EVALUATION OF THE LENGTH-TENSION RELATIONSHIP IN AN ELDERLY POPULATION

BY

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ABSTRACT

The effects of aging on the muscle length (as inferred by joint angle)-tension relationship was studied in the ankle dorsiflexors of male and female subjects aged 20-40 years ($\bar{x}$=25.3; 15♂, 15♀) and 60-80 years ($\bar{x}$=68.8; 15♂, 15♀) at 10 joint angles (15°D through 30°P, in 5° increments). Isometric twitches, voluntary contractions, and 1-sec evoked tetanic contractions (20, 50 & 80 Hz) were measured in the R-tibialis anterior muscle. The resting joint angle for the ankle dorsiflexors was similar between elderly and young adults (13°P ± 3.44). On average, evoked and voluntary torque output increased upon muscle lengthening beyond resting length, and decreased upon shortening. Evoked single twitches of the TA revealed that peak total torque occurred at the extreme of plantarflexion (30°P) in both elderly and young adults. Most importantly, elderly individuals produced similar twitch torque values at *all* joint angles compared to young adults. Maximal voluntary torque was stronger at the more plantarflexed compared to the dorsiflexed angles, for all subjects, regardless of age, with maximum torque plateauing at 15°P. Elderly subjects demonstrated much reduced MVC torque values compared to young adults at all joint angles (ave.= 18% reduction, $p<0.01$) while maintaining no less than 96% motor unit activation (MUA). Stimulation of the dorsiflexors at 20, 50, & 80 Hz revealed that the 1-sec peak tetanic torques declined from a maximum at 30°P through to 15°D for all subjects. Elderly adults produced significantly less tetanic torque at all joint angles compared to young adults ($p<0.05$). There was no difference between the elderly and young adults in the rate at which the rise in tetanic torque was developed at all joint angles, but elderly adults displayed a significantly greater twitch/tetanus ratio as compared to young adults ($p<0.005$).

In conclusion, these results suggest that there is no age-associated change in the elastic properties of the ankle dorsiflexors, and thus, the length-tension relationship of this muscle group is similar between elderly and young adults.

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LIST OF ABBREVIATIONS

APB = adductor pollicis brevis
Ca = calcium
CAT scan = computerized axial tomography
CSA = cross sectional area
D = dorsiflexion (direction of ankle rotation)
EHB = extensor hallucis brevis
gms = grams
Hz = hertz
ITT = interpolated twitch torque
kHz = kilohertz
min = minute
mm = millimeter
ms = millisecond
MUA = motor unit activation
MU = motor unit
MVC = maximal voluntary contraction
M-wave = compound muscle action potential
n = number
Nm = Newton meter
NMJ = neuromuscular junction
P = plantarflexion (direction of ankle rotation)
PEE = passive elastic component
P_t = peak isometric twitch torque
R = right
sec = second
SEC = series elastic component
TA = tibialis anterior muscle
TPT = time to peak torque
T-tubules = transverse tubules
twt/T = twitch:tetanus ratio
yrs = years

SYMBOLS

1/2 RT = half-relaxation time
μm = micrometer
Δ = change
$\bar{x}$ = mean
% = percent
° = degree

CHAPTER 1

INTRODUCTION

1.1 THE RELATIONSHIP BETWEEN LENGTH AND TENSION IN SKELETAL MUSCLE: The passive, total, and developed (active) tensions during isometric contractions of skeletal muscle vary as the length of the muscle is changed. This phenomenon, termed the length-tension relationship, has been an integral part of skeletal muscle research since the mid-nineteenth century (Heindenhain, 1864; Blix, 1894). Blix, (1894), proposed that the variable factor among the mechanical conditions which determines the mechanical performance is the initial length of the muscle. While Heindenhain agreed in theory, there was a considerable lack of consensus between the exact interdependence of total tension sustained by a contracted muscle and the initial length of the muscle. Blix demonstrated the relation is often expressed as an S-shaped curve, while Heindenhain had discovered an initial increase followed by a diminution of tension with increasing initial length during an isometric contraction. In the years to follow, collaborative efforts towards improved experimental techniques gradually revealed that while Heindenhain's results were not actually incorrect, as they were only flawed in methodology, the observations of Blix proved to be more widely accepted.

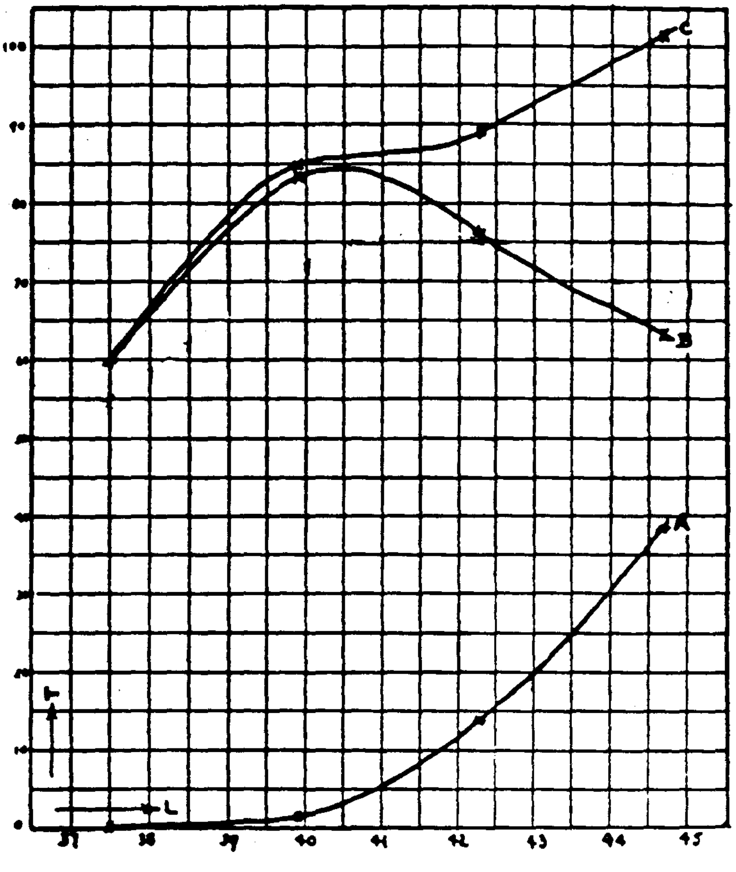
Currently, the relationship between the various forms of tension has been described as follows:

Total Tension = Passive Tension + Active Tension
(Evans & Hill, 1914)

