THE RELATIONSHIP BETWEEN LENGTH, VELOCITY, EMG AND FORCE IN THE ISOLATED HUMAN BICEPS BRACHII MUSCLE

BY

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ABSTRACT

The force-velocity and force-length relationships of skeletal muscle have been thoroughly investigated in the literature. Unfortunately many of the relationships that have been applied to models of the human anatomy have been based upon investigations that have been performed under in-vitro conditions. It was the intention of this study to investigate whether the relationships determined by in-vitro investigation and assumed to be correct could accurately and properly be applied to actual human examples. Previous investigation by Leedham and Dowling (1991) displayed that when investigating human elbow flexors and in particular the biceps brachii that the force-length relationship did not concur with in-vitro results. The purpose of this study was to investigate the relationships between length, velocity, EMG and force of the biceps muscle.

Eight young adult males (22-26) were fastened into an isovelocity device (CYBEX) which allowed only flexion and extension of the right elbow. The forearm was then rotated eccentrically or concentrically through a range of motion from 50 to 170 degrees of extension (or vice-versa). The biceps muscle was either maximally contracted voluntarily or was excited using electrical stimulation at 40 Hz. Using the constant angle torque (CAT) method and three dimensional surfaces the force-velocity, force-length and EMG-velocity relationships were investigated.

The main conclusions of the study were that the neural drive provided by electrical stimulation over the motor point provided CMAPS of consistent amplitude regardless of the joint angle or angular velocity. The concentric force-velocity relationship of the biceps was in agreement with most accounts in the literature however the eccentric contraction condition displayed a peak force production at 30°/s then showed a slight decline to plateau across faster eccentric velocities. Increased eccentric force production was thought to be more mechanical than neurological in nature.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

When an individual wishes to perform a specific motor task, for example elbow flexion, the central nervous system (CNS) generates an electrical signal which travels to and physiologically excites the muscle tissue. The active muscle tissue then generates forces that are transferred through the tendons to the skeletal system. The combination of muscle force output and the mechanical advantage provided by the muscle moment arm as the muscle crosses the joint, results in torque production about the joint causing angular motion. The muscles and tendons are seen to act as the liaison between the CNS and the articular system. Therefore, it can be seen that the properties of this liaison (muscle) must be investigated to provide a better understanding of the components of human movement.

The effect of movements of varying velocities, direction of contractions (eccentric and concentric) and varying muscle lengths of the human articular system on the force-generating properties of the contractile component of muscle tissue is of great importance to the prediction of individual muscle forces. Prediction of individual muscle force is important to those scientists investigating bone-on-bone forces during movement, the flows of power from one segment to another during movement, the qualitative interpretation of human movement and to those who use models of muscle to design prosthetic devices. The force-length and force-velocity characteristics of muscle, as well as the EMG activity, are qualitatively considered in the estimation of these individual muscle forces.

Models of the musculo-skeletal system use a black box approach to the prediction of muscle force (Dowling, 1986). That is models are based upon an input-output description of the tissue. The contents of the black box are modelled by matching the inputs (muscle activation and joint kinematics) to the output (joint torque). Better isolation of components within the black box will allow better prediction of output from input. The purpose of this experiment is to further investigate some of the mechanical factors composing this black box to provide more accurate components for a model of the biceps muscle.

1.1 Investigations of Muscle Properties

Many early investigations into the characteristics of muscle force production involved the electrical stimulation of the in-vitro muscle or muscle sub-unit (fiber). These muscle fibers were held in an apparatus and manipulated into varying lengths and velocities, while being electrically stimulated. Simultaneously, the forces being produced by the muscle were measured and recorded for analysis. These investigations proved to be effective in attempting to study the force production of the contractile component of the muscle under changing lengths (Gordon, Huxley and Julian, 1965) and velocities (Bigland and Lippold, 1954; Edman, 1988). Many studies have examined the kinetics of the contractile component during varying movement conditions (Gordon *et al.*, 1965; Rack and Westbury, 1969; Lieber and Boakes, 1988; Granzier, Burns and Pollack, 1989), however, there is little information about the interrelation between force, length and velocity at this level of investigation.

Most in-vitro investigations of the contractile component have attempted to support their findings based on the Sliding Filament Theory (SFT)(Gordon et al., 1966) or some variation of this theory. Although this theory is accepted as being fundamentally correct, at the microscopic level, the mathematical equations used to describe the kinetic relationships may be inadequate to be transferred to models of human muscle during movement.

1.2 In-Vivo Investigations

1.2.1 Problems:

The literature displays a vast number of studies that have investigated the force-length and force-velocity relationships in humans. Measurement of the kinetic properties of intact human muscle is difficult due to an inability to directly measure the force output of the muscle under investigation. There are many other problems with the investigation of these properties on individual, intact and in-vivo human muscles:

1a. The complexity of the human anatomy; for example, when investigating the torque being produced by a voluntary contraction of the elbow flexors, it is impossible to isolate the biceps as the sole contributor to torque output. This is because there are 24 muscles spanning the elbow joint and under voluntary contractile conditions it is impossible to selectively recruit only those motor units in the biceps muscle. Co-contraction of synergist or antagonist muscles will change the net moment about the elbow.

b. Determination of the cross-sectional area of the biceps (Brand *et al.*, 1986). Is the cross-sectional area proportional to the force generating abilities of the muscle.

c. Moment arm determination. The biceps moment arm is known to change as the joint angle changes due to an overlapping of muscles and tendons, thus changing the mechanical advantage of the muscle based upon the joint angle (An, Hui, Morrey, Linschied and Chad, 1981). These changes in moment arm as the joint angle changes are not the same for all of the elbow flexors.

2. During most voluntary investigations of torque output, a constant level of activation is required (usually an MVC). This is difficult to achieve trial after trial due to changes in subject motivation, perceived pain and exertion.

1.2.2 Electrical Stimulation

Electrical stimulation is a method which allows the investigator to allay the error associated with voluntary contraction by overriding the central nervous system and controlling the activation of a single muscle or group of muscles externally. The use of percutaneous electrical stimulation over the motor point of the biceps muscle permits effective isolation of the muscle, allowing for the investigation of the torque production qualities of the muscle. Unlike direct stimulation of the nerve, which induces a reversal of the motor unit recruitment order (Gorman and Mortimer, 1983), stimulation of the muscle body over the motor point may permit a more natural recruitment order that may correspond to Henneman's Size Principle (Henneman (1965), Knaflitz, Merletti and DeLuca (1990)). This should present a more realistic force output in accordance with the size principle of motor unit recruitment and motor unit properties. Knaflitz et al. (1990) have suggested that when stimulated over the motor point, motor units are recruited in the standard ascending order (ie. small to large) 72% of the time. Stimulation of a muscle via the nerve also may result in the recruitment of other muscles innervated by the same nerve, resulting in synergistic co-contraction and a change in the net moment being measured.

1.2.3 Previous In-vivo Investigations

There are few studies in the literature that have used electrical stimulation as a means to selectively isolate an in-vivo muscle to permit investigation of the muscle's kinetic characteristics. Ismail and Ranatunga (1976) and Leedham and Dowling (1991) have both attempted to investigate the force-length relation of the isolated, in-vivo biceps muscle using electrical stimulation techniques. These studies provided a framework for the present investigation. Leedham and Dowling (1991) determined biceps EMG amplitudes remained constant during stimulation conditions, regardless of joint angle, during isometric contraction conditions. Assuming that

EMG is a constant regardless of velocity or angle will permit the removal of one variable from the equation and will lead to a better understanding of the mechanics of muscle contraction under varying conditions and eventually a better basis for the prediction of force generation from surface EMG.

Westing *et al* (1991) have investigated the force-velocity relationship of the quadriceps muscle group by superimposing electrical stimulation over the maximal voluntary effort of the subject. Westing's investigation determined that eccentric torque output can be increased by 25% over voluntary levels by superimposition of electrical stimulation to the knee extensors. This suggests neural inhibition could play a role in shaping the force-velocity curve. In a further study Westing (1990) suggested that electrical stimulation applied to the relaxed muscle resulted in eccentric torque output exceeding voluntary levels by 10%, however contrasting results were found in isometric and concentric trials. Westing's studies have suggested the possibility that different mechanisms, either neuromuscular or mechanical may provide the explanation of the force-velocity relationship. These studies may also help to provide insight to the mechanisms by exploiting the differences between in-vitro and in-situ investigations of muscle.

Dudley *et al.* (1990) using artificial activation of the knee extensors determined that the force-velocity relationship in-situ was much closer to in-vitro investigations of muscle and suggested that the ability of the central nervous system to activate the knee extensors during maximal efforts depended upon the speed and the type of contraction being performed. The present investigation will further attempt to determine the mechanisms responsible for the force-velocity relationship of the biceps.

1.3 Force-Length Relation

1.3.1 In-vitro Investigation

It is well established that, at constant levels of excitation, the amount of isometric force generated is directly proportional to the length of the muscle under investigation (Gordon *et al.*, 1966 a,b; Rack and Westbury 1969; Vrendenbregt and Rau, 1973). The classic investigation of this property of muscle is the one by Gordon *et al.* (1966 a,b), in which isolated amphibian muscle fibers where maximally stimulated at differing sarcomere lengths. The resulting force outputs resulted in the classic inverted-U force-length relationship (figure 1). The sliding filament theory (SFT) was proposed by Gordon *et al.* (1966 a,b) to explain many features of the force-length relationship. SFT suggests that as sarcomere length changes the amount of overlap between the contractile proteins (actin and myosin) varies, allowing variable amounts of cross-bridge formation and proportionate force production to occur. The SFT is assumed to be essentially correct and applicable to human striated muscle fiber. However, the use of the inverted-U relationship when modelling the force output of single human striated muscles in-vivo may be incorrect.

1.3.2 In-vivo Investigation

Little information is available regarding the in-vivo force-length relationship in human striated muscle. This lack of information, as previously mentioned, is due to the inability to effectively isolate and measure forces created by single muscles. Herzog *et al.* (1988a) isolated a two-joint muscle, rectus femoris, by manipulating the angle of hip flexion while maintaining a constant knee angle. This allowed measurement of torque while changing the length of the rectus femoris. They determined that the force-length relationship of the rectus femoris was much less arched and more drawn out than the predicted relationship based upon Gordon *et al.'s* theory. Two assumptions were made in this study:

1. ~~it was assumed that~~ the use of MVC's ensured that the muscle was equally activated for each trial.
2. ~~it was assumed that~~ the contributions of the synergist and antagonist muscles were consistent for all trials.

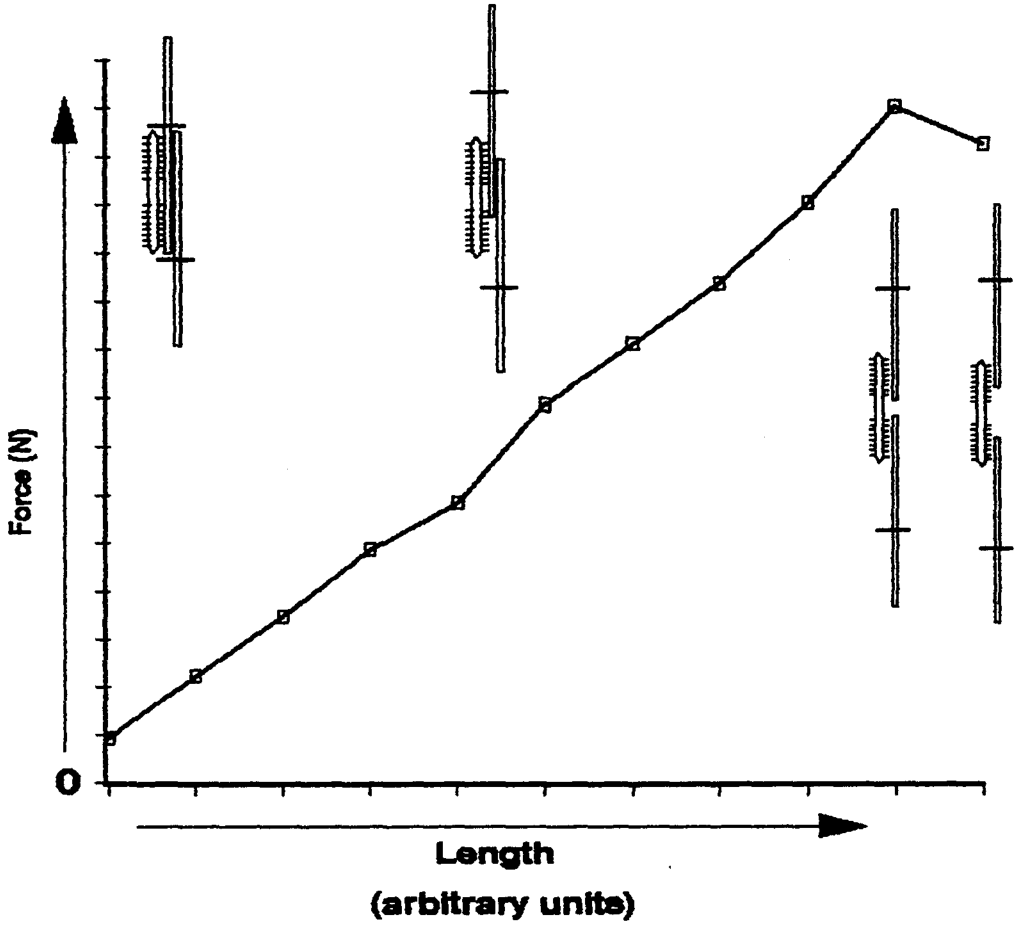


Figure 1. Force-length relationship of the in-vivo biceps.
The amounts of estimated cross-bridge overlap are displayed corresponding to the amount of force they generate.
(Leedham and Dowling, 1991)

Ismail and Ranatunga (1978) and Leedham and Dowling (1991) made use of percutaneous electrical stimulation over the muscle motor point to isolate the biceps muscle. The use of electrical stimulation techniques allowed the amount of recruitment to be monitored ensuring constant levels of activation from trial to trial. Ismail and Ranatunga determined torque and muscle lengths for elbow joint angles of 40 to 150 degrees and reported that a nearly complete "inverted U" length-tension relation was found for the in-vivo biceps muscle. Contrasting this, Leedham and Dowling (1991) used a similar technique for elbow joint angles of 60 to 160 degrees and reported that the length-tension relationship was monotonically increasing with a slight decline at 160 degrees of extension. The reason for the differing results between the two studies may have been the method used in the determination of the biceps moment arm, which is used to convert torque data to force data. Ismail and Ranatunga used a straight-line approach in the determination of the moment arm whereas Leedham and Dowling used data provided by An *et al* (1981) for moment arm determination. The data by An et al. (1981) suggested that the moment arm varies during flexion due to muscles and tendons being stacked around bones. Further data by Amis, Dowson and Wright (1979) determined that the moment arm shortens as the elbow extends until 146 degrees and greater where it remains constant at 2.0 cm. These modifications to the moment arm data used by Ismail and Ranatunga would result in a change in the shape of their length-tension relation, especially as it approaches full extension. These investigations also lend provide support to the argument that specific neuromuscular relationships that have been determined in-vitro or in-vivo (using voluntary contractions) may not be applicable to the prediction of force from individual muscles in-vivo. This is most likely due to restrictions of muscle length due to range of motion of joints.

1.4 Force-velocity Relationship

1.4.1 In-vitro Investigation

There are many references in the literature to studies that have investigated the effects of concentric\eccentric contraction, and the speed of this contraction, on the force production capabilities of skeletal muscle. Early investigations into the nature of the force-velocity relationship involved maximally stimulating isolated, in-vitro muscle fibers and then measuring the velocity at which the muscle could pull an isotonic load. (Fenn and Marsh, 1935; Katz, 1939). Fenn and Marsh (1935) reported that Levin and Wyman (1927), using muscles from dogfish, investigated the relation between speed of shortening and lengthening of contraction and the force generated. The expected linear relationship was not determined, which lead Levin and Wyman (1927) to suggest that muscle could be represented by a two component system, an undamped elasticity and a damped elasticity. Fenn and Marsh (1935) went on to suggest the above model would predict a linear relationship between force and velocity of contraction (of the visco-elastic component) and could not correctly model muscle. This is due to the fact that after the damped spring in the viscous medium has had its elasticity increased (representing contraction of the contractile component) the undamped spring will stretch until the tension in the system is equal to the weight of the object to be moved. After this point the model will not allow for any change in the length of the undamped spring, which in turn will not allow it to participate further in the mechanical events of contraction. Fenn and Marsh determined that the relationship during isotonic contractions was not linear but logarithmic in nature.

