.30  S  A(G)=S100 S  S=01 S  R=E F I=1,100 D 3
02.40  S  E(G)=S/500

03.10  S  S=S+FCOR(K+I-1)

04.10  T  "EMG MILLIVOLT INPUT IS" IT %1, J A EA(J)
04.20  S  EF(J)=EA(J)/(E(J)-EH); IT "  EF(" %1, J,")",%15.06,EF(J)," MV/U" !
NEWMIS.SV

01.05 A "TF"TF,"AF"AF,!;S N=40;S C=-(TF/AF)
01.10 F G=1,4;D 2
01.20 Q

02.10 S A=8351+40*G-40;S T=8511+40*G-40
02.15 S LT=FCOR(T+1);F I=1,N;D 6
02.17 F I=1,N;S X=FCOR(T+I)-LT;S Z=FCOR(T+I,X*5)
02.20 S LA=FCOR(A+I);F I=1,N;D 7
02.25 F I=1,N;S X=FCOR(A+I)-LA;S Z=FCOR(A+I,X*5)
02.30 F I=1,N-4;D 3
02.40 S L=A;S A=T;F I=1,N-4;D 3
02.50 S P=0;S A=L;S S=0;F I=3,N-3;D 4
02.60 S IN=S/P;T "IN"IN," P"P,1

03.10 S X=0;F J=1,5;S X=X+FCOR(A+I+J-1)
03.20 S Z=FCOR(A+I+2,X/5)

04.10 S TO=FCOR(T+I+1)-FCOR(T+3);S AC=FCOR(A+I+1)-FCOR(A+3)
04.15 I (AC-20)4.16,4.16,4.17
04.16 T "PING",!;R
04.17 I (TO/AC)4.19,4.18,4.19
04.18 T "PONG"!,!;R
04.19 S P=P+1;S S=S+(TO/AC)*C;T %5.04,(TO/AC)*C,1

06.10 I (LT-FCOR(T+I))6.2,6.2,6.3
06.20 R
06.30 S LT=FCOR(T+I)

07.10 I (LA-FCOR(A+I))7.2,7.2,7.3
07.20 R
07.30 S LA=FCOR(A+I)
*
GRAV.SV

01.10 A "Fr""Fr""Hr""Hr", !
01.20 F G=0,171 D 2
01.30 @

02.20 S S=0; S X=0; S T=9992+100*G; S R=3192+100*G
02.30 F I=0,99: S S=S+FCOR(T+1): S X=X+FCOR(R+I)
02.40 T %12.05,(X/100)*RF-HR," "S/100, !

CURFIT.SV

01.06 E
01.07 A "L1""L1""L"L", !
01.09 F J=1,L1:A X(J1),Y(J1), !
01.15 D 2
01.20 @

02.17 S N2=2*L-1
02.20 F J=1, N2:S SX(J1)=0
02.22 F J=1,L1:S YX(J1)=0
02.25 F J2=1,N2:F J=1,L1:S SX(J2)=SX(J2)+X(J1)*((J2-1))
02.27 F J2=1,L1:F J=1,L1:S YX(JP)=YX(J2)+Y(J1)*(X(J1)*((J2-1))
02.30 F J2=1,L1:F J=1,L1:S A(J2+J1*L)=SX(J1+(J2-1))
02.35 D 15
02.78 F K=1,L; T !"B(",%2,%K, ")"", %, B(K)
02.80 F J=1,L1:S YX(J1)=0
02.82 S SD=0
02.85 F J=1,L1:S YX=0; D 8
02.86 S SD=FSQ(T/SD/(L1-L))
02.88 T !"MEAN SQUARE DEVIATION",SD; R

08.05 F J=1,L1:S Y=XY+B(J2)*(X(J1)*((J2-1))
08.15 S D=Y(J1)-YX; S SD=SD+D*D

14.05 S N=K+1; S DD=A(N+II*L)/A(II+II*L)
14.10 F J=II,L; S A(N+J*L)=A(N+J*L)-A(II+J*L)*DD
14.15 S YX(N)=YX(N)-YX(II)*DD; R

15.05 S MM=L-1
15.10 F II=1,MM:F K=II,MM; D 14
15.15 S B(L)=YX(L)/A(L+L*L)
15.20 F M=2,L; S N=L+1-M; S KK=N+1; S B(N)=YX(N)/A(N+N*L); D 15.25
15.21 G 15.30
15.25 F K=KK,L; S B(N)=B(N)-A(N+K*L)*B(K)/A(N+N*L)
15.30 R