The passive tension is the tension produced when muscle is stretched and NOT stimulated and is therefore reflective of the elastic components of the muscle (i.e. connective tissue). In contrast, the active tension is the tension produced by the muscle in response to electrically evoked or voluntary stimuli and hence is indicative of the contribution of the mechanical contractile elements to tension developed. The total tension is simply the algebraic sum of the passive and active components of tension and therefore represents whole muscle tension. By the early 20th century the relationship between the tension developed and muscle length was described (Figure 1) in which tension increases to a maximum with increasing length of muscle, and then diminishes again (Evans & Hill, 1914). It can be seen from this figure that the composite length-tension relationship is a reflection of the active and passive tensions within the muscle. Therefore, the total, passive, and active muscle tensions are affected by changes in muscle length. Thus, when a muscle is stretched or shortened

<u>Figure 1</u>:

The length-tension curve of the double sartorius muscle of the R. esculenta frog for the (A) passive tension, (B) active tension developed on contraction, and (C) total tension. The X-axis indicates muscle length measurements in millimeters (mm), whereas the Y-axis represents corresponding tension values in grams (grms). Adapted from Evans & Hill, 1914.


100
90
80
70
60
50
40
30
20
10
0
I
L
37
38
39
40
41
42
43
44
45
A
B
C

beyond an optimal length, the corresponding active tension will decline.

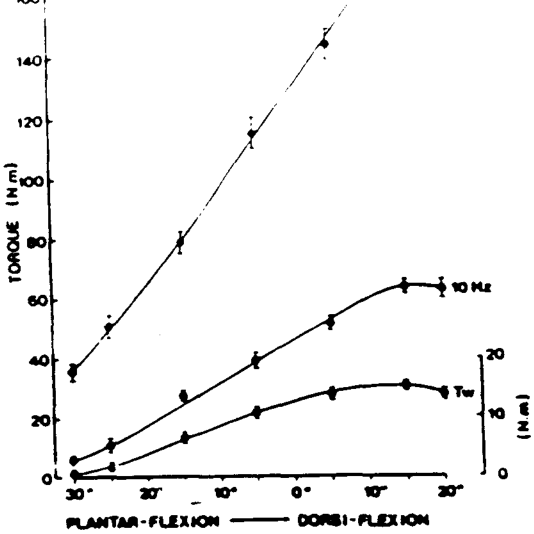
The definition of "optimal length" in human skeletal muscle is somewhat confusing in the literature. Some authors state that optimal length for tension development is reached at resting length (Ganong, 1979), and therefore use the two terms interchangeably. Others are more literal in their interpretation and use "resting length" as the length the muscle assumes at rest in the body (Zierler, 1974). Currently, the most appropriate clarification between the two terms has been provided by Marsh et al., 1981. Marsh and colleagues term "optimal length" as the muscle length (as inferred from joint angle) at which the greatest torque is achieved. This is independent of the resting length, which is the muscle length when the joint is in its natural resting position. Therefore, there is no obligatory correspondence between the resting and optimal positions for a joint (Marsh et al., 1981).

1.2 THE LENGTH-TENSION RELATIONSHIP: Since the classic investigation of Evans & Hill, (1914) the length-tension relationship went relatively unnoticed until the 1940's when Ramsey & Street, using more advanced technological methods, described the first account of a complete length-tension relationship for single isolated muscle fibres. They demonstrated that the maximum tension of isolated frog skeletal muscle fibres decreases linearly with stretching, but exponentially with shortening past an optimal length. Many later studies have been conducted on single muscle fibres (Page & Huxley, 1963; Huxley, 1957; Gordon, et al., 1966a), and whole mammalian muscle preparations (Banus & Zetlin, 1938; Buller et al., 1960; Buller & Lewis, 1963; Close, 1972) and confirm the early findings of Ramsey & Street (1940).

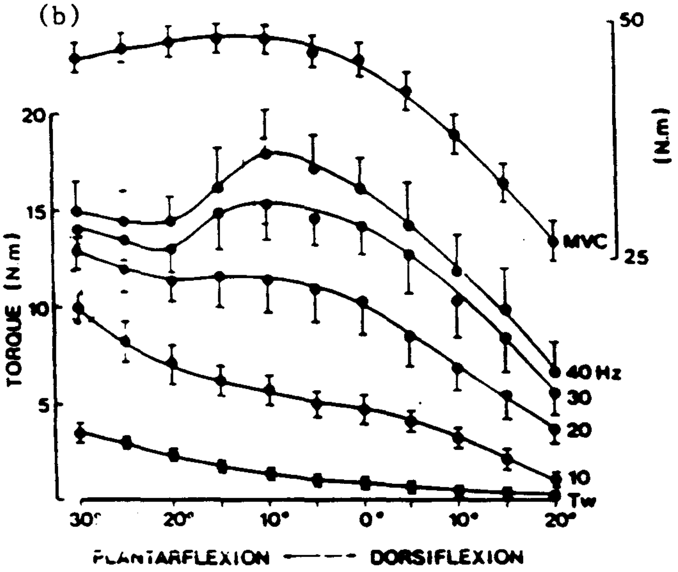
In addition to those studies described above, the length-tension relationship has also been investigated non-invasively in several human skeletal muscles including tibialis anterior (Marsh et al., 1981; Vander Linden et al., 1991), plantar flexors (Herman & Bragin, 1967; Kitai & Sale, 1989; Sale et al., 1982), extensor hallucis brevis (EHB) (Sica & McComas, 1971), adductor pollicis brevis (Botelho et al., 1954), and biceps brachii (Ismail & Ranatunga, 1978). In each case, length-tension relationships have been established across a full range of movement, however joint angle is commonly used in human studies to estimate muscle length, for example as illustrated in figure 2. The variations in torque that are evident at the different joint angles in figure 2 have been suggested to be due to several factors: (a) lever arm; (b) degree of motor unit activity; and (c) muscle length (Sale et al., 1982). For the purpose of this thesis, explanations for

Figure 2:

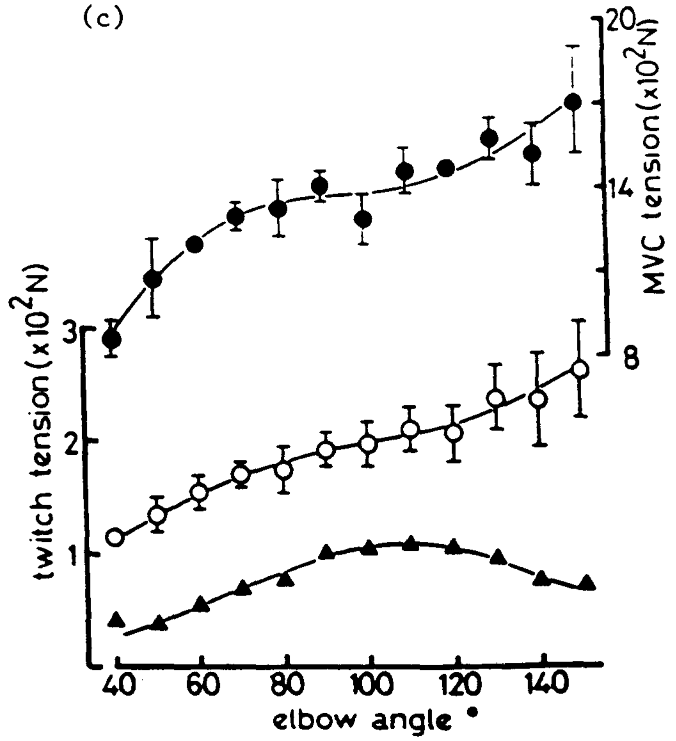
The influence of joint position on isometric muscular contraction of the (A) plantarflexors, (B) dorsiflexors, and (C) biceps brachii; solid circles representing MVCs, open circles representing maximal twitch contractions and, solid triangles representing submaximal twitch contractions. All values are means ± standard error of the mean. Taken from Sale et al., 1982; Marsh et al., 1981; and Ismail & Ranatunga, 1978.


TORQUE (N.m)
140
120
100
80
60
40
20
0
10 Hz
Tw
20
10
0
(N.m)
30°
20°
10°
0°
10°
20°
PLANTAR-FLEXION —— DORSI-FLEXION

(b)


50
(N.m)
25
MVC
20
15
10
5
TORQUE (N.m)
40 Hz
30
20
10
Tw
30°
20°
10°
0°
10°
20°
PLANTARFLEXION —— DORSIFLEXION

(c)


20
14
8
MVC tension ($\times 10^2$N)
3
2
1
twitch tension ($\times 10^2$N)
40
60
80
100
120
140
elbow angle °

the variation in torque across joint angles will be limited primarily to the effects of muscle length.

The new surge of research regarding the length-tension relationship in the mid-20th century, coupled with the advent of the electron microscope, led to the emergence of several new features. Of significant importance was the classic work of A.F. Huxley and co-workers, and H.E. Huxley and co-workers in the 1950-1960's. Their description of the sliding filament theory of muscle contraction enabled researchers to develop hypotheses to accurately explain the length-tension relationship based on the interaction of actin and myosin during muscle contraction.

1.3 <u>SLIDING FILAMENT THEORY OF MUSCULAR CONTRACTION</u>: The contractile material in skeletal muscle consists of a long series of partially overlapping arrays of actin and myosin filaments which form the myofibrils. When a muscle fibre shortens isometrically, the two sets of interdigitating filaments (actin and myosin) slide with respect to one another (Huxley & Niedergerke, 1954; Huxley & Hansen, 1954). Thus, when a muscle changes length, independent of the mode of length change, the lengths of the actin and myosin filaments themselves remain constant. Shortening, and consequently the development of tension, are produced by a distribution of force-generators, or cross-bridges, within each region of overlap (Huxley, 1957; 1963). The tension developed by the muscle is proportional to the number of cross-linkages between the filaments. When a muscle is stretched beyond optimal length, there is a reduction in the amount of overlap between actin and myosin. If the cross-bridges are distributed evenly, this would result in a decreased number of attached cross-bridges. Conversely, when the muscle is appreciably shorter than optimal length, the thin filaments overlap, also reducing the number of cross-linkages. Therefore, it is thought that each attached cross-bridge contributes a fixed amount of tension, with maximum tension being produced when there is optimal overlap between the actin and myosin filaments, i.e., maximum cross-bridge formation.

Application of this direct proportionality between generated tension and filament overlap to the results of Ramsey & Street, (1940), however, resulted in a significant anomaly to become apparent. Scrutinization of the length-tension curve reported by Ramsey & Street, (1940), (Huxley & Peachey, 1959; 1961) revealed that developed tension did not fall to zero until muscle fibre lengths much greater than the length of zero overlap. These authors attributed the discrepancy to their observation that skeletal muscle fibres do not stretch uniformly. In isolated fibre preparations of frog muscle, they observed no overlap between the filaments in the middle portion of stretched fibres, however, an appreciable amount of overlap was evident in the very distal fibre ends. Moreover, electron microscopic observations provided further evidence for the sliding motion of one set of filaments relative to the other, and thereby provided the first concrete evidence for contraction depending on the physical interaction of the filaments in the area where they overlap. Additional support for non-uniformity of muscle fibre contraction (Posolsky, 1964) and cross-bridges and physical interaction site (Gordon et al., 1966a) was provided in the years to follow.