Based upon the findings of Fenn and Marsh (1935) which suggested that the energy requirements of shortening muscle be investigated, Hill (1938b) devised an equation which could calculate force without the need to measure energy consumption (equation 1). Hill's equation was found to predict a hyperbolic curve for the force-velocity relationship.

$$(P+a)(v+b)=(P_0+a)*b \qquad (1)$$

where:
P = force of contraction
P_0 = maximal isometric force
v = velocity of shortening
a = heat constant
b = rate of constant energy liberation

Katz (1939) investigated the force-velocity relationship and compared his results to the predicted rectangular hyperbola of Hill's equation. Katz's results supported the energy equation, determining that for concentric contractions as the velocity of contraction increased, the amount of tension produced decreased in a hyperbolic fashion. The hyperbolic relationship between force and concentric velocity has been well researched and is well supported in the literature (Mashima, Akazawa, Kushima and Fujii (1972); Edman, 1979; Granzier, Burns and Pollack, 1989)

The relationship between force production and eccentric contraction velocity for in-vitro muscle has not been as thoroughly examined in the literature. Mashima *et al.* (1972) using frog semi-tendinosis muscle displayed the relationship under isotonic lengthening and isokinetic (isovelocity) conditions. They determined that under both conditions a hyperbolic increase in the force production with increased lengthening velocity was present. Although the eccentric relationship was hyperbolic in nature it must be noted that the magnitude of force change is smaller than that seen for concentric contractions. It is also important to note that the force production quickly reaches a maximum and then levels out as velocity increases. Mashima et al (1972) reported that the force for any given eccentric velocity (F_v) was 1.4 times larger than that of concentric under the same activation and velocity conditions. Granzier et al (1989) found that yield (the point at which slippage of the actin filaments past the myosin filaments due to the inability to maintain the bonds at high tension) occurred during eccentric conditions at tensions of 1.6 - 1.7 times the maximal isometric tension; however this was found to be dependent upon the length of the sarcomere. Granzier et al. (1990) pointed out that at sarcomere lengths of 2.65 - 3.15 μm yield was absent even at loads as high as 2.2 to 2.6 times the sarcomere-isometric load. This suggests that there is some discrepancy in the literature regarding the force-velocity relationship during eccentric contraction conditions, particularly at different muscle lengths.

1.4.2 Possible Mechanisms for Force - Velocity

1.4.3 In-Vivo (Human) Investigations

The torque-velocity relationship of various muscle groups is well documented in the literature (Wilkie, 1950;

Komi, 1973; Jorgensen, 1976; Perrine and Edgerton, 1978; Eloranta and Komi, 1980; Westing, Seger, Karlson and Ekblom, 1988; Dudley et al., 1990, Hortobagyi and Katch, 1990). The torque-velocity relationships for the living human have, for the most part, reflected the findings determined for the in-vitro investigations. However, there are some discrepancies between the in-vitro findings and the in-vivo human findings. Reasons for these differences are most likely due to the problems associated with investigations of the human system, as mentioned earlier (neurological, anatomical), or the method used to investigate the relationship.

Many investigations have displayed data that suggest when torque is measured at shorter muscle lengths divergence from the standard hyperbolic curve occurs (figure 2)(Perrine and Edgerton, 1978; Fuglevand, 1983; Marshall *et al.* 1990). This inconsistency manifests itself as a decrease in the torque outputs and is especially noticeable at the slower velocities (< 90°). Perrine and Edgerton (1978) suggested that the decrease in force output of the muscle at these shorter lengths was due to a neural mechanism that restricted the muscle's maximal tension. Such a mechanism would require inhibition of the motor neuron pool to the agonist muscle or conversely an excitation of the motor neuron pool of the antagonist muscles, both of which would decrease the measured net moment. Perrine and Edgerton did not provide any myoelectric measures of the muscle activity as support for this hypothesis. In a later investigation by Fuglevand (1983) no consistent changes in agonist activation with changes in velocity were determined in the EMG data. Hortobagyi and Katch (1990) have suggested that neural inhibition is an "ubiquitous feature of untrained subjects in the studies that observed flattened TVC (torque velocity curve)". After investigating the effects of high and low strength subjects it was determined that the high strength individuals did not plateau during low velocity concentric conditions. They suggested that individuals with high strength may be able to somehow bypass this neurological inhibition, however, no EMG data was provided to support this hypothesis. A possible explanation of Hortobagyi and Katch's finding is that their high strength subjects had undergone resistance training and if this training occurred at the low-velocity conditions there may have been an enhancement of the contractile mechanism under these conditions. This may increase the ability to produce force under these conditions suggesting that the reason may be mechanical, not neurological. No direct neurophysiological evidence has been found in the literature to support this tension restricting mechanism.

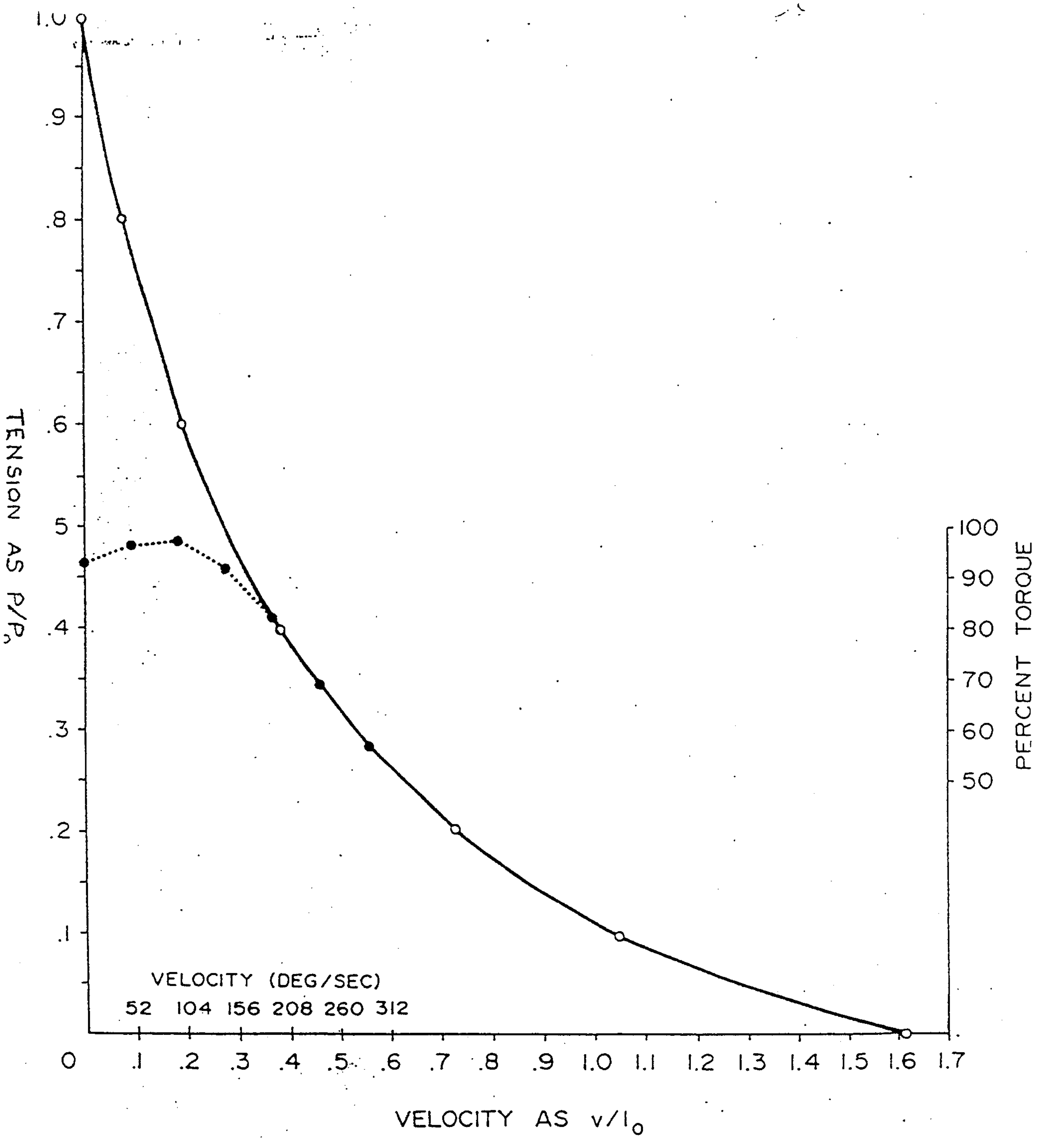


Figure 2. Experimental force-velocity relationships of isolated animal and in-vivo human muscles. o - isolated animal muscles ($V=.42(P_o-P)/P +.26$. • - in-vivo muscle experiment by Perrine and Edgerton (1978)

Another possible explanation for the decrease in torque output at the shorter muscle lengths and velocities was presented by Gregor, Edgerton, Perrine, Campion and DeBus (1979). In their investigation the fiber composition of elite female athletes (vastus lateralis) and its relationship to the torque-velocity relation was established. It was determined that in subjects with a greater percentage of fast twitch fiber, decreased tension was produced at more extended positions. Conversely, subjects with a greater proportion of slow twitch fibers displayed the standard force-velocity relation. This suggests that it is possible that different muscle groups may display different variations in the force-velocity relation due to their differing muscle fiber composition.

Another possible explanation may still exist in the form of a mechanical process, for example the series elastic element. The present investigation will attempt to further elucidate the mechanism responsible for this phenomenon by carefully controlling myoelectric activation and selectively isolating the biceps muscle.

Two methods are generally used to investigate the torque(force)-velocity relationships in the human subject. One common method is to have the subject move an isotonic load as quickly as possible and measure the velocity of the movement (Wilkie, 1950), or have the subject perform an isokinetic movement and measure the torque production (Fuglevand, 1983). Both conditions require a maximal effort by the subject. It is important to note that the measurements of the dependent variables always occur at the same joint angle from load to load between different velocities (constant angle torque or CAT). Measuring at the same joint angle assumes that the muscle is at a constant length for all measurements, which should remove any length-tension effects and also negates any mechanical advantage due to moment arm.

The second method used to discern the torque-velocity relationship is to normalize all of the measurements to the peak torque that is created throughout the range of motion for a particular isokinetic velocity. A composite of all the peak torques for each velocity is then generated providing the torque-velocity relationship. The peak torque method assumes that peak torque always occurs at the same joint angle during the movement. Partridge (1979) supports this assumption in his three dimensional representation of muscle. Partridge compiled force-length and force-velocity data from previous literature and showed that although the magnitude of the length-tension curves decreased with increased shortening velocity, the length-tension curves were symmetric about a single muscle length of optimal force production. This suggests that peak torque should always occur at the same joint angle (muscle length) regardless of the shortening velocity of the segment (muscle). Komi and Ishii (1981) investigating the elbow flexors also supported this assumption by determining that the position of peak torque was independent of angular velocity. Fuglevand (1983), investigating the knee extensors, displayed contrasting results. He determined that there was an interaction between angular velocity and the peak torque production, demonstrating that as angular velocity increased, the joint angle for peak torque shifted towards the more extended positions. The present investigation will use the CAT method due to the discrepancies reported within the rationale behind the peak torque method.

Although investigations comparing the two methods have suggested that there is not a significant difference between the results of the two methods of testing (Westing et al., 1988; Yates and Kamon, 1983) there appears to be some slight differences between the results. These differences being the decline in force production at shorter muscle lengths and low-velocity concentric contractions.

While there has been considerable investigation of the force-length and force-velocity relationships there are only a limited number of studies which have examined the force-length-velocity interactions during human movement (Fuglevand (1983); Marshall, Mazur and Taylor (1990)). The investigation of the three variables (force, length, velocity) together permits the construction of a three-dimensional surface plot. Three-dimensional plots allow the investigator to better identify trends of force production for any given velocity and muscle length (joint angle). Zajac (1989) suggests that, from a set of length trajectories, an empirical force velocity relation can be constructed for any muscle length. Zajac goes on to say that "the fact that the observed length trajectories can be described well by integrating the inverted velocity-force expressions supports the use of a force-length-velocity relation to model muscle behavior."

1.5 Purpose

The purpose of this study was to provide a better understanding of the components of human movement by investigating the force-length-velocity relationship of the in-vivo human biceps brachii muscle. The results of this thesis will be limited to the subject pool that was investigated, that being young, athletic white males. It is not the purpose of this thesis to investigate a hypothesis but to determine and identify relationships that can be incorporated into various models of human movement.

The use of percutaneous electrical stimulation techniques will enable the various kinetic relationships of dynamic muscle contraction to be investigated in isolation.

The relationship will be conducted under the following conditions:

- high and low contraction velocities
- eccentric and concentric contractions
- isokinetic movements
- voluntary and stimulated contractions

2.1 Subproblems

a) to further investigate the plateauing effect that has been detected at low shortening velocities and short muscle lengths. The maintenance of a constant level of activation to the isolated muscle may enable the investigator to determine the mechanism responsible for the decrease in force production.

b) to further investigate the eccentric force-velocity relationship of the in-vivo biceps under voluntary and stimulated conditions.

c) to investigate the relationship of biceps EMG activity under differing velocity and length conditions.

Limitations:

The results of this investigation will be limited to those muscle models that predict force from EMG activity in the human biceps brachii muscle, particularly in young adult males.

CHAPTER II

METHODOLOGY

Eight (8) male subjects participated in this investigation after providing their informed consent in accordance with the McMaster University ethics of research on human subjects guidelines. Subject information is included in table 1.

Table 1. Subject Information

Subject	Age	Weight (Kg)	Forearm Length (M)	MVC100° (N.m)
DP	24	75.2	0.290	87.6
NC	22	84.0	0.250	51.5
CP	24	72.5	0.260	63.2
AC	24	75.0	0.270	83.9
SR	26	94.1	0.280	74.1
DA	23	72.0	0.295	74.0
PC	23	82.4	0.300	97.0
CL	23	79.8	0.270	87.9
MEAN	23.62	80.18	0.274	76.13

2.1 Muscle Selection

The Biceps Brachii muscle was selected to be the muscle under investigation as it is the most superficial and most easily distinguishable of the three major elbow flexors, (brachialis, brachial-radialis and biceps). This allowed simple investigation of the myoelectric activity. The biceps has a well defined motor point (McComas, Kereshi and Manzono, 1984) which allows for effective and uncomplicated use of percutaneous electrical stimulation. Stimulation of the biceps over the motor point with low level voltage should result in only localized recruitment of the biceps without activation of other elbow synergists or antagonist muscles (Leedham and Dowling, 1991). There are other logistical reasons for selecting the biceps muscle:

1. regional anatomy of the upper limb and the nature in which the biceps spans the elbow joint permit the biceps to be easily manipulated into different lengths simply by changing the joint angle at the elbow, while maintaining the shoulder and trunk positions constant.
2. the geometry of the biceps has been well studied, allowing more precise prediction of moment arm data to be used during this study.
3. the biceps muscle has been used quite extensively in the past as a muscle equivalent of the elbow flexor group (Bouisset, 1973).
4. Results determined by this investigation may provide information for models that attempt to predict muscle forces or elbow torques about the elbow.

5. the human elbow has two degrees of freedom (pronation-supination and flexion-extension). However, when the wrist is held at zero degrees of pronation, the elbow then can be considered to be a hinge joint with a single degree of freedom. This will ensure that the function of the biceps is limited to only one action, flexion.