31.01 S Z=FCOR(1139,3584)
31.02 S Z=FCOR(1139,2409)
*

PLOTDA.SV

23.05 S T1=9791;S Y1=5943;S G=0
23.10 A "N""N," PI"PI;S G=G+1
23.20 S Y1=Y1+200;S T1=T1+G*400-400
24.50 S J=0
24.55 S J=J+1;D 25
25.50 S C=0;F I=1,N;D 27
25.53 S L=Y1;S Y1=Y1+400;F I=1,N;D 27
25.56 S P=3000/C;T "MAX ABCISSA",%8.04,C,!
25.58 S C=0;S Y1=T1;F I=1,N;D 27
25.60 T "MAX TORQUE"C/40,1;S C=2000/C;S Y1=L
25.65 D 26
25.70 I (J-1)25.8,25.8,25.85
25.80 T "RESET PLOTTER G 24.55";S Y1=Y1-200;Q
25.85 T "RESET PLOTTER G 23.1";Q
26.50 S X=0;S Y=0;S Z=FEXP(X,Y,1)
26.52 F I=1,N;D 28
26.53 S X=0;S Y=0;S Z=FEXP(X,Y,1)
26.55 T "RESET PLOTTER";A "RESET? ANSWER 1(YES) OR 0(NO)"ST,!
26.57 I (ST)26.55,26.55,26.6
26.60 S X=0;S Y=0;S Z=FEXP(X,Y,1);S Y1=Y1+400;F I=1,N;D 28
26.70 S X=0;S Y=0;S Z=FEXP(X,Y,1)
27.10 I (FCOR(Y1+I+P1+2)-C)27.2,27.2,27.4
27.20 S C=C
27.30 R
27.40 S C=FCOR(Y1+I+P1+2)
27.50 R
28.10 S Y=FCOR(T1+P1+2)+C;S X=FCOR(Y1+P1+2)+I)*P
28.20 S Z=FEXP(X,Y,1)
31.01 S Z=FCOR(1139,3584)
31.02 S Z=FCOR(1139,2409)
*
MAK ON LEVEL (VOLTS): "HI,17S HI=FITR(HI*102.4)

TOTAL ACQUISITION TIME IN MSEC IS: "TM,!!!

NO OF CHANNELS ACTIVATED : "NCJ!!

TOTAL ACQUISITION TIME IN MSEC IS: "TM,!!!

NO OF PASSES FOR THIS INITIALISATION : "NG,!!

CHANNEL START ADDRESS FIELD ARAY SIZE"!!!

AMOUNT OF DATA"IT %6,AA,!!

AMOUNT OF DATA"IT %6,AA,!!

TOO MUCH DATA

COLLECTING FROM CHANNEL X1,A A

THIS IS ALL THE DATA HEQUIHED TO INITIALISE"AVSI

THIS IS ALL THE DATA HEQUIHED TO INITIALISE"AVSI

TOO MUCH DATA

GAIN FOR CHANNEL"IT %1,A/A "!"G(A),!

PERIOD FOR CHANNEL"IT %1,A/A "!"T(A),!!
ADFOCA.SV (continued)

05.10 I (SW(A)) 5,11,5,11,5,12
05.11 S G(A)=01H
05.12 I (C(A)-10) 5,16,5,14,5,28
05.14 S G(A)=A1H
05.16 I (C(A)-5) 5,20,5,16,5,28
05.18 S G(A)=64+A1H
05.20 I (C(A)-2) 5,15,5,24,5,22,5,28
05.22 S G(A)=128+A1H
05.24 I (C(A)-1) 5,25,5,28,5,22,5,28
05.26 S G(A)=192+A1H
05.28 T "INCORRECT GAIN FOR CM";IT %I,ALIT %I

06.10 I (SW(A)) 6,12,6,12,6,14
06.12 H
06.14 S AA=AA+TM/T(A)

06.10 I (SW(A)) 6,12,6,12,8,14
06.12 H
08.14 I (DL) 15,8,15,8,16
08.15 S AD(A)=11S CF(A)=24 JS D=1IS C=11S TE=MI 8,24
04.16 S TE=TE+(TM/T(C)) IS C=11S AD(A)=TEIS CF(A)=24
06.17 I (TE-T1) 8,24,8,18,8,18
08.18 I (TE-T2) 8,20,8,22,8,22
08.20 S AD(A)=TE-T1IS CF(A)=11G 8,24
08.22 S AD(A)=TE-T2IS CF(A)=11G 8,24
08.24 T %3,ALIT %12,AD(A);IS Z=AD(A);ID 10IT %6,0CIT %8,CF(A)
08.25 T %3,TM/T(A)IS Z=TM/T(A);ID 10IT %6,0CIT
08.26 S JD=JD+1
08.28 I (AJL) 32,6,30,8,32
08.30 S JN=AD(A);IS JL=1
08.32 I (NG-JD) 8,16,8,34,8,16
08.34 T ,11S AD(A)=,11S JL=0IS JD=0

09.10 I (SW(A)) 9,12,9,12,9,14
09.12 H
09.14 S TE=T(A)/CP;IS T(A)=FTR(T)I;I (T(A)-TE)5,16,9,18,9,16
09.16 T "CHANNEL";IT %1,ALIT "PERIOD NOT COMPATIBLE WITH INTERRUPT PERIOD"
09.18 S T(A)=01H

10.10 S OC=015 JJ=0
10.12 S JD=JJ+1IS Z=Z;B1S ZZ=FTR(Z);IS DI=(Z-ZZ)*8
10.14 S OC=DI*10I(JJ-1)+OC1S;IS ZZ
10.16 I (Z) 10,12,10,12,10,12
10.18 H

30.50 A !!!OCTAL:;IS DE=0;F I=1,5;S M=5-JD 30.70
30.60 T %5,08,?DECIMAL?G 30.50
30.70 S X=FTR(OC/10;M)I;IS OC=OC-X;10;M;IS DE=DE+X;8;M