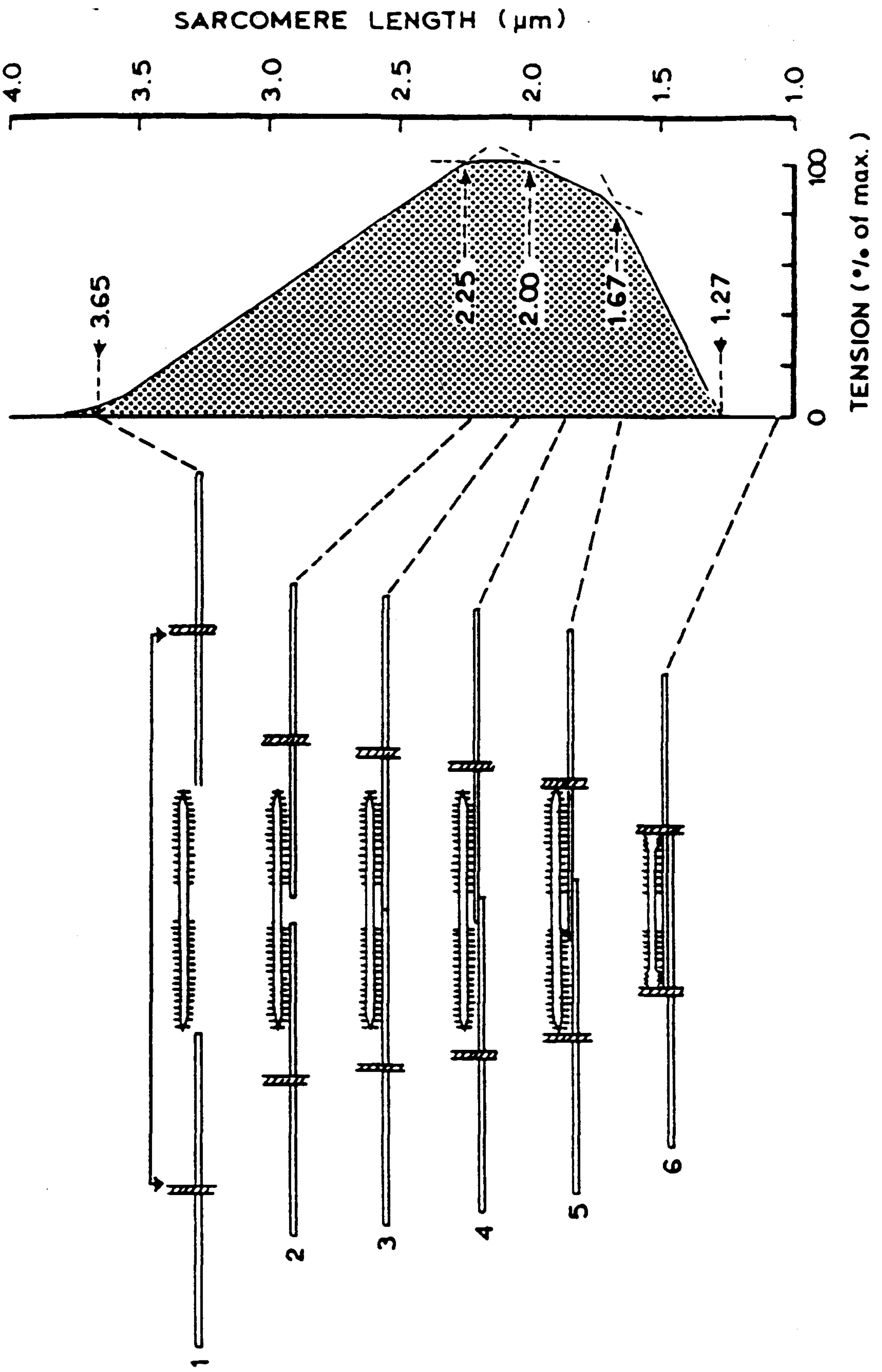
Collectively, these findings have provided the framework for a coherent understanding of tension development in contracting vertebrate skeletal muscle to consist of 3 components (Figure 3): maximal tension occurring in sarcomere lengths of 2.05 μm to 2.0 μm; tension gradually declining as sarcomere lengths decrease from 2.05 μm to 1.65 μm and reaching zero at 1.3 μm or less; and lengthening of sarcomeres beyond 2.2 μm causing a steep decrease in tension generating capacity, approaching zero tension at 3.65 μm.

1.4 <u>FACTORS WHICH AFFECT THE LENGTH-TENSION RELATIONSHIP</u>:

The mechanical properties of stretched muscle can be described in terms of 3 constituents: (1) the main contractile proteins; (2) a passive elastic component (tendons and tendon bundles) in series with the contractile one (SEC); and (3) a passive

Figure 3:

Length-tension curve of single frog muscle fibre (taken from McComas, 1977).


SARCOMERE LENGTH (µm)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
3.65
2.25
2.00
1.67
1.27
TENSION (% of max.)
0
100
1
2
3
4
5
6

elastic component (intramuscular areolar and reticular tissues) in parallel with (1) and (2) (PEE) (Hill, 1953). Researchers have identified a variety of factors which affect the active length-tension relationship. These factors include the tendons, which are in series with the contractile elements (Ramsey & Street, 1940; Huxley, A.F. & Peachey 1961; Huxley,A.F., 1973; Marsh et al., 1981) the connective tissue lying between fibre bundles (Weber, 1846; Banus & Zetlin, 1938; Huxley, A.F., 1973), sarcotubular calcium release (Close, 1972; Blinks et al., 1978; Stevenson & Williams, 1982), and, as previously discussed, the degree of actin and myosin overlap.

Tendon elasticity makes a sizable contribution to the influence of joint position on muscle tension. Marsh et al., (1981) explained that at progressively shorter than resting muscle lengths the series elastic component, residing in the tendon, becomes gradually more slack thereby absorbing a large portion of the force developed by the muscle fibres. Conversely, as a muscle is stretched the tendon loses part of its elasticity resulting in a greater proportion of the developed tension being transmitted to the attachments of the tendon.

It has been known since the time of Weber, (1846) that resting muscle has elastic properties. The elasticity of whole muscle is due to the meshwork of connective tissue surrounding the muscle fibres and to the sarcolemma and sarcoplasmic reticulum membranes. These structures which comprise the elastic nature of resting muscle are directly influenced by changes in resting muscle length. The nature of the relationship between passive elasticity and increasing muscle length is explained as tension rising slowly at first, almost linearly, up to 130% of resting length, beyond which tension increases exponentially as the muscle is further stretched (Guyton, 1981; Ganong, 1979). The exponential relationship between passive elasticity and increasing muscle length is well established in isolated muscle fibres (Sichel, 1934; Ramsey & Street, 1940; Buchthal, 1942; Buchthal & Kaiser, 1951), empty sarcolemma (Ramsey & Street, 1940; Sichel, 1941; Fields & Faber, 1970), and in whole muscle (Weber, 1846). When muscle contracts it must first stretch the connective tissue elastic element to effectively take up the slack in the system before any torque can be developed at the musculotendinous junctions. Muscles which have more connective tissue, are not only more resistant to stretching, but also show a greater tendency to return to resting length after a contraction has terminated.

Although other factors may be of more significance, changes in calcium (Ca) release also may play a role in determining the influence of fibre length on maximum tension development. Reductions in calcium efflux, and therefore depressed force production, have been reported during activity (Sopis & Winegrad, 1957; Frank & Winegrad, 1976) and high degrees of fibre lengthening and shortening (Blinks et al., 1978; Close & Lannergren, 1984). The mechanism of the decreased release of calcium at fibre lengths greater than optimal is unknown, though it seems that the junctional region between the terminal cisterna and the T-tubules could be responsible (Blinks et al., 1978). At high fibre lengths, electron microscopy experiments (Frank & Winegrad, 1976) have shown a reversible distortion of this junctional region which is associated with reduced calcium efflux during activity (Sopis & Winegrad, 1967; Frank & Winegrad). Decreased force at fibre lengths less than optimal may be due to, in part, decreased calcium release in the core of the fibre. This hypothesis has been substantiated by microscopic observations (Taylor & Rudel, 1970; Costantin & Taylor, 1973) which verify decreased activation of the core of the muscle fibre. Even if the cytoplasmic calcium concentration reaches saturating levels during a twitch at all fibre lengths, changes in the amount of calcium released would be expected to have an influence on the duration of activity, and therefore on the extent of shortening or amount of force developed by a twitch (Blinks et al., 1978).