2.2 Electrical Stimulation

The stimulating electrode consisted of a plastic housing containing a cathode and anode with a 5 cm separation. This housing maintained the stimulating electrodes at a consistent separation which ensured that the field which they stimulated was constant, so long as the stimulation voltage remained the same. The motor point of the biceps was established using a constant voltage (Grass model S88) square wave pulse of 0.05 ms duration and varying the location of the stimulating electrode until the amplitude of the M wave was maximized. Once the location of the motor point over the biceps had been determined the stimulating electrode was firmly secured to the subject and a low voltage 40 Hz train of pulses was then given to the subject to familiarize the subject to the sensation of the tetanus. A stimulation frequency of 40 Hz was used which allowed a fused contraction shortly after the onset of stimulation while maintaining the force production capacity at greater than 90% of that of much higher frequencies (Sale, Quinlan, Marsh and McComas (1982) using ankle dorsiflexors). The voltage of the stimulation was then increased until the maximum torque could be generated without undue discomfort to the subject. This procedure ensured that the biceps muscle was equally activated under all conditions. This procedure elicited torques of 4-7 N·m which Leedham and Dowling (1991) found to represent approximately 20% of the MVC torque generating capabilities of the biceps. Leedham and Dowling also found that this level of percutaneous stimulation selectively evoked a response in only the biceps muscle leaving the antagonist and synergist muscles quiet.

2.3 Electromyography

The subject's skin was prepared (shaved, cleaned and abraded) to remove unnecessary agents (hair, dead skin, oils and dirt) from the detection surface ensuring low skin impedance and an optimum myoelectric signal conduction from the muscle to the electrodes. Ag\AgCl surface electrodes of 0.8 cm diameter were placed 2 cm apart longitudinally on the medial aspect of the belly of the biceps muscle such that the biceps remained underneath for the complete range of motion at the elbow. The ground electrode was placed distally over the lateral forearm. Detection electrodes were also placed 2 cm apart over the belly of the triceps (figure 3). The two bipolar arrangements were differentially amplified with gains of 2000 and 3000 respectively and a bandwidth of 10-500 Hz (CMRR >90 db). A cutoff frequency of 500 Hz was used to remove high frequency noise before analogue to digital conversion.

2.4 Kinetic Measurements:

2.4.1 Angular Displacement:

Joint angle was measured by securing an electrogoniometer (elgon) on the medial aspect of the subject's arm such that the axis of rotation of the potentiometer was aligned collinearly to the elbow joint axis. The arms of the elgon ran parallel to the forearm and humerus respectively (figure 3).

2.4.2 Torque Measurement:

Torque was measured by a torque transducer (Lebow model # 1253-117; 0-500 N.m range) that was placed in-line between the subject's elbow joint axis and the modified Cybex (figure 4). This transducer was used instead of the one built into the Cybex because:

1) the transducer had greater sensitivity and accuracy than the Cybex transducer.

2) the transducer could be zeroed between each trial, thus removing any drift in the instrument.

3) the transducer recording was independent of applied loads and measured only the torque produced by the elbow flexors or biceps and by gravity acting on the forearm and jig.

The signal from the torque transducer was amplified with a variable gain amplifier then sampled on-line and stored digitally on computer disk. The signal was then dualpass filtered, digitally, with a low pass cutoff frequency of 3 Hz (zero lag). The jig to which each subject's right forearm was attached was fastened to the Cybex arm such that the combined subject\jig arm moved in unison with the Cybex allowing accurate torque measurement at all joint angles throughout the range of motion. The location of the torque transducer permitted the measurement of only those torques created by the contraction of the biceps (elbow flexors during MVC condition), gravity and inertial torques of the subjects forearm and jig. Since the Cybex ensured that isovelocity conditions were maintained, the accelerations were zero and the inertial torques could be ignored.

The torque due to gravity, determined from anthropometric data (forearm length)(table 1) and joint angle, using equations 2a-c, was subtracted from the transducer

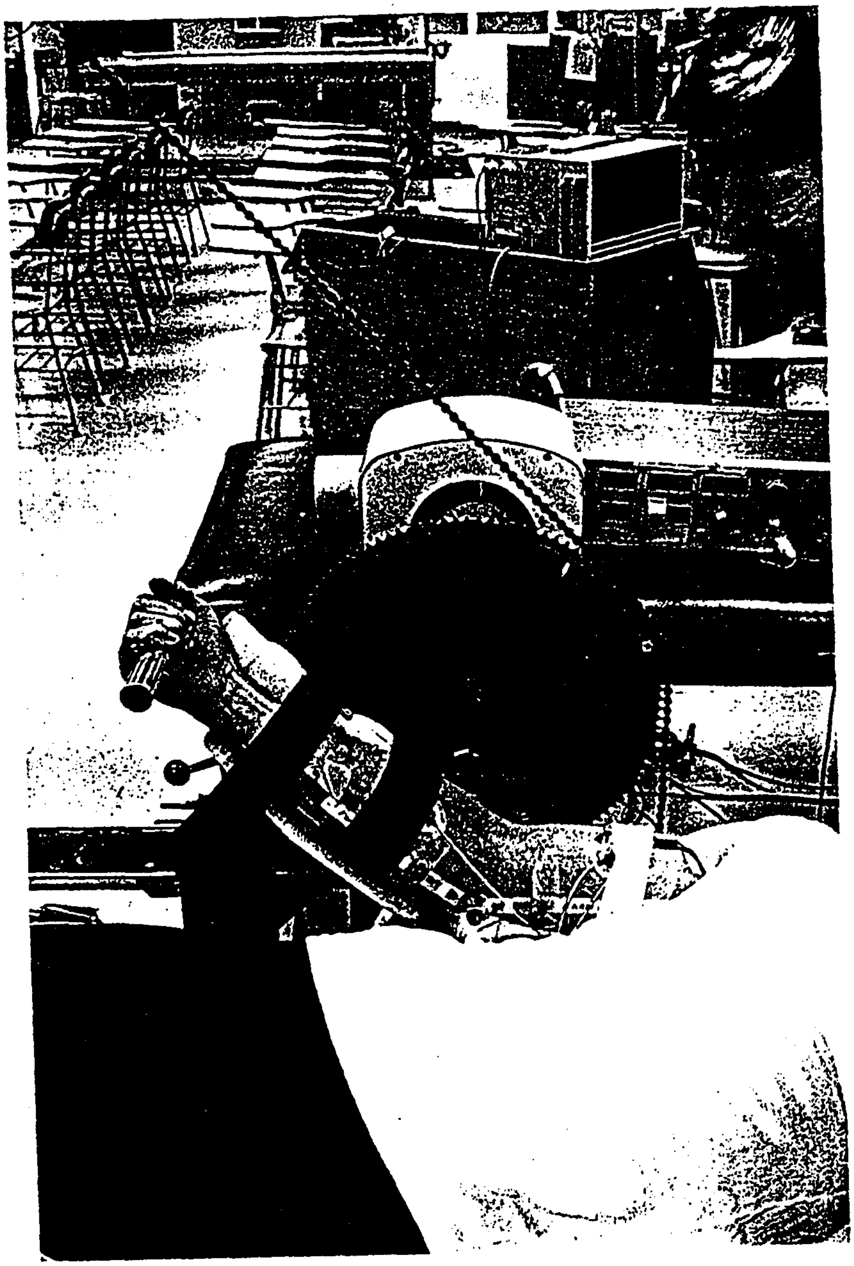


Figure 3. Experimental setup. Note the position of the electromyography, stimulation and ground electrodes. Also, note the presence of the electrogoniometer for measurement of angular displacement at the elbow.

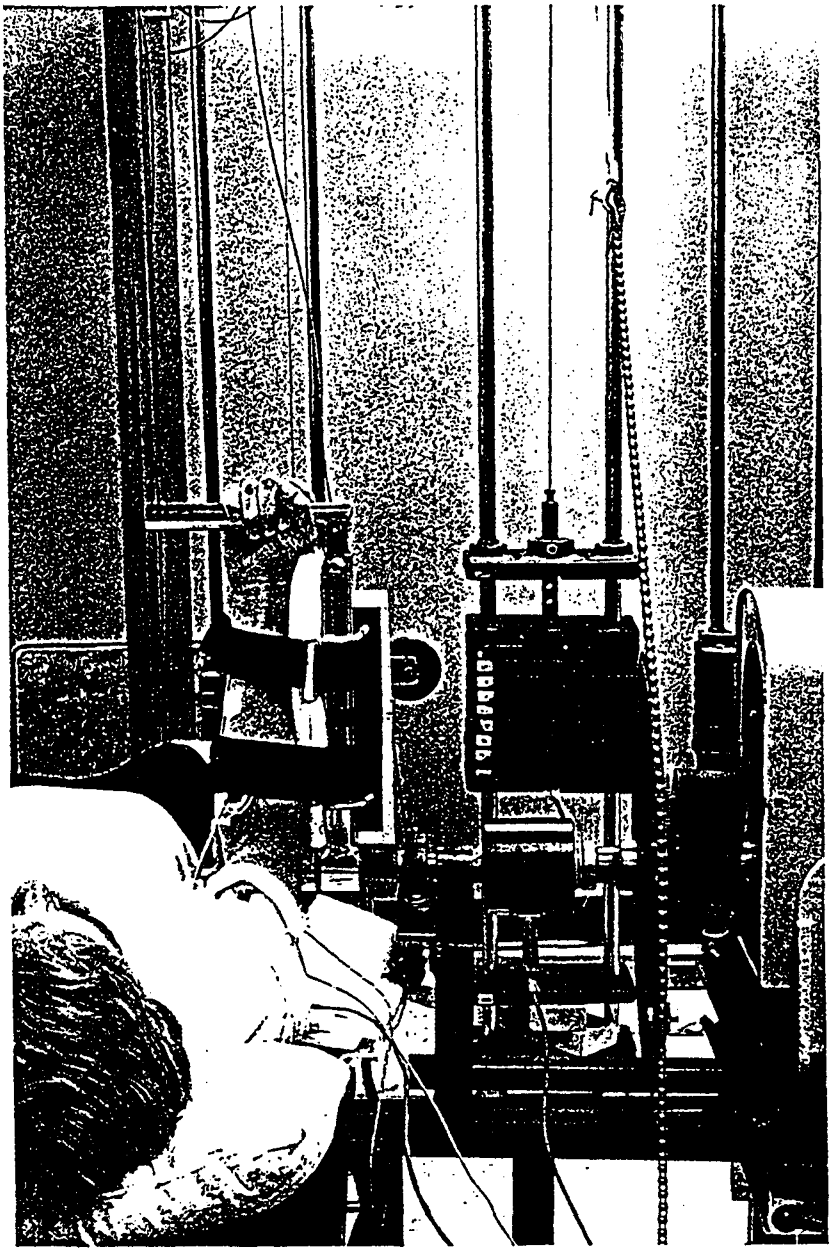


Figure 4. Experimental setup displaying the torque transducer between the Cybex and the elbow jig. Also displayed is the weight stack used to move the Cybex and arm through the selected range of motion.

recording so that the net torque reflected only that produced by the muscles crossing the elbow joint.

$$\lambda_s(t) = COG_3(\cos\theta(t))SW \qquad (2a)$$

$$\lambda_c(t) = (COG_c(\cos\theta(t))m - (COG_c(\cos\theta(t_1))m \qquad (2b)$$

$$\lambda_{tot}(t) = \lambda_o(t) - \lambda_s(t) - \lambda_c(t) \qquad (2c)$$

Where:
t = any specific data point
t_1 = the starting data point
SW = forearm weight (N)
COG_s = center of gravity of the subject (m)
COG_c = center of gravity of the cybex arm (m)
T_s = gross torque generated by the subject (N.m)
T_c = torque due to the cybex arm (N.m)
T_{tot} = Net torque (N.m)
θ = degrees of elbow extension
m = weight of Cybex arm (26.5 N)

2.5 Experimental Procedure

The subjects were asked to lie in the supine position with their right forearm supinated and firmly secured into the dynamic elbow jig such that the elbow joint axis, the jig axis and the Cybex axis of rotation were aligned collinearly (figure 3). A foam pad under the small of the back provided lumbar support; padding was also placed between the table and the subjects humerus to prevent downward movement of the upper arm during maximum voluntary contraction. A pillow was provided to support the subject's head. All efforts were made to ensure that the subject was safe, comfortable and firmly secured to the apparatus.

Movement of the forearm was effectively limited to 1 degree of freedom, thus allowing only flexion and extension. To ensure that only the elbow flexors were being recruited and that the joint angle was representative of only the isolated elbow subjects were strapped around the chest to the back of the bench. This precaution safeguarded the isolation of the biceps by ensuring that the position of the shoulder did not change the mechanical advantage or joint angle by changing positions. Attachment of the elbow jig to the Cybex machine permitted the manipulation of the biceps muscle by isokinetically controlling the angular velocity at the elbow through a set range of motion. The Cybex moved the elbow joint through approximately 130° range of motion (50 to 180 degrees of extension) while allowing a range of velocities from isometric (0) to 300°/s to be tested. A stack of weights were attached by chain to a large sprocket on the modified Cybex (figure 4), which enabled the Cybex to be used for eccentric and stimulated concentric contraction conditions. When the quick-release mechanism released the Cybex, the weights would drop a preset distance forcing an isotonic eccentic contraction. The weight had to be heavy enough to overpower the maximally contracting subject. To perform the stimulated concentric trials the chain direction was reversed on the sprocket so that when the quick-release mechanism was activated the subjects arm would passively be moved through a set range of motion, at a set velocity while undergoing electrical stimulation.

Once the subject was firmly fastened into the apparatus they were instructed to perform a single isometric biceps MVC and a single isometric triceps MVC, for EMG calibration purposes. The subject then underwent a series of experimental trials at varying angular velocities (30, 90, 150, 210, and 300 degrees per second) in either the positive (concentric) or negative (eccentric) direction. Three isometric conditions followed at 75, 100 and 135 degrees of extension. During each trial a 12 bit A\D converter (Northern Digital) was used to sample the EMG (biceps, triceps), elgon and the torque transducer. The data were collected at a sampling frequency of 1000 Hz for 5.5 seconds allowing for the complete range of motion of the task to be measured (figure 5). All of the experimental trials were performed under both MVC and electrically evoked conditions. Due to limitations in the design of the modified Cybex the trials could not be completely randomized. To ensure a certain degree of randomization of trials the velocities were mixed such that velocities did not constantly increase or decrease, but were varied (eg. 30, 210, 150, 300, 90). Subjects were informed prior to each trial of the angular velocity that was to be used.