1.5 EVALUATION OF THE LENGTH-TENSION RELATIONSHIP TO DATE:

It is clear from animal studies that the isometric tension developed by a muscle depends in a characteristic way on the length at which it is held, declining steeply on either side of an optimum length. However, the evaluation of the length-tension relationship in humans has only been looked at in a young population; a population whose elastic components and muscle properties are functioning optimally (Herman & Bragin, 1967; Haffajee et al., 1972; Ismail, 1978; Marsh et al., 1981). With the advent of literature on the effects of aging on skeletal muscle, it has become increasingly evident that the muscular properties of elderly individuals differ significantly from those of young individuals. To date, the evaluation of contractile properties in elderly muscles has involved an assumption that is inherently problematic; that the length-tension relationship in the elderly is equivalent to that of a young population. Such an assumption could be troublesome if in fact the relationship is not the same in people of different ages. For example, in a comparison of populations it is important to know that the experimental length of the muscle is optimal for tension development in each population, otherwise one is not comparing the true capabilities of the different age groups. Presently, only a few studies have examined the length-tension relationship in elderly human (Botelho et al., 1954; Sica & McComas, 1971) and animal muscle (Arabadjis et al., 1990). Botelho et al., (1954) were the first to examine this relationship in an elderly versus young population. However, flaws such as small sample size (n=11), gender restriction (females), and a low upper range in age (61 yrs) made the interpretation of the results, as truly representative of an elderly population, questionable. In examining fast and slow twitch motor units in the EDB muscle of subjects aged 3-94 years, Sica and McComas, (1971) showed that the relationship between the initial length of the muscle and its active tension changes with age; an appreciably greater fraction of the maximum twitch tension was achieved in the resting position by elderly subjects. One possible explanation was that the difference may be partially due to the loss of elasticity in tissues which is known to occur with aging. Additional possibilities were that the influence of the length of the tendon on twitch tension is less, or that some other structural changes took place within the muscle belly itself. One study has investigated the effects of increasing muscle length on tension development in the senescent rat. Arabadjis et al., (1990) found no difference in the stimulating voltage required to elicit maximal contractile tension in the plantaris muscle of young and old rats. In contrast to the results of Sica & McComas, (1971), these authors observed no variation in the percentage of maximal force at any muscle length between the young and aged rats.

1.6 AGING EFFECTS IN HUMAN SKELETAL MUSCLE: From a physiological point of view, the loss of motor function which parallels the aging process is a very complex phenomenon involving alterations in other body systems, i.e., nervous, vascular, and endocrine, with which advanced aging is commonly associated. The characteristic decline in muscular performance which accompanies the aging process is therefore not only caused by primary aging of skeletal muscle, but also by secondary influences on muscle tissue of disuse, malnutrition, and the influences of disease. Adding to this complication is the fact that skeletal muscle lacks homogeneity, and therefore considerable variations occur between the muscles themselves. Thus, several problems have inhibited research in aging human muscle. The intent of this section is not to be totally comprehensive, as this is not the central focus of this thesis, but to present some of the literature on aging skeletal muscle that might be relevant to the length-tension relationship. For a more detailed description of changes in muscle function with age, excellent reviews can be found by Fitts (1980) and Grimby and Saltin (1983).

Several physiological changes in skeletal muscle occur with advancing age, and these changes often affect the functional capabilities of elderly individuals. Various research groups (Sica & McComas, 1971; Davies & White, 1983; McDonagh et al., 1984; Vandervoort & McComas, 1986; Klein et al., 1988) have shown that elderly individuals (60+ yrs) are significantly weaker than their younger counterparts, 20-40 years of age. This age-related loss in voluntary strength is not apparently associated with progressive weakness beyond young adulthood, but rather there seems to be a critical later age (late 6th decade) at which strength begins to decline (Asmussen et al., 1962; Kroll & Clarkson, 1978; Larsson et al., 1979; Vandervoort & McComas, 1986). This is in agreement with previous findings of preserved muscle strength in middle age (Petrofsky & Lind, 1975; Fugl-Meyer et al., 1980; Belanger et al., 1983). Furthermore, it is now generally accepted that, in addition to the loss of strength that occurs with age, elderly muscle is also slower to contract (Davies et al., 1983; Davies & White, 1983; McDonagh et al., 1984; Vandervoort & McComas, 1986; Klein et al., 1988; Cupido et al., 1992; Hicks et al., 1991) and less elastic (Botelho et al., 1954; Campbell et al., 1973; Lexell, 1983).

1.6.1 Morphological Changes: One of the most profound age related alterations which occurs in skeletal muscle is the marked muscle wasting, or decreased muscle volume. The observation that older subjects have less muscle capacity for tension generation has largely been determined from the body composition of elderly individuals (Forbes & Reina, 1970; Parizikova et al., 1971; Steen et al., 1977; MacLeenan et al., 1980; Dill et al., 1982). However, these early investigations of body composition were generated from anthropometric measurements such as densitometry, Potassium 40 scanning, or basic skin fold thickness, and therefore were unable to discern whether in fact the loss of lean body tissue was due to loss of muscle mass, or to the loss of other fat free tissue. In addition, differences in the lean tissue lost by different muscle groups could not be assessed due to the lack of direct tissue measurement. Recently, an alternative tool has been to use ultrasonic imaging or computerized axial tomography (CAT scan) for measuring muscle mass in the elderly. With the aid of both of these techniques, elderly muscle has been shown to have reduced cross sectional areas (CSA) in both males and females as compared to young adults (Young et al., 1982; Stodes et al., 1983; Borkan et al., 1983; Vandervoort & McComas, 1986). The most accurate assessment of the degree of muscle wasting in the elderly was performed by Lexell et al. (1983). These investigators conducted a post mortem study comparing the CSA of the M. vastus lateralis muscle between 2 groups of healthy males ($\bar{x}=72$, $\bar{x}=30$ yrs) who had suffered a sudden death accident. Their findings indicate an 18% reduction in vastus lateralis CSA of elderly males as compared to young adult males.

A variety of studies have been undertaken to speculate on the physiological events underlying this atrophy. Generally, two hypotheses have been proposed:

(1) a decrease in the mean area of type I and type II fibres, with type II fibres being more greatly affected (Jennekens et al., 1971; Larsson, 1978; Poggi et al., 1987; Larsson et al., 1979; Grimby et al., 1982; Nygaard & Sanches, 1982; Aniansson, 1978; 1986; 1980), and/or

(2) a reduction in the total number of fibres (Lexell et al., 1983; Aniansson, 1986). This would be consistent with findings of an increased proportion of type I fibres, and thus, a more homogeneous fibre type distribution in aged muscles (Larsson, 1978; Sjostrom et al., 1980; Lexell et al., 1983; Poggi et al., 1978). However, contradictions to these results have been reported elsewhere (Grimby et al., 1982).

Thus, there is considerable lack of agreement on the effects of aging in the number and size of muscle fibres. A possible explanation for unaltered mean fibre area in whole muscle studies may be due in part to imprecise measurements which do not account for the existence of blood vessels, the general increase in connective tissue which occurs with advancing age, and the influence of post mortem event on the fibre size (Lexell et al., 1983). Moreover, a meaningful interpretation of the age-related changes in skeletal muscle concerning alterations in fibre composition and size must realize that the characteristics of the atrophy are not uniform among all muscles, and can therefore not be solely based on the analysis of a single muscle (Aniansson et al., 1986). For example, in humans, age related muscle atrophy is more marked in the lower extremities than in the upper extremities (Asmussen et al., 1962; Serratice et al., 1968; Tomlinson et al., 1969; Kamon & Goldfuss, 1978; McDonagh et al., 1984). However, it is also conceivable that at least some of the noted changes in muscle with advancing age can be related to a possible alteration of the length-tension relationship. For example, reduced fibre size would be an advantage at short muscle lengths because the action potential would not have to penetrate as deeply into the fibre to activate all of the myofibrils.

Increased stiffness beyond middle age has been a characteristic feature of elderly muscle (Botelho et al., 1954; Campbell et al., 1973; Lexell, 1983). Stiffness is the ratio of the change in tension to the change in length ($\Delta T/\Delta L$) (Buchthal et al., 1944) and therefore is a measure of muscle elasticity. Accordingly, for a given length, an increase in the passive tension of a muscle is an indication of the stiffness of the passive elastic structures, the tendons.

Extensibility, the reciprocal of stiffness (Walker, 1953), is a measure of the compliance of the structures, so that the greater the passive tension at a given length the less extensible are the structures (Botelho et al., 1954). Increased rigidity of the non-muscular structures in older women has been documented (Botelho et al., 1954), and therefore corresponds with observations of increased connective tissue with advancing age (Lansing, 1951; Lowry et al., 1942; Jennekens et al., 1971; Lexell et al., 1983). This is in agreement with findings that tissues with less connective tissue are more extensible (Hill, 1952). With these changes, it is not unusual to observe declines in flexibility in the aging population (Smith & Zook, 1986). Johns & Wright, (1962) attributed 98% of the observed decline in flexibility with advanced age to changes in the connective tissue, ligaments, joint capsules, and tendons. However, more current reports suggest that the alterations in flexibility which occur with age are more precisely related to disuse than to age degeneration (Chapman et al., 1972; Lesser, 1978; Munns, 1981). The well documented decline in elasticity (↑ stiffness, ↓ extensibility) with advancing age could be profitable at short muscle lengths since the series elastic component (SEC) could be more readily taken up, thereby implicating muscle elasticity as an influencing factor in an age-related altered length-tension relationship.

1.6.2 Mechanical Changes: Aside from the morphological changes that occur during the aging process, several research groups have demonstrated changes in the mechanical or contractile properties of aging muscle. The contractile properties of elderly muscle are significantly different when compared to the younger adult population. Davies et al., (1983) demonstrated that the triceps surae muscle of elderly men and women was slower to contract and weaker than that observed in young individuals, as indicated by longer times to peak tension and half relaxation time of the maximal twitch as well as a slower rise in tetanic force. Further support for an increased time to peak tension (Davies & White, 1983; McDonagh et al., 1984; Vandervoort & McComas, 1986; Klein et al., 1988) and slower relaxation time in elderly muscle (Davies & White, 1983; Vandervoort & McComas, 1986; Klein et al., 1988; Newton et al., 1988; Cupido et al., 1991; Hicks et al., 1991) has been well documented in the literature. In addition, there has been some support for less pronounced age-related mechanical changes in upper limb skeletal muscle as compared to the lower limbs (McDonagh et al., 1984). Based on the slower contractile properties of elderly muscles, which may be attributed to an increase in the proportion of the slower Type I fibres, one could expect a reduction in the peak twitch tension of the older adult population since this fibre type population is unable to generate the same magnitude of force as compared to the Type II fibre population. However, this expectation has met with some uncertainty. Vandervoort & McComas, (1986) demonstrated that the twitch tension of both the plantarflexors and dorsiflexors decreased with age; they reported a decrease of almost 40% when comparing the twitch torque of elderly subjects to those of young adult subjects. In contrast, Hicks et al., (1991) found no difference in the twitch torque of the ankle dorsiflexors between elderly and young adults. To further add to the quandary concerning the effects of aging on evoked torque production, Cupido & co-workers, 1991, have recently observed greater evoked twitch torques in the tibialis anterior muscle of elderly subjects. An age-related alteration in the length-tension relationship, at least for the ankle dorsiflexors, might explain the similar and greater twitch torque in the elderly versus the young adults (Sica & McComas, 1971). For example, the unequivocal prolongation of twitch contraction time with aging would be advantageous at short muscle lengths since a longer active state would allow for the series elastic component (SEC) to be more readily taken up.