2.5.1 Stimulation Protocol

During each trial the subject was instructed to totally relax the arm to prevent any torque production from other sources than the stimulating electrodes. The stimulator (Grass model S88) sent a train of 0.05 ms square wave electrical pulses at 40 Hz until the completion of the movement. Once the muscle reached a fused tetanus the quick-release mechanism of the Cybex apparatus released the arm to rotate at the selected velocity through 135 degrees of motion. Due to the relatively small torque values that were generated during stimulation trials, the vibration effect of the weights on the torque values were not reflective of the actual torques being generated by the biceps. To correct for this error each stimulation trial was followed by a trial in which the subject was requested to remain completely relaxed and the previous trial condition was repeated with no stimulation. The relaxed trials provided a baseline torque which was subtracted, point by point, from the coinciding point (with respect to joint angle) in the stimulated trial. The torque amplifier was zeroed prior to each trial to eliminate any effects of drift

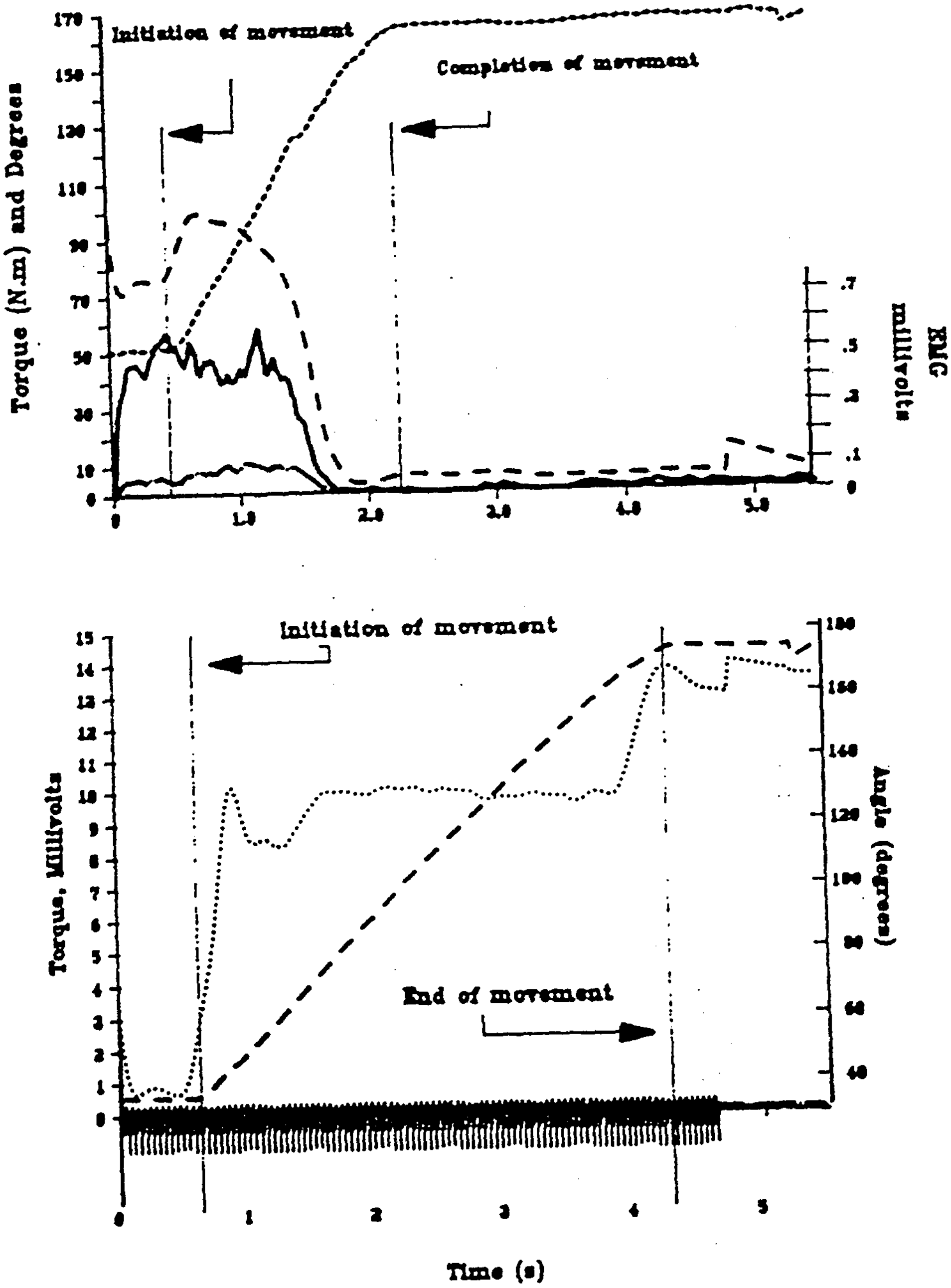


Figure 5. **Top figure** displays raw data from a MVC, eccentric trial from 50° to 170° of elbow flexion (·····). Torque ----, Biceps EMG ——, Triceps EMG -·-·. **Bottom figure** displays raw data from an eccentric stimulation trial from 40° to 170° of elbow flexion. Torque ····, Biceps EMG ——, note the presence of the stimulation artifact (spikes) and the triceps EMG is hidden behind the Biceps EMG.

or any slight torques due to the elastic properties of the muscle.

2.5.2 MVC Protocol

During each trial the subject was instructed to maximally pull against the jig throughout the full range of motion of the trial. The subject was instructed to maximally contract isometrically at the starting angle of the trial. When maximum isometric torque was achieved the modified Cybex was turned on by means of a quick release mechanism forcing the subject through a range of motion in either the eccentric or concentric direction. A quick release mechanism was employed to ensure that the contraction was initiated from a condition in which the muscle was neither lengthening or shortening prior to the initiation of the trial. Use of the quick-release mechanism also ensured maximal recruitment prior to release of the limb. Encouragement was provided to the subject by the investigators to ensure that a maximal voluntary effort was provided by the subject through the complete range of motion. Any trials in which the investigators felt that the subject did not provide a maximal effort were performed a second time. Adequate time was provided between trials and subjects were regularly asked "does your arm feel fatigued?" to prevent any undesirable results due to fatigue.

2.7 Data Analysis

2.7.1 Torque Data

The torque data were dual-pass filtered with a 3 Hz lowpass filter (4th order butterworth). Similar cutoff frequencies were used by Marshall et al. (1990) and Fuglevand (1987). Means and standard deviations were calculated for the torque data at specific joint angles (75°, 100°, 135°). To account for any strength differences between subjects the data were then normalized within each subject by dividing the torque at each joint angle by the maximum isometric torque produced by that subject, at specific joint angles (75°, 100°, 135°).

2.7.2 Force Data

Torque-joint angle values were converted to force-joint angle data by dividing each torque value by the instantaneous length of the biceps moment arm at the corresponding joint angle. The calculation of the biceps moment arm at each joint angle used a least squares polynomial fit to the data of Amis et al, (1979). The data of Amis et al (1979) included a discontinuity at an elbow angle of 2.55 radians (146 degrees) and therefore required two polynomials. These are shown in equations (3a) and (3b).

$$L = 0.331 + 0.02\theta \qquad for\ \theta > 2.55\ rads \qquad (3a)$$

$$L = b_0 + b_1\theta + b_2\theta^2 + b_3\theta^3 + b_4\theta^4 \qquad for\ \theta < 2.55\ rads \qquad (3b)$$

Where: L = Biceps muscle length (meters)
θ = Elbow joint angle (radians of extension)
$b_0 = 0.292$
$b_1 = -9.91 \times 10^{-4}$
$b_2 = 4.18 \times 10^{-2}$
$b_3 = -1.359 \times 10^{-2}$
$b_4 = 1.091 \times 10^{-3}$

Means and standard deviations were calculated with the force-joint angle data at specific joint angles (75°, 100°, 135°). These data were then normalized, to alleviate some intersubject variability, by dividing the force at each point (joint angle) by the maximum isometric force for each subject at specific joint angles (75°, 100°, 135°).

2.7.3 Displacement Data

The elgon was processed such that the electrical signal was converted to a digital format, digitally lowpass filtered at a cutoff frequency of 10 Hz (zero lag) and then calibrated to represent degrees of elbow extension (humerus-radial).

2.7.4 Torque-velocity

Two dimensional torque-velocity graphs were created using the constant-angle-torque (CAT) method often cited in the literature (Perrine and Edgerton (1978); Fuglevand (1987); Jorgensen (1976)). This method of displaying the force-velocity characteristics assumes that by always measuring the torque output at the same joint angle, the muscle length remains constant. A two dimensional plot can then be formed with torque as the dependent variable and angular velocity the independent variable. The range of velocities investigated were 0, 30, 90, 150, 210 and 300 $^{\circ}/_{s}$ for both eccentric and concentric conditions. Three separate joint angles were used to determine if an effect for joint angle was present (75°, 100°, 135°). Means and standard deviations of all subject's torque and normalized torque data were used to generate the torque velocity graphs.

2.7.5 Force-velocity

Two dimensional force-angular velocity plots were generated using the force data that had been converted from the torque data. Means and standard deviations of the force data were used to generate the graphs. Force data were not normalized as they would exhibit the same shape as the normalized torque plots as they used the same joint angles as reference points and therefore would simply be divided by the same moment arms.

Two dimensional plots were also generated for force-muscle velocity data. Hinson, Smith and Funk (1979) demonstrated in elbow movements that constant limb angular velocity was not followed by a constant rate of biceps shortening because the moment arm was not constant. Biceps linear velocity was determined to be dependent on joint angle (moment arm is also dependent on joint angle). Equation 4 was used to determine biceps muscle velocity.

$$v_{bic}(t) = \frac{\omega(t)\,(\pi)}{180}\,(MA)\,(t) \qquad (4)$$

Where:

$\upsilon_{bic}(t)$ = the velocity of the biceps at time (t) (m/s)
$MA(t)$ = moment arm at time (t) (m)
$\varpi(t)$ = angular velocity of the trial at time (t) (degrees/s)

Table 2. Calculated biceps velocity values from equation 4

	Biceps Linear Velocity		
Angular Velocity (°/s)	75°	100°	135°
-300	-0.254	-0.230	-0.129
-210	-0.177	-0.161	-0.090
-150	-0.127	-0.115	-0.064
-90	-0.076	-0.069	-0.039
-30	-0.025	-0.023	-0.013
0	0	0	0
30	0.025	0.023	0.013
90	0.076	0.069	0.039
150	0.127	0.115	0.064
210	0.177	0.161	0.090
300	0.254	0.230	0.129

2.7.6 Force-length-velocity

Three dimensional surface plots (3D) were generated for the force-length velocity relationship. All force files were modified such that each file had only those points which fell within a range of motion 60 to 150 degrees of flexion. The files then had to be interpolated to ensure that each file had an equal number of data points within the range of motion (201). All of the data files were then put into an array and a 3D plot was generated.

2.7.7 EMG Data (MVC)

The biceps EMG data were fullwave rectified and lowpass filtered at 3 Hz. A 3 Hz lowpass filter was used as this provides a delay which is representative of the electromechanical delay of muscle action (Hof, 1983). The data were then converted to millivolts from their digital form. Each EMG file was interpolated so that all files contained an equal number of points through a range of 60 to 150 degrees of elbow flexion (201). The data files were then put into an array to create a three dimensional surface plot of the biceps EMG with joint angle, angular velocity and EMG as the separate axis. To account for differences in magnitudes of electrical activity the biceps EMG for each subject was normalized by dividing the value at each point by the highest EMG value that was achieved by the subject on any trial. This maximal value was used rather than the calibration file as there were values within the trial files that reached greater voltages than that of the calibration trial. This then prevented any normalized values from being greater than 1. A second EMG surface was then plotted for the normalized biceps EMG vs. joint angle vs. angular velocity.

2.7.8 Biceps EMG (Stimulation Condition):

The biceps EMG from the stimulation trials underwent modification prior to the analysis of the data. This modification was necessary to ensure an accurate reading of the actual EMG activity of the biceps. The modification consisted of manually deleting those data points corresponding to the stimulus artifact generated by the electrical impulse. After the removal of stimulus artifact the remaining EMG signal consisted of only the CMAP (Compound Muscle Action Potential, M-wave) that was generated by the electrical stimulus. The M-wave is considered to be a measure of the electrical activity of the biceps during this investigation.

The modified data files then underwent full wave rectification and were low pass filtered at 3 Hz. A lowpass filter of 3 Hz was used as this value best represents the relationship of EMG to movement (Hof, 1983). The data were then converted to millivolts from their digital form. Each EMG file was interpolated so that all files contained an equal number of points through a range of 60 to 150 degrees of elbow flexion (172). The data files were then put into an array to create a three dimensional surface plot of the biceps EMG with joint angle, angular velocity and EMG as the separate axes.

The triceps EMG was normalized by dividing each point in each of the subject's file by the value attained during the triceps calibration file. This enabled the investigator to establish the amount of triceps activity as a percent of maximal triceps activity.

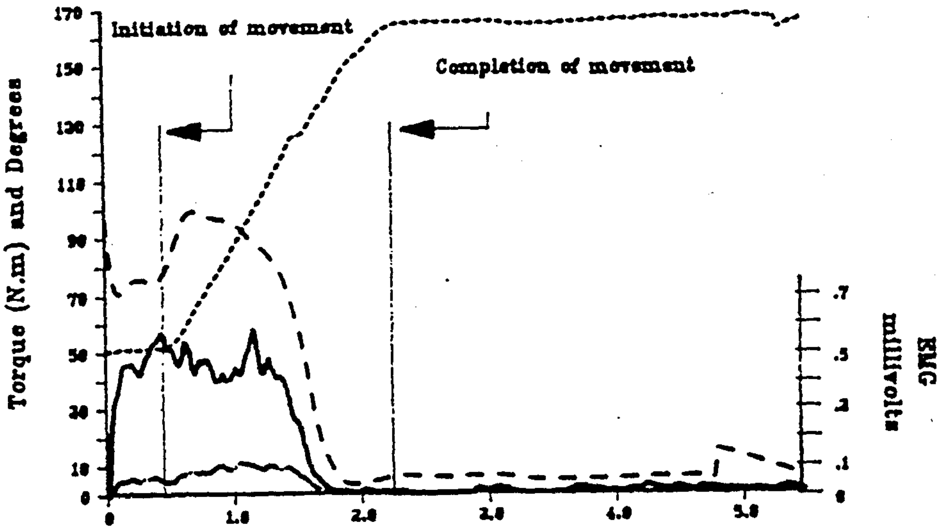
CHAPTER III

RESULTS

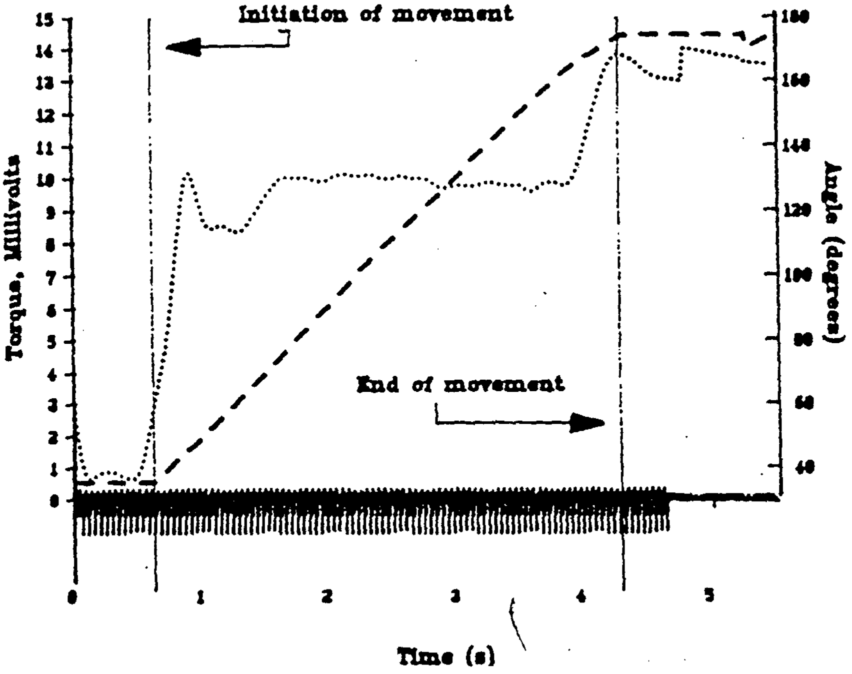
Figures 6 and 7 display the collected data for the voluntary and stimulation protocols of a single subject. Figure 6 shows an eccentric voluntary trial with a velocity of 90 $^\circ/_s$, while figure 7 shows a trial with an isolated biceps eccentric trial at 30 $^\circ/_s$. The voluntary trial displays the linear enveloped EMG of the biceps and triceps. Potentiometer data shows that the forearm moved through approximately 120° of motion at a constant velocity. Most measures were taken between 60 and 150 degrees as this ensured a range of motion in which most subjects were still maximally activated and not adversely affected by the approaching endpoint of the movement. The triceps activity in the stimulation graph is covered by the biceps signal, but tends to have an amplitude of less than 0.05 mV, which is only 5 to 8 % of the triceps activation during the triceps MVC.

3.1 Torque-velocity

The torque-velocity relationship was determined using the constant-angle-torque method (CAT). Means and standard deviations of the voluntary torque-velocity relationships at 75, 100 and 135 degrees of the 8 subjects are shown in



<u>Figure 6.</u> Raw data from a MVC, eccentric trial from 50° to 170° of elbow flexion (·····). Torque ----, Biceps EMG ——, Triceps EMG -·-·.

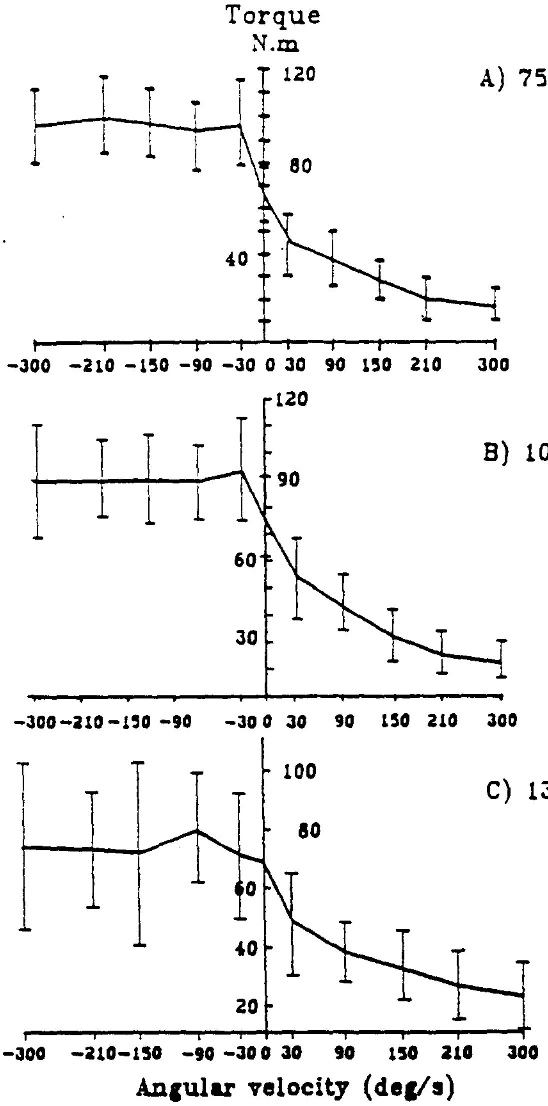


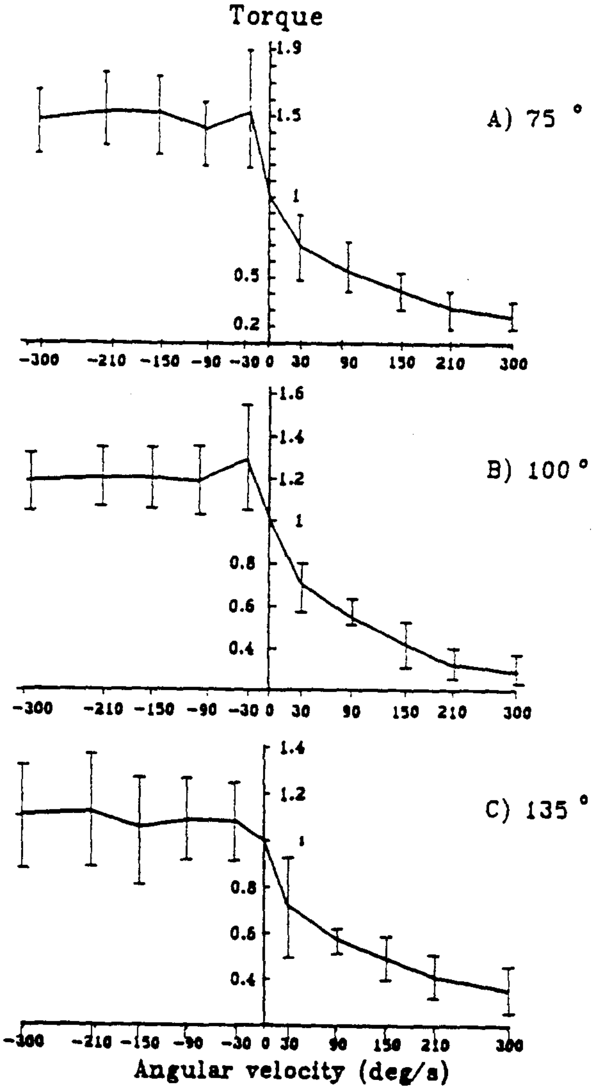
<u>Figure 7.</u> Raw data from an eccentric stimulation trial from 40° to 170° of elbow flexion. Torque ····, Biceps EMG ——, note the presence of the stimulation artifact (spikes) and the triceps EMG is hidden behind the Biceps EMG.

figure 8. The large variability indicated by the large standard deviation bars was due to the wide range of intersubject strength differences. Variability was slightly reduced by normalizing to the isometric values (compare figure 8 with figure 9).

Concentric torques generated by the elbow flexors are seen to follow a very consistent pattern across joint angle with the torque decreasing from 70-75 N.m at isometric to 25-30 N.m at the highest velocity ($300°/_s$). The decreasing torque with increasing velocity displays a hyperbolic curve and corresponds well to similar investigations in the literature (Perrine and Edgerton (1978); Fuglevand (1983)). Normalizing the data to the isometric values (figures 9 and 10) showed that the torque-velocity relationship at the different angles was identical at the slower concentric velocities but began to diverge at velocities greater than $90°/_s$.

Eccentric torques produced voluntarily displayed very even torque production across angular velocities. Figure 11 shows that eccentric torques ranged from approximately 80 to 100 N.m depending on the joint angle at which the measurements were sampled. Observation of data normalized to isometric values suggest that eccentric values can vary from 1.1 to 1.5 times greater than the isometric values when measured at the same joint angle (figure 10). Figures 10 and 11 display the normalized torque and mean torque velocity curves at three





<u>Figure 8.</u> Mean torque-velocity data with standard deviation bars at 75°, 100° and 135° of elbow extension.

<u>Figure 9.</u> Normalized torque-velocity data with standard deviation bars at 75°, 100° and 135° of elbow extension.

different joint angles (75, 100, 135 degrees, respectively). Observation of these data suggest that the amount of torque that can be generated eccentrically is dependent on joint angle, with the greatest torques being produced at the more flexed joint angles. Close analysis of the normalized data (figures 9 and 10) determined that during eccentric contraction conditions the highest torques were measured at $30°/_s$ followed by a decline and levelling out of the torque across the remaining velocities.

Observation of the mean torque-velocity values of the isolated biceps provide less clear results for analysis. Figure 12 represents the means and standard deviations for the torque-velocity relationships of the biceps at 75, 100 and 135 degrees. Large variability indicated by the large standard deviation bars were due to a wide range of intersubject tolerances to electrical stimulation as well as strength differences. Concentric torques were found to be from 2 - 6 N.m which represents approximately 20% of the concentric torque generated by the biceps in a voluntary condition whereas eccentric torques varied from 5-12 N.m representing nearly 25% of voluntary biceps torque (MVC_{bic} based upon .40 x MVC_{tot}). Concentric torques were found to always be less than the eccentric torques (figure 12). Observation of the data normalized to isometric values suggest that the eccentric

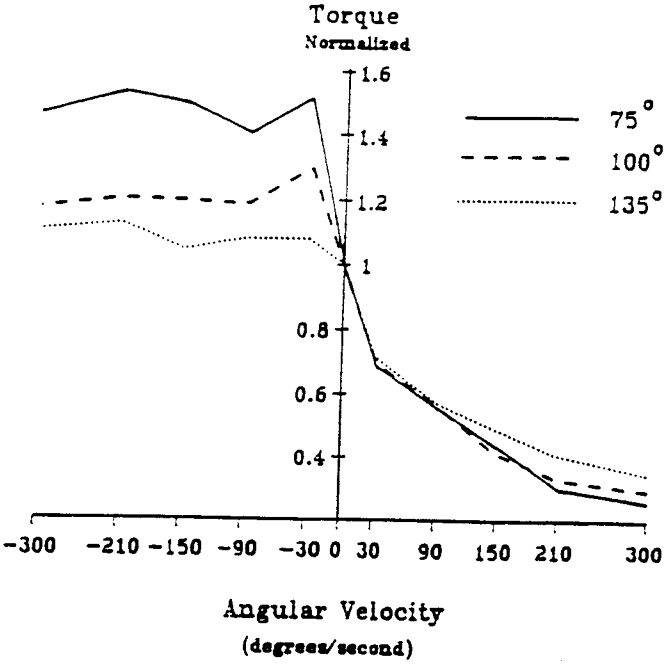


Figure 10. Normalized torque-velocity data for MVC data at 75°, 100° and 135° of elbow extension for all subjects. Note how similar the concentric data remains regardless of elbow joint angle.

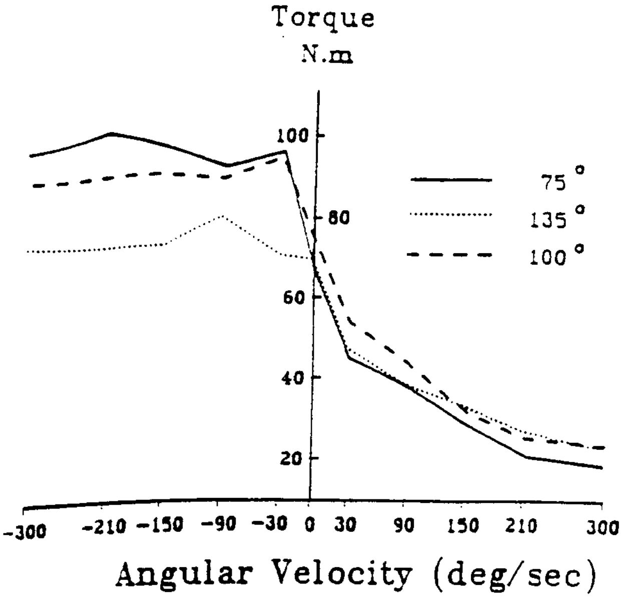


Figure 11. Mean MVC torque-velocity values for all subjects. Note the measured torque values generated during eccentric contraction.

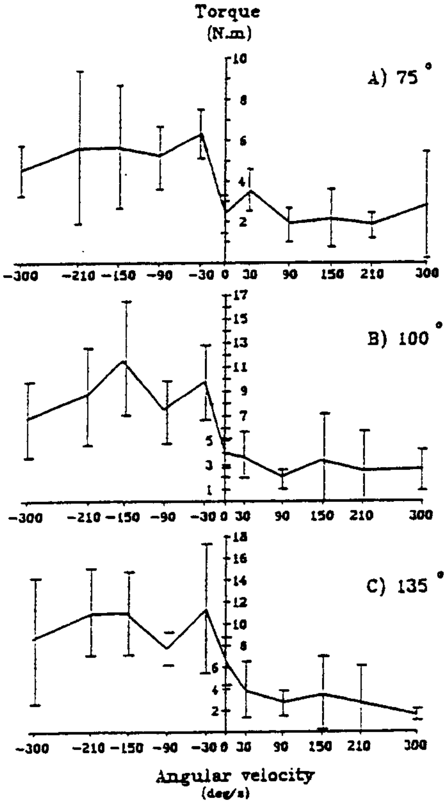


Figure 12. Mean stimulated torque-velocity data of the isolated biceps muscle at 40 Hz for all subjects.

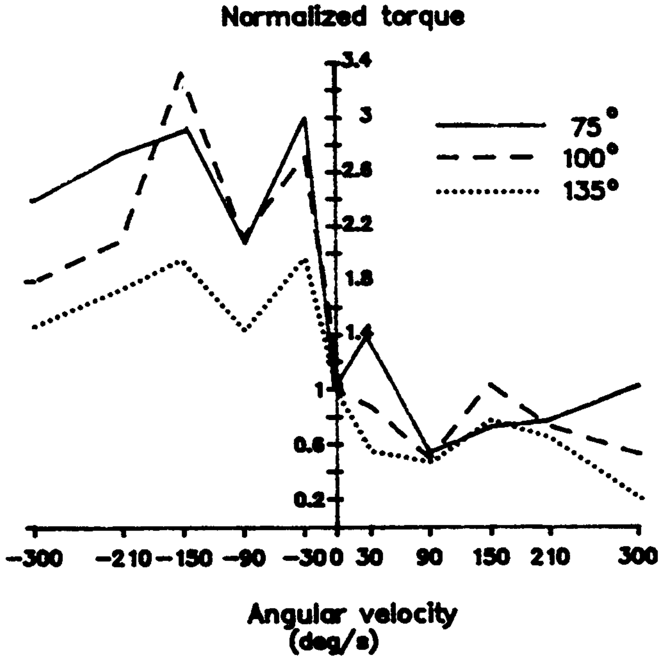


Figure 13. Normalized torque-velocity data of the isolated biceps at 40 Hz stimulation.

torque values range from 1.6 - 3 times the isometric values (figure 13). Figure 13 also displays an effect for joint angle on eccentric torque production. Similar to the MVC condition the greatest torques were found at the more flexed the joint angles. The stimulated eccentric torques displayed peak torques at 30 $^{\circ}/_{s}$, although the decline in torque at the other velocities tended to be less consistent than in the MVC condition.

Figure 14 displays stimulation torque-velocity data from a single subject (DP). Similar trends are seen between this data and the MVC data. The concentric torque-velocity relationship displays a hyperbolic relationship (" Hill-like ") such that as the concentric velocity increased the torque production decreased. The eccentric torque-velocity relation showed an increase in torque above isometric levels followed by a reasonably constant torque production throughout all eccentric velocities tested. A length effect was also seen in that the more flexed joint angles generated more torque than did the more extended joint angles.

3.2 Force-velocity

The force-angular velocity relationship displayed a curve of identical shape to that of the torque-angular

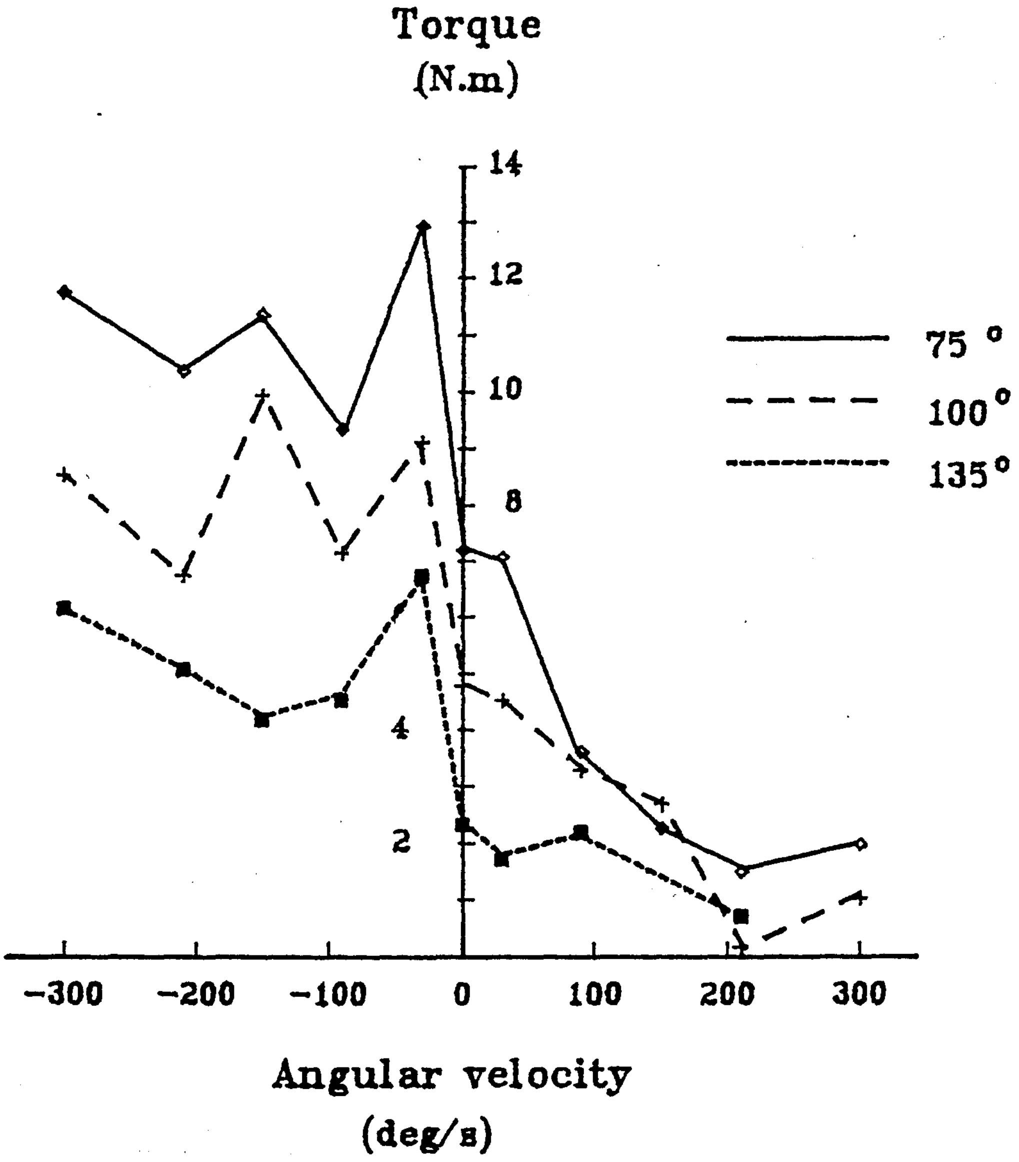


Figure 14. Torque-velocity data from the isolated biceps muscle of a single subject (DP) at 40 Hz electrical stimulation.

velocity data. This was because the CAT method of determining the force velocity curve was employed. The use of a constant joint angle necessitates the use of a constant moment arm which when divided into all torques at each velocity resulted in identically shaped curves. Force values for the MVC conditions were found to range from 200 N at the highest concentric velocities to 1300 N during eccentric contraction conditions. Forces determined to be due to the isolated biceps during MVC conditions (approximately 40% of MVC force according to An et al, 1981) were found to range from 80 N to 1200 N. Force values during the stimulation conditions were found to range from 40 N to approximately 475 N. This suggests that depending on the conditions of contraction, the stimulation condition was recruiting from up to 35% (most trials 20-35%) biceps muscle.