1.6.3 Motor Neuron Changes: In addition to the morphological and mechanical properties of aged muscle, research has also focused on the age associated changes in the electrical nature of muscle. There is evidence that the number of motor neurons is decreased in elderly human muscle. In a pioneering study of motor neuron counting, Gardner, (1940) estimated a 25-30% reduction of myelinated fibres in the eight and ninth thoracic ventral roots of cadavers between the third and eight to ninth decade of life. However, failing to account for the effects of disease in these subjects made it difficult to discern the true effects of the aging process alone on motor unit numbers. In the early 70's, McComas and co-workers, using a non-invasive electrophysiological technique where motor unit counts are obtained by dividing the individual motor unit potential into the compound muscle action potential, estimated the number of functioning motor units in elderly muscles. Reduced motor unit estimates have been reported for the extensor hallucis brevis (Sica & McComas, 1971) and the extensor digitorum brevis (Campbell et al., 1973), dorsi and plantarflexor muscles of the foot (Vandervoort & McComas, 1986), and thenar and hypothenar muscles of the hand (Sica et al., 1974; McComas, 1977). Inasmuch as other investigations support this finding of a decreased number of functioning motor units with advancing age (Brown, 1973; Hansen & Ballantyne, 1978; Salberg & Fawcett, 1982), none nearly reflect the number of motor units which would be expected based on the number of motor neurons alone. The considerably lower number of motor units for any given muscle has been suggested to possibly be a result of a decreased percentage of functioning motor units (McComas, 1977) and/or a collateral reinnervation process (Cavanagh, 1964; Campbell et al., 1973; Sabin, 1982). In addition to the decline in the number of functioning motor units in the elderly, researchers have also noted an enlargement of the surviving motor units, which is in accordance with the reinnervation process (Brown, 1973; Campbell et al., 1973; Hansen & Ballantyne, 1978; Stalberg & Fawcett, 1982). Furthermore, Campbell et al., (1973) and Hicks et al., (1991) have demonstrated that the surviving motor units of elderly individuals display reduced muscle membrane excitability, as inferred by a smaller compound muscle action potential.

1.7 SKELETAL MUSCLE CHANGES IN OLD ANIMALS: Ultrastructural changes in aging muscle have been studied mainly in the rat. However, as was seen in the human literature, animal studies have also yielded some inconsistent and apparently contradictory results. Many studies have reported a decrease in the total number of fibres in aged rodent limb muscles (Rowe, 1969; Tauchi et al., 1971; Gutmann & Hanzlikova, 1972; Hooper, 1981; Larsson & Edstrom, 1986). However, others have shown that the total fibre number in the tibialis anterior (Larsson & Ansved, 1987) and soleus muscles of rats (Eddinger et al., 1985; Brown, 1987; Alnageeb & Goldspink, 1987) remains consistent with advancing age. This lack of consensus as to the effects of aging on total fibre number may be due in part to the methodology employed or to the sampling of muscles, or areas within muscles (Arabadjis et al., 1990). In order to clarify some of the uncertainty in the literature, Arabadjis et al., (1990) compared histological sectioning and direct counting as methods of determining total fibre number in young and old rat plantaris muscle. Their results indicate that a reduction of approximately the same magnitude (9% & 5%, respectively) in the mean number of muscle fibres in aging rats was found using both methods. However, histological sectioning tended to overestimate fibre number estimates in young rats, while an underestimation was observed in old rats. It appears then, that a decline in the number of fibres does occur with advanced aging in animals.

Smaller fibre area is also a prominent feature in aged rat muscle (Tauchi et al., 1971; Bass et al., 1975; Klitgaard et al., 1989). For the mouse, however, both reductions (Banker et al., 1983) and increases in fibre size (Rowe, 1969) have been reported, although, the mean ages of the animals were considerably different.

Electrophysiological studies of aged rodents have revealed prolongation of the isometric twitch duration in slow (Fitts et al., 1984) and fast twitch muscles (Gutmann & Hunzlikova, 1971; Gutmann & Syrovy, 1974; Fitts et al, 1984). However, reports of decreased contraction time in the slow twitch soleus have also been cited (Gutmann & Hanslikova, 1966; Gutmann & Syrovy, 1974).

Therefore, it appears that many aging related muscular changes in humans and animals are muscle specific and seem to be related to muscle function. Although many of the effects of aging in skeletal muscle remain controversial, a large portion of this can be attributed to differences among the species, preparations, or methodologies used (De Luca et al., 1990).

1.8 SUMMARY AND STATEMENT OF PURPOSE: In summary, much remains yet unresolved regarding how the length-tension relationship regulates muscle function, specifically in an elderly population. A considerable amount of research is still required to develop a more thorough understanding of the aging process in skeletal muscle. Despite the many conflicting properties reported in aged skeletal muscle, decreased elasticity beyond middle age has been unequivocal. Although several authors have suggested that elasticity changes, or influences of tendon length, may explain some of the peculiar findings in senescent muscle, no attempts to determine the validity of such speculation have been undertaken. The short term impact of such a project might explain some of the differences found between young and aged muscles. Furthermore, the long-term benefits of such a study might allow a more accurate evaluation of muscular properties in individuals of different ages. Therefore, the purpose of the research outlined in this thesis was to examine the effects of aging on the muscle length (as inferred by joint angle)-tension relationship. It was hypothesized that based on the changes that are known to occur in skeletal muscle with advancing age, optimal functioning in the elderly would occur at a shorter muscle length as compared to young adults.