Hinson et al. (1979) mathematically determined that constant limb (forearm) angular velocity was not coincident with a constant rate of biceps shortening. Biceps velocity was in fact dependent on joint angle and a changing moment arm). Using equation 4 to determine the velocity of the isolated biceps it was determined that the maximal velocity attained was 25.4 $cm/_s$. It was determined that at a constant angle of 75°, where the moment arm was largest, the velocities displayed the largest range (-25.4 to 25.4 $cm/_s$), whereas at 135° where the biceps moment arm was the smallest the velocities only ranged from -12.9 to 12.9 cm/$_s$. Figures 15 and 16 display the mean force-linear velocity data for the MVC and stimulation conditions respectively. Both recruitment conditions display a definite effect for the joint angle (muscle length) at which the data was collected. Under both conditions (stimulated, MVC) force was seen to increase as the joint angle became more extended. Each of the tested joint angles displayed the typical Hill force-velocity relationship for the concentric velocity conditions. Similar to the torque-velocity findings, the eccentric data were found to level off at 1.1 to 1.5 times the isometric force for voluntary and 1.6 to 3 for stimulated rather than follow an inverse hyperbolic curve as some literature has suggested (Mashima, 1982, 1984).

Figure 15 and figure 16 show the force-linear velocity relations for the biceps muscle. The relationship is shown a three separate joint angles (75°, 100°, 135°) for the MVC and stimulated conditions.

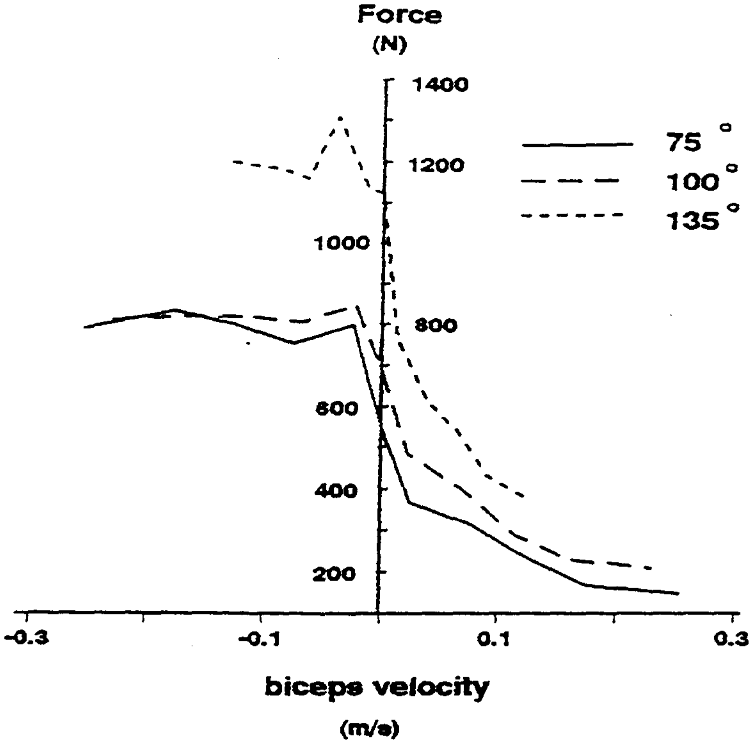


Figure 15. Mean force-linear velocity data for the biceps muscle during MVC for all subjects. Biceps force based upon 0.4 times MVC force for all flexors combined.

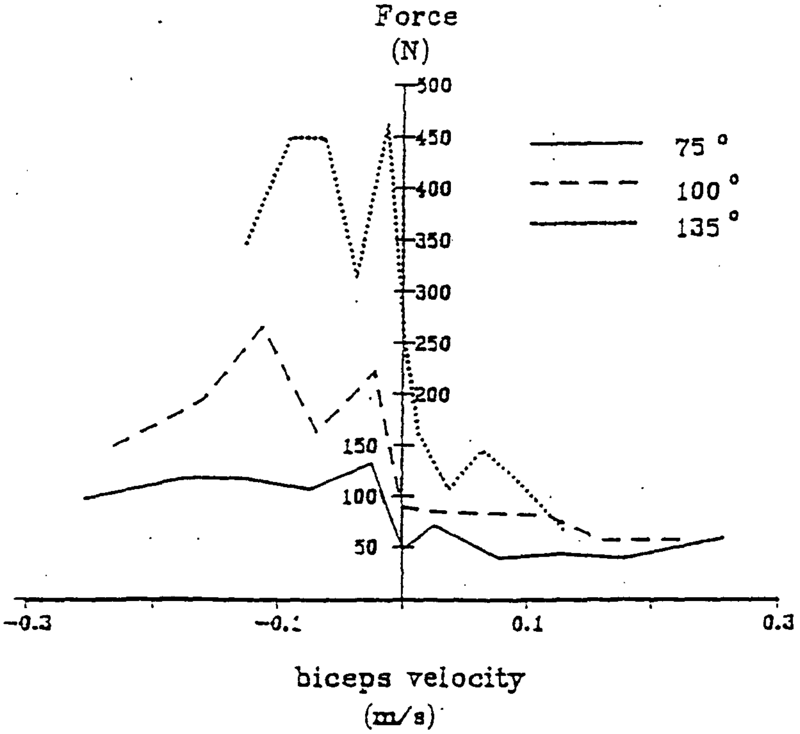


Figure 16. Force-linear velocity data from the stimulation condition.

These graphs clearly display the effect of joint angle (muscle length) on the force production.

3.3 Force-length-angular velocity

A three dimensional surface of the mean force data (MVC) for 8 subjects is displayed in figure 17. Standard deviations are not shown as this would further complicate the graph making it difficult for analysis. Force is represented on the vertical axis, angular velocity on the X-axis and joint angle on the Y-axis. The most obvious finding was that as the joint angle became more extended, ie. from 60° to 150°, the force generated by the elbow flexors increased monotonically. This result was found to be similar to those found by Leedham and Dowling (1991) using isometric contraction conditions. A second trend that is noticeable from the surface plot is that as the joint angle becomes more flexed the hyperbolic curve representing the concentric force production becomes increasingly less hyperbolic in nature. However when compared to the 2-D plots it was seen that in the 75-135° range the force-velocity relationship was similar in shape. A third observation was the presence of a trough in the surface at the low concentric velocities and at the shorter muscle lengths. This finding is similar to the trough found at slow concentric velocities and short muscle lengths in the quadriceps (Perrine and Edgerton, (1978) and Fuglevand (1987)).

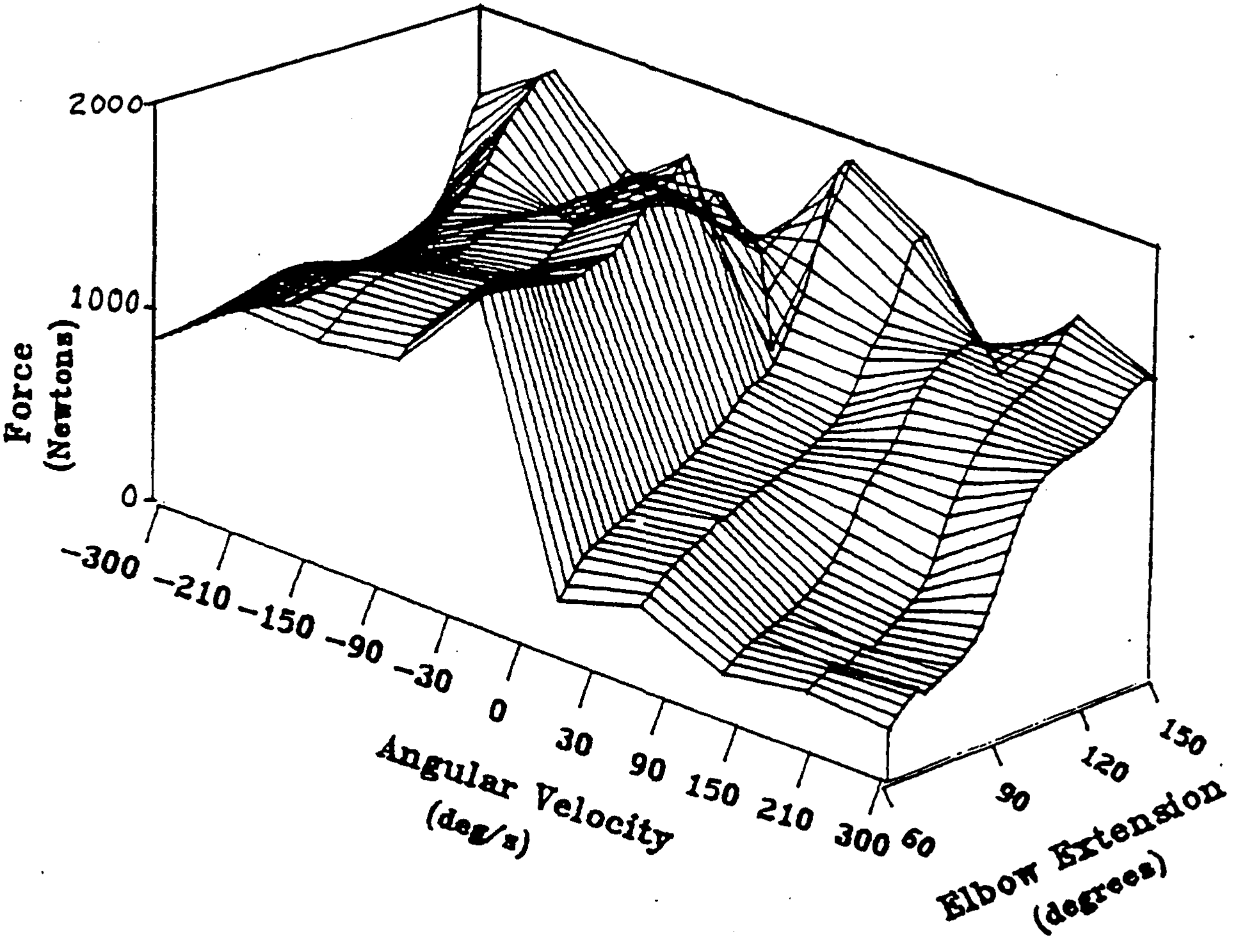
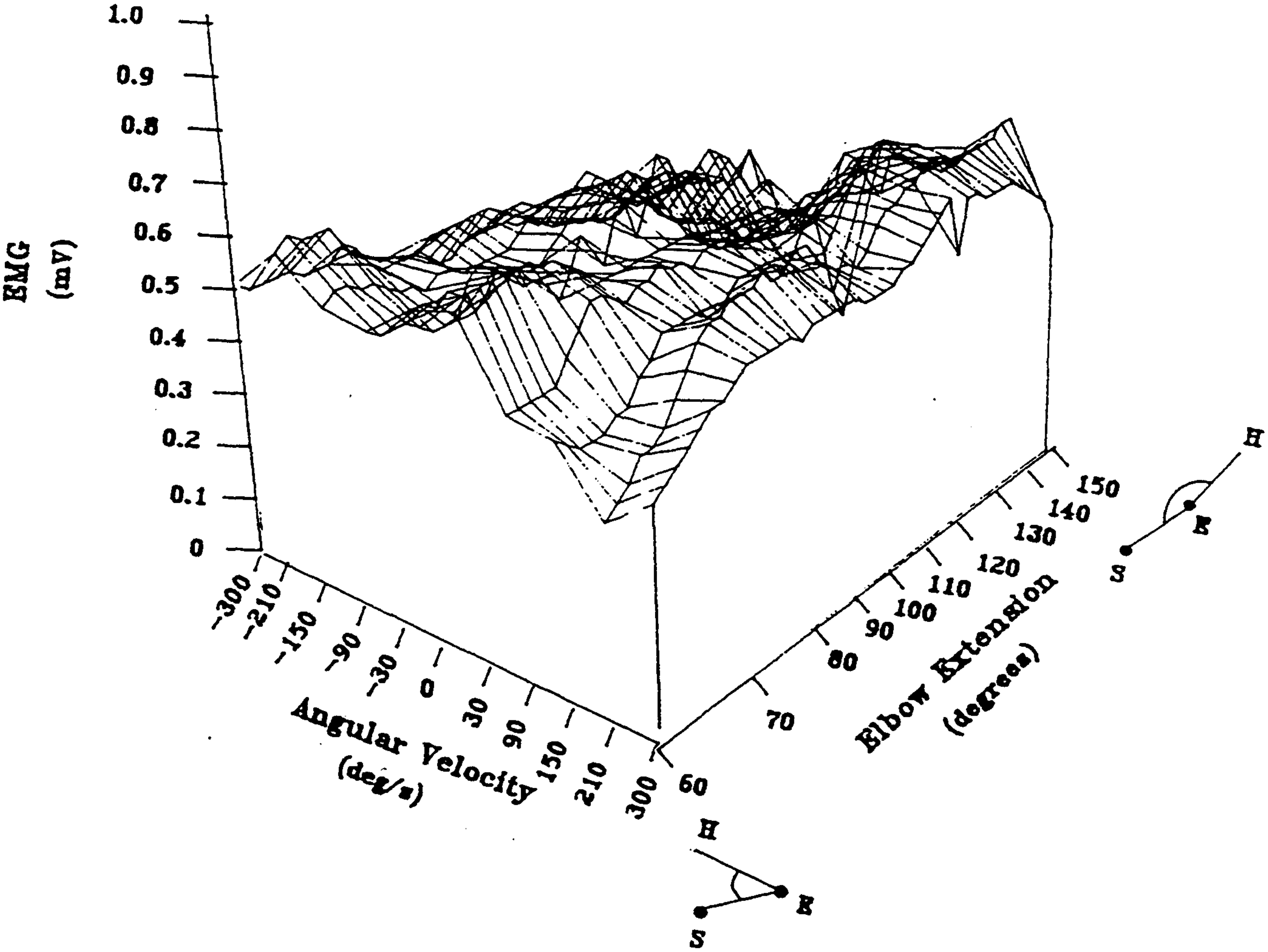


Figure 17. Three dimensional surface of the mean force data for an MVC contraction. X-axis displays angular velocity from 300°/s to -300°/s. Joint angle from 60° to 150° of extension is in the Y-axis. Force (N) is displayed in the vertical or Z-axis.



<u>Figure 18.</u> Three dimensional surface of EMG vs joint angle vs angular velocity.

The eccentric half (left side) of the surface produced some interesting results. It was found that at the slowest eccentric velocity (30°/$_s$) a ridge of high force values was generated. The force was found to decrease slightly at eccentric velocities greater than 30°/$_s$ and became quite level, with a slight decline, until velocities were greater than 210°/$_s$. Force production was seen to decline dramatically at the highest eccentric velocity. A large decrease in force was determined at the more extended joint angles at the 30 and 90°/$_s$ velocities (eccentric).

3.4 Biceps EMG-velocity-length

Figure 18 represents a 3-D surface of the mean electromyographic signal from the biceps of the 8 subjects. This figure shows the amplitude in millivolts of the biceps EMG throughout the range of motion that was corresponding to the range of motion analyzed for the force-length-velocity surface (60-150°). This graph suggests that the EMG activity of the biceps during the MVC condition was reasonably constant, with perhaps slightly more EMG activity during the concentric trials than in the eccentric trials. There appears to be no effect for joint angle, or velocity within eccentric, concentric conditions with the exception of a decrease in the EMG amplitudes at the more extended joint angles and

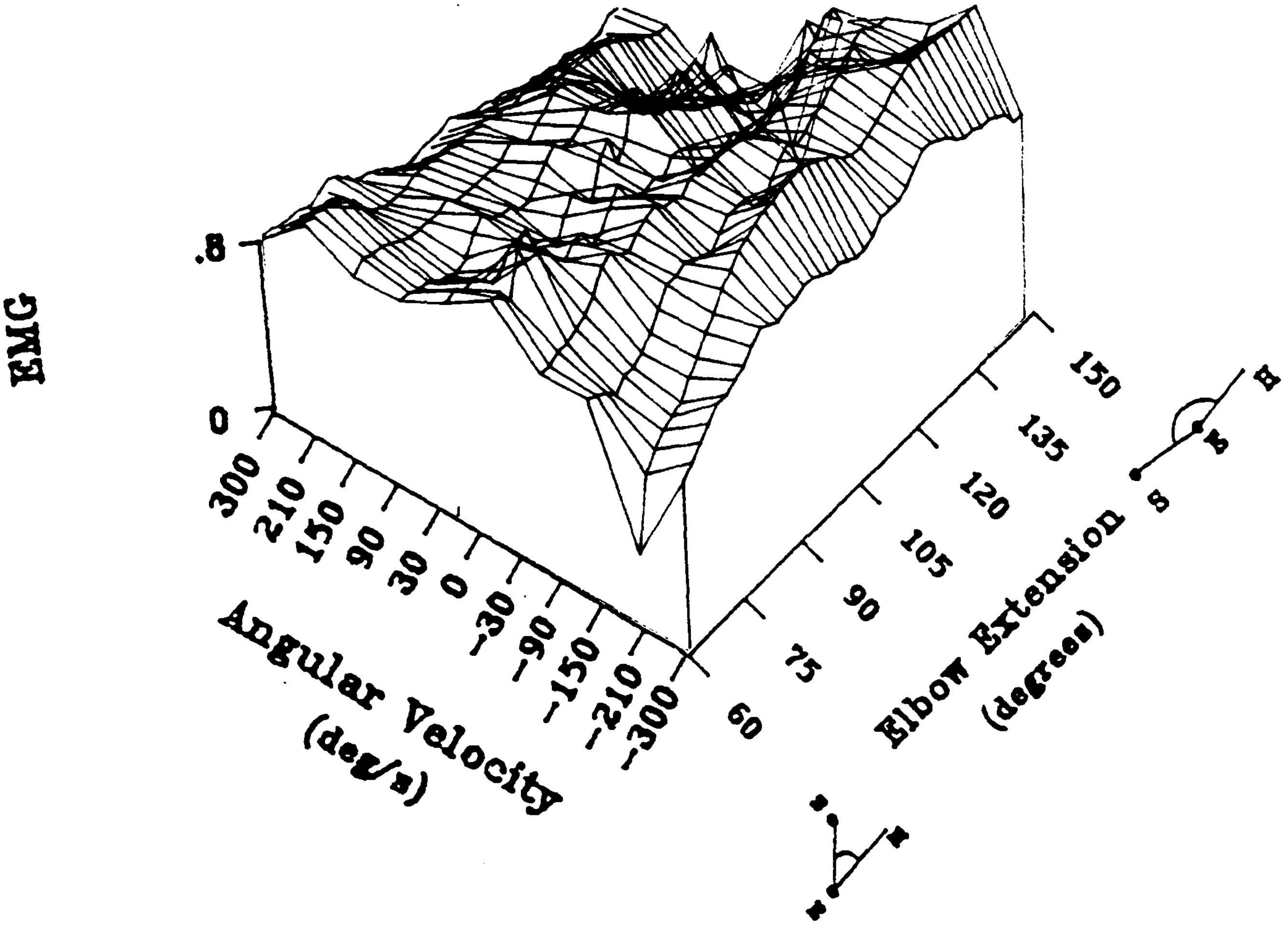


Figure 19. Three dimensional surface of the normalized biceps EMG vs joint angle vs angular velocity.

slower eccentric velocities. This corresponds to the decrease in force output experienced at the same position in the force-length-velocity surface (figure 17). However, due to the large variability of the EMG signal between subjects this surface plot may not display some important features. To better accommodate for this fact a 3-D surface plot of the normalized and averaged biceps EMG data through the complete range of motion was constructed. Figure 19 represents the average biceps EMG data from the 8 subjects when the EMG was normalized to the peak amplitude for each subject. The most important finding was that there was a more definite effect of contraction type (eccentric, concentric) on the EMG activity. It was found that EMG during eccentric contractions was of less amplitude than the corresponding velocity concentric EMG. There is no apparent effect of joint angle on the amplitude of the EMG for either the concentric or eccentric conditions. A trough was found during concentric contractions at high velocities and highly flexed elbow angles. This drop in biceps EMG was found to correspond with a corresponding dip in the force-length-velocity surface (figure 17).

The most interesting view of the biceps EMG was seen in a 3-D surface plot of a single subject's (AC) data. Figure 20 represents this subjects biceps EMG data (during MVC). It is important to note that the eccentric and concentric data have been reversed so as to better display the changing EMG

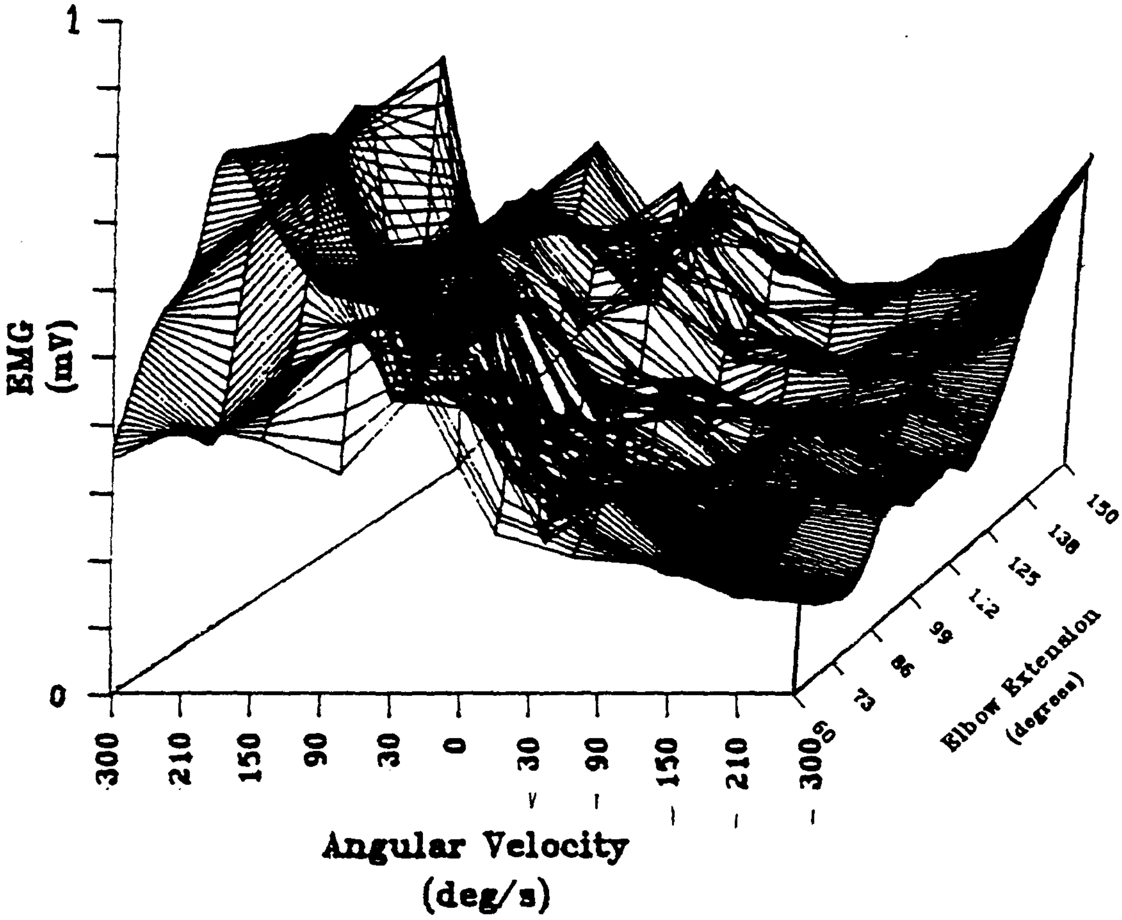


Figure 20. Three dimensional surface of biceps EMG vs joint angle vs angular velocity of a single subject (AC).

activity. The eccentric data (right side) was determined to be very even and approximately half that of the concentric data. The concentric data on the other hand was found to vary greatly from velocity to velocity and was seen to be approximately twice the amplitude of the eccentric data of the same subject.

4.4 Biceps data (stimulation condition):

Figures 21 and 22 represent the mean EMG activity of the biceps during the stimulation condition (N=7). The eccentric trials display a slight inverted U pattern whereas the concentric data tends not to change with joint angle (muscle length). The EMG values varied from 0.3 - 0.6 mV range but did not display any systematic changes.

Figure 23 displays a three dimensional surface of the mean EMG-length-velocity (stimulation condition) data (N=7). This data shows the amplitude of the biceps CMAP (Compound Muscle Action Potential) throughout the range of motion (60-150 degrees). Similar to the voluntary EMG surface this surface displays little change in the amplitude of the EMG data between velocities or joint angle (muscle length). The EMG amplitude data for the mean EMG data (N=7) ranged from 0.3 - 0.6 mV. However, it does appear that a slight effect of joint angle during eccentric contractions is present for the stimulated EMG data.

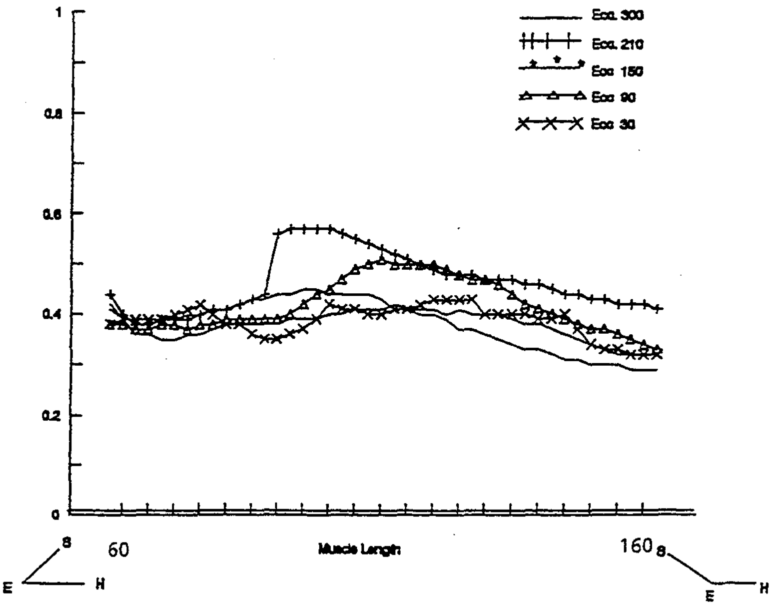


Figure 21 Stimulated EMG vs. Muscle Length (Eccentric Data)

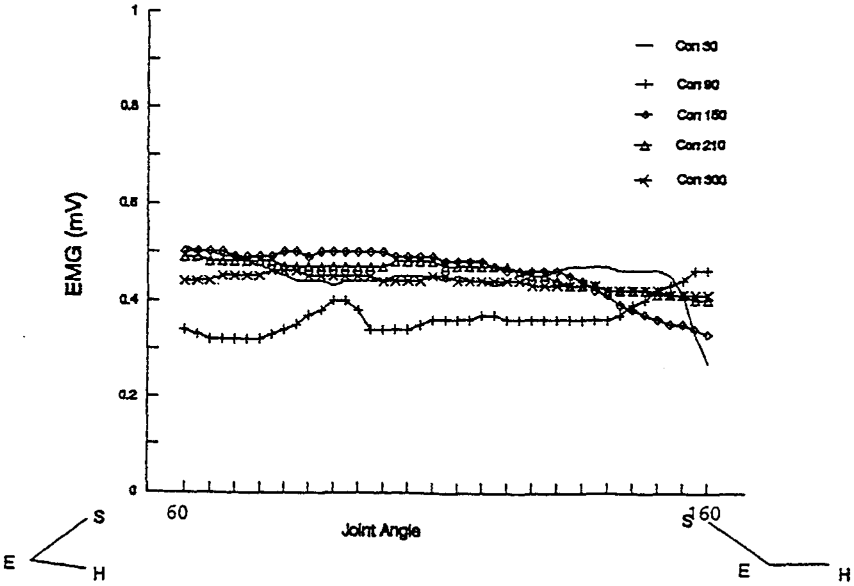


Figure 22 Stimulated EMG vs. Muscle Length (Concentric Data)

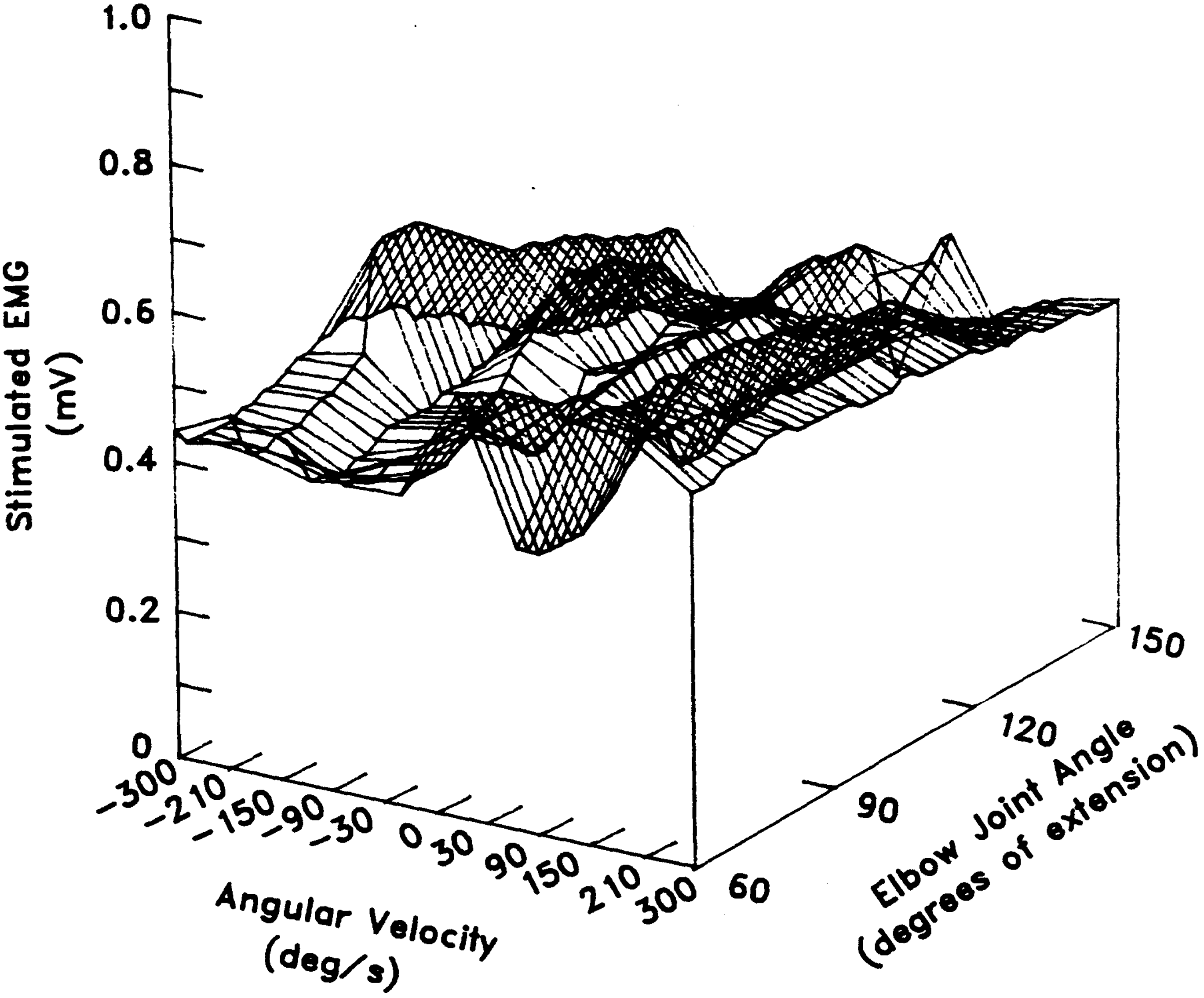


Figure 23. Mean three dimensional surface plot of EMG vs joint angle vs angular velocity during stimulation of the biceps.

4.5 Triceps data:

Analysis of the triceps EMG determined that the triceps were activated only slightly during all conditions. It was determined that the triceps was only 5 - 10% active, when compared to the maximal EMG amplitude of the triceps during the calibration file. Thus during the discussion it will be assumed that triceps contribution was negligible.

CHAPTER IV

DISCUSSION

5.0 Explanation of the movement condition

Observation of the raw data figures (MVC trial) display many properties that are characteristic to voluntary movements. Subjects were asked to maintain an isometric MVC contraction prior to the release of the modified Cybex apparatus. After the initiation of the eccentric contraction three of the measured conditions were seen to change concurrently. The most noticeable change was that the filtered torque data initially 70 N.m rose to 100 N.m (within the first 10° of the extension). It was interesting to note that the peak torques did not occur at the expected optimal joint angle, but early in the movement (at a less extended position, 110°). This may suggest that the optimal joint angle is based more so on the conditions of the contractile component of muscle rather than the mechanical advantage of the muscle due to the moment arm length at that time. At first this may seem to contradict the sliding filament theory of muscle contraction which suggests that at shorter muscle lengths the actin and myosin interfere with each other resulting in less crossbridge formation and therefore less force. However during an eccentric contraction when the contractile proteins are being drawn past each other, it seems reasonable that the resistance may arise from the reattachment of cross bridges that had been previously broken or from the attachment of additional crossbridges to sites that are initially not available but which have become accessible as a result of the movement (Flitney and Hirst, 1976). Flitney and Hirst go on to suggest that if the rate constant for cross-bridge formation is high the maintained force should vary little with the eccentric velocity. Coincident to this increase in torque the linear enveloped biceps EMG was seen to decrease very slightly or remain relatively constant. The decrease in EMG activity during eccentric contraction can perhaps be explained by examining the chemical activity during contraction. Assuming that eccentric and concentric contraction differ in that many of the bonds formed between actin and myosin by the cross-bridges are not chemically broken by ATP but are forcefully broken apart would explain why less metabolic energy is required by the muscle during eccentric contraction. Thus, because the electrical impulse from the motor nerve is the drive behind this metabolic process leading to contraction, less electrical input is required, to break the bonds, which will in turn be displayed as a decrease in the amount of EMG detected by the EMG electrodes. This is supported in this investigation in that biceps EMG decreased during voluntary eccentric contraction.

Observation of the stimulation condition torque values show a similar pattern of a quick jump from the isometric torques to a plateau at approximately 1.5 times greater torque production. The presence of this plateau during the stimulation condition trials is of importance because the level of activation to the biceps during these trials remained at a constant amplitude. Should the CMAP amplitudes have decreased during stimulation trials then it would be expected that the mechanical relationship should continue to increase the force with increased velocity of contraction. Torque displayed a plateau with equal neural drive, suggesting that the torque is being limited mechanically and not by neural inhibition of the biceps. Further support for this hypothesis was observed in the slight decrease in torque productions during higher velocity eccentric stimulation trials. This suggests that again a mechanical event was the limiting factor and that the slight decline at higher eccentric velocities was the result of the inability to re-establish cross-bridges at a fast enough rate to maintain torque output.

The biceps EMG was also seen to remain quite steady until late in the movement, where a sharp decline was seen to occur. This decline in the EMG was followed by a similar decline in torque at 150 degrees of elbow extension. This is considered to be a protective mechanism in that the high force production range for the elbow flexors seems to peak as the elbow approaches full extension. This turning off of the muscle may be to prevent muscle damage due to the high forces. This decrease in the EMG was also seen in the 3-D plots (figure 20). A second possible explanation for the decrease in EMG activation as the elbow angle approached full extension is that the subjects, anticipating the end, may have simply quit. The triceps EMG was seen to increase slightly after the initiation of the eccentric contraction from approximately 5 to 8% of the triceps activation as calibrated to a triceps MVC. The activation of the triceps is suggested to be only to protect the integrity of the elbow joint.

The torque was seen to decrease as the elbow joint was extending, even though the force-length relationship for the elbow flexors, as was suggested by Leedham and Dowling (1991) does not reach an optimal state until nearly full extension. This is strictly due to the decreasing length of the biceps moment arm as the elbow extends. An electromechanical delay was also displayed in figure 7, which is also characteristic of muscle action.

5.1 Torque - velocity Relationship

5.1.1 Concentric relationship - Voluntary

The voluntary torque-velocity results (figure 8) and the normalized voluntary torque-velocity relationships of the combined elbow flexors (figure 9) suggest the concentric data (the right or positive side of each graph) which portrays almost a textbook "Hill - like" relationship with decreasing torque production as the angular velocity of the segment increased. Observation of the normalized data show that when normalized to isometric torque only 30% of the torque can be generated at the maximal tested angular velocity (300°/$_s$). This is in agreement with Dudley et al (1990), investigating elbow flexors. The torque-velocity relationship determined for the elbow flexors in this study supports findings of Kojima (1991), Hortobagyi et al (1990), Westing et al (1988), Nygaard et al (1983), Jorgensen (1976), Bigland and Lippold (1954), Wilkie (1950) and Hill (1938). However these data do not seem to support the data of Marshall et al (1990), Fuglevand (1983), Caiozzo et al (1983), Gregor et al (1979) and Perrine and Edgerton (1978) that determined that at slow angular velocities and short muscle lengths that a decrease in the torque output was present. Investigators claiming that a deviation in the Hill equation is seen at high torque, low velocity conditions have investigated the quadriceps (knee extensors), however Perrine and Edgerton (1978) have suggested that this phenomenon is also present in the elbow flexors. This is, as noted above, in disagreement with this investigation and the generally accepted findings for voluntary recruitment of the elbow flexors. Possible suggestions as to why the elbow flexors do not display this decrease in torque output under these conditions include:

1) The change in moment arm, throughout the full range of motion of the elbow, for the elbow flexors (assuming the biceps is an equivalent flexor (Bouiset, 1973)) changes more dramatically than the moment arm for the knee extensors. The biceps moment arm goes from 2 cm at full extension to over 4 cm at 100 degrees. This is not observed in the quadriceps muscles because of the natural pulley of the patella which maintains a much more constant moment arm. Thus even if force production of the biceps muscle was decreased somewhat, a decrease in torque production may not be coincident.

2) It may be possible that the amount of neural control the central nervous system (CNS) has over the elbow flexors is greater than for muscles in the lower extremity. That is, it may be possible to fully recruit the elbow flexor muscles with greater ease than the knee extensor muscles. Investigation of developmental literature may provide some support for this in that as the human grows from infancy to maturity the nervous system physically and functionally develops cephalocaudally

(Haywood, 1986). That is, as we develop, the elbow flexors will be fully developed prior to the complete development of the knee extensors. For example, the elbow flexors are likely used for a wide variety of functions, which will require greater refinement and varying levels of activation more often than the knee extensors (which are basically used for locomotion). This may in turn permit more complete activation of the muscle under high tension conditions.

3) A third possibility may be due to the differences in the anatomy of the elbow flexor and knee extensor groups. Compared to the knee extensors which have each muscle's tendon merging into a common patellar tendon which inserts on the tibia, the forces acting on the tendon and insertion being the algebraic sum of each of the quadriceps muscle, each elbow flexor maintains its own tendon and insertion site. Tension sensing organelles, the golgi tendon organs (GTO) located within the tendons, will receive less tension each in the elbow flexors than in the single patellar tendon (knee extensors) due to the dispersion of the force throughout each tendon. Thus the knee flexors may be more prone to neural inhibition from the GTO's which would result in a decreased torque output under high torque, low velocity conditions. Unfortunately this theory does not explain why most investigations have displayed greater torques/forces being produced during eccentric movements. This may suggest that

the increased force during eccentric contraction is the result of a mechanical event, not a change in the neural drive to the muscle. Support for this was seen in that biceps EMG activity was slightly depressed during eccentric contraction. This suggests that perhaps the contractile mechanism can create more force during the eccentric condition than in concentric conditions, negating activation, simply due to the mechanical structure of the contractile component itself. Evidence provided by the 3-D plots of the force - average velocity relationship (figure 20), display the occurrence of some inhibition, tend to support the original theory that it is the mechanical advantage of the biceps group that allows the torque output to continue following the hyperbolic Hill relationship at slow velocities and short muscle lengths (highly flexed).

Observation of the normalized torque-velocity results suggested that during the slower angular velocities the decline in the torque with the increasing velocities is identical at each of the first 3 joint angles tested (75, 100, 135 degrees).

To better define how a single muscle (biceps) would behave under differing movement conditions direct electrical stimulation of the biceps motor point was performed which effectively isolated the biceps as the torque generator.

Observation of the biceps (in-vivo) concentric torque-velocity data displayed rather inconsistent results. At shorter muscle lengths the torque production was unrealistic at any velocities greater than approximately 90 deg/s, with negligible torques being generated. However, as the joint angle of measurement was extended the forces generated increased and a more acceptable force-velocity relationship began to emerge. Factors which may have lead to these less than desirable results are as follows:

- Firstly, during concentric contraction (stimulated) it was not possible to attain any torque values at angular velocities greater than that of 90 deg/s. This is most likely due to the mechanical process involved with concentric contraction. This phenomenon was only seen in the stimulation trials as the amount of biceps recruited was small and this would not allow the production of torques at higher velocities. In simple terms the contractile mechanism may not have been able to keep up under the stimulation conditions.
- Secondly it was determined that at greater biceps muscle lengths, ie. more extended elbow angles, sufficient torque was produced for detection by the load cell. This finding suggests that as the biceps muscle neared it's optimal length, it was able to produce sufficient torque such that a more normal force-velocity curve was

determined. This suggests that although only a small portion of the biceps was being activated, when the muscle length approached optimal, the stimulated muscle was better able to keep up with the velocity demanded by the modified cybex apparatus.

A method that has been used to attempt to counter this stimulation condition error was to stimulate over the biceps muscle during an already maximal contraction (Westing *et al.*, 1988). By comparing the superimposed stimulation torques with the MVC torques Westing was able to infer characteristics of the in-vivo biceps. However, this method does not allow for the complete isolation of the biceps. Similar to voluntary contraction conditions the addition of moments due to agonist and antagonist muscle groups must be accounted for. This research does however provide some valuable information. The essence of this thesis was to investigate the mechanical properties of the biceps muscle in isolation. Unfortunately it appears that to properly investigate the concentric action of the isolated biceps would require the application of much greater levels of electrical stimulation.

5.1.2 Eccentric torque - velocity relationship:

Using the constant angle torque (CAT) method the torque - velocity relationship of the eccentric contraction conditions (left or negative side of the graphs) displays an almost immediate torque increase ranging from 1.1 to 1.5 times the isometric torque value, however as the eccentric velocities increased the force (torque) production was determined to decrease slightly and remain at 1.1 to 1.5 times isometric levels. These findings are not consistent with those determined by Mashima et al (1972) in the investigation of the in-vitro force-velocity relationship of eccentrically contracting amphibian muscle. Mashima and co-workers determined that during eccentric contraction, under any level of activation, the force-velocity relationship was hyperbolic in nature and force (torque) output would continue to increase with increasing speed of muscle lengthening. Observation of the stimulation data displays similar findings in that an immediate increase in force (torque) was seen at low eccentric velocities with a levelling off of force production as the velocities increased. It was noted that the level of force (torque) output was not consistent across eccentric velocities. As previously discussed varying tolerances to stimulation may have had an effect on the results of the stimulation conditions.

Mashima's hyperbolic curve was not consistent with this investigation and may be explained by the following possible reasons:

- the amount of voluntary eccentric force generation is limited by the rate constant of cross-bridge formation
- there may be some neural inhibition of the biceps muscle during the voluntary eccentric contraction (to prevent injury to the muscle), whereas the in-vitro conditions in Mashima's investigation where directly stimulated, tend to limit the number of variables in the equation. In this study, neural inhibition of biceps is supported by the surface EMG recorded from the muscle in that a slightly less amount of EMG was recorded during eccentric trials. Examination of data from a single subject (figure 20) display the definite effects of inhibition during the eccentric condition.

Observation of the normalized torque - velocity data revealed that the eccentric torque is always greater than the concentric torques regardless of the angular velocity. This difference in torque output can be explained by the mechanical events occurring in the contractile component during stretch and shortening of the individual sarcomeres. During stretch from an isometric condition the sarcomere resists stretch and remains in the isometric configuration. As the tension increases the force between actin and myosin rods increases until the units "melt" and the actin and myosin filaments begin to slide past one-another. This mechanism generates greater force than the concentric or isometric conditions of the contractile component.

CONCLUSIONS

Three main conclusions have been drawn from this investigation:

1) The amount of "neural drive" provided by percutaneous electrical stimulation over the motor point of the biceps was of consistent amplitude regardless of angular velocity or joint angle.

2) The force-velocity relationship as determined by Hill's equation was supported by this investigation for the concentric MVC contractions of the biceps. It was also applicable for the stimulation trials up to velocities of $90_o/_s$. Had more current been used to drive the contraction it is believed that the Hill equation would hold up at greater concentric velocities.

3) The results of the eccentric contraction condition were determined to plateau at a level of approximately 150% of the isometric torque generated for corresponding joint angles. This plateauing effect disagrees with the force-velocity relationship reported by Mashima et al. (1972). The consistency of the EMG and CMAP amplitudes support the hypothesis that the plateauing of torque during eccentric contraction is due to a mechanical factor rather than a result of change in the neural drive to the muscle.

In conclusion, for modelling purposes, this investigation provided more accurately the relationships between force, length, velocity and EMG activity of the biceps brachii muscle in athletic young adult males.

5.2 Suggestions for Future Research

The stimulation procedure that was used in this experiment and in Leedham and Dowling (1991) effectively isolated the muscle under investigation (biceps). However, using the above stimulation procedure to evoke a response and generate force/torque from the biceps only generated small amounts of torque. This small torque/force output made collection of accurate and acceptable torque values during the concentric stimulated protocol difficult. Future research into the force\torque generating capabilities of an in-vivo muscle may wish to modify the stimulation technique to elicit greater responses from the muscle under examination. Increasing this interelectrode distance will result in an increase in the volume of muscle being stimulated which will increase the number of muscle fibers being recruited and will therefore allow more torque/force to be generated. Subsequent research performed in this lab has suggested that twitch tensions were markedly increased simply by increasing the interelectrode distance of the stimulating electrodes (Dowling, personal communication). Increasing the interelectrode distance makes the M-wave difficult to measure, however EMG results from the present investigation have supported the assumption that the amplitudes (which reflect muscle activation) show no systematic changes. Thus, adapting the distance between the stimulating anode and cathode can be done as the CMAP amplitudes do not have to be measured. The use of larger stimulating electrodes will also provide more current to the muscle and result in increased activation. Westing, Seger and Thorstensson (1988) investigating the eccentric and concentric torque velocity relationships in the quadriceps group, used larger surfaced silicon electrodes placed proximally and distally on the quadriceps group (approximately 0.41 m in the normal human male). These investigators determined that during an isometric contraction 90% (3% S.D.) of the voluntary torque could be elicited involuntarily by electrical stimulation. This is a much higher percentage than the 20% of the biceps that was being recruited in this investigation. However, Westing et al. were stimulating a group of muscles rather than attempting to isolate a single muscle. To this end any future research using the above suggestion must ensure that electrode placement, voltage and electrode surface site are properly tested to ensure isolation of the biceps from the elbow flexor group.

Another suggestion for future research into this area of study would be to use equipment with a smaller degree of vibration. Due to the design of our apparatus, vibration due to acceleration of the weight stacks and looseness of fit in various connections were present, especially in the earliest phases of the movement. This vibration was very repeatable and could mostly be removed by subtraction. However the use of a high velocity isokinetic device designed for eccentric contractions (eg. Kin/Com) may provide a smoother movement and a greater range of motion may possibly be investigated.

Investigation of the movement in the horizontal plane would be a practical step in future research. This would remove any forces generated by gravity. Although gravity was mathematically removed in this investigation, any error in calibration of the goniometer or position in which the torque transducer was zeroed would have been negated by performing the task in the horizontal plane.

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