CHAPTER 2

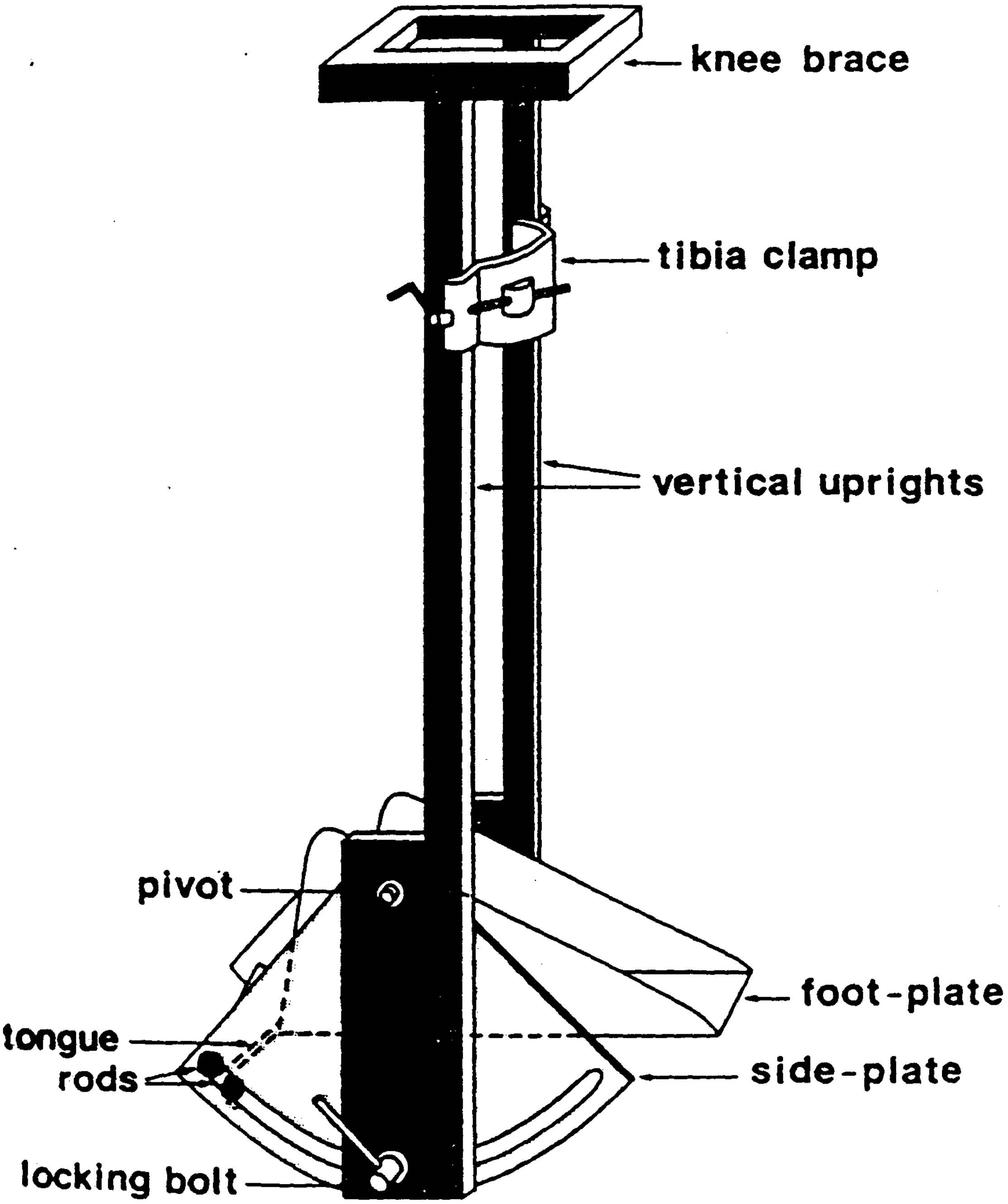
METHODS

2.1 SUBJECTS: Sixty subjects aged 20-40 ($\bar{x}$=25.3 yrs; 15♀, 15♂) and 60-80 yrs ($\bar{x}$=68.8; 15♀, 15♂) voluntarily participated in this study. Volunteers were recruited from the Hamilton-Wentworth region through McMaster University and the Hamilton media. All subjects were in good health and free from any neurological deficit and orthopaedic disability. Older subjects were living independently within the community, and while all were able to walk free of any assistance, some were involved in more strenuous activities, such as swimming, running, and weight training. The procedures utilized in this study were approved by the McMaster University Ethics Committee.

2.2 STIMULATING AND RECORDING APPARATUS: All measurements were conducted on the right tibialis anterior muscle (TA) with the subjects seated in a vertically adjustable chair such that the R-leg was flexed 90° at the knee, while the leg was secured in the leg holder and foot plate first employed by Marsh et al., 1981 (refer to Figure 4). The muscle under

Figure 4:

The leg holder-foot plate apparatus. Joint position could be varied 30° from the horizontal plane in either direction.


knee brace
tibia clamp
vertical uprights
pivot
foot-plate
tongue
rods
side-plate
locking bolt

investigation was chosen because of its simplistic innervation as well as its common usage across individuals. In addition, current literature favours experimentation with the dorsiflexors, therefore making any results easily comparable with the existing research.

Briefly, the subject's leg was secured by 2 clamps; one positioned over the knee, and the other positioned over the mid-lower leg to prevent any vertical (up or down) or horizontal (back and forth) leg movement. In addition, a velcro strap was anchored to the metal frame behind the leg in the mid-lower calf position to further prevent any leg movement. The subject's foot was fastened to the foot plate by two velcro straps tightened over the top of the foot. Strain gauges housed on the under side of the foot plate measured torque production. The plane of the foot plate could be set at up to 40° plantarflexion (that is, 40° of downward rotation of the foot-plate from the horizontal) through 40° dorsiflexion (40° of upward rotation of the foot-plate from the horizontal).

The stimulating electrodes consisted of a lead plate cathode and rubber anode. The cathode (radius=15mm) was wrapped in gauze, dampened and secured over the common peroneal nerve just distal to the proximal head of the fibula, while the anode (37mm x 45mm) was placed on the anterior aspect of the leg, approximately 50 mm distal to the patella.

Prior to electrode placement, the skin was shaved, scraped, and cleansed with alcohol, while the electrodes were covered with conducting gel in order to minimize electrical resistance.

A high-voltage stimulator (Devices Systems, Model 3072) triggered by a Stoelting (WoodDale, Illinois) laboratory controller with custom interfacing, was used to deliver single 50 μsec rectangular pulses and 1 sec tetanic trains (20,50, and 80 Hz) to the peroneal nerve. The EMG signals from the recording electrodes were fed into amplifiers with bandwidths of 20 Hz to 1.5 kHz and were displayed on a VGA computer monitor (CTX, model 2431P). Concomitantly, data were streamed continuously to disc by means of a Dataq (Arkon, Ohio) waveform scrolling board (WFS-200DC; Dataq Instruments Inc.) configured in an IBM compatible system.

Custom designed Advanced CODAS software was used to analyze all of the voluntary and evoked mechanical recordings: voluntary torque; evoked single twitch torque (Pt), time to peak torque (TPT), ½ relaxation time (½RT); and evoked tetanic torque (Pt), rise of tetanic torque, and twitch/tetanus ratio. During the maximal voluntary contractions (MVCs) the interpolated twitch technique (Belanger and McComas, 1981) was used as an assessment of the degree of muscle activation achieved by the subjects. A theoretical motor unit activation was calculated as follows:

$$\% \text{ MUA} = \frac{Pt - ITT}{Pt} \times 100,$$ where ITT represents the interpolated twitch torque.

2.3 EXPERIMENTAL PROTOCOL: Prior to any data collection, the experimental test began with an orientation of the subjects to the purpose and procedures of the study, as well as any discomfort involved with the stimulation. Passive tension, isometric twitches, voluntary contractions (MVC), and 1 sec evoked tetanic contractions (20,50,and 80 Hz) were measured in the R-tibialis anterior muscle at 10 joint angles (15°D through 30°P in 5° intervals). In order to avoid any potentiation effects, evoked twitches were collected at all joint angles first, followed by collection of MVC and evoked tetanic contractions.

The protocol commenced by adjusting the foot-plate to 15°P and securing the subject's leg, as described above. Prior to the collection of any evoked responses, passive tension measurements were made as the torque created about the ankle joint at each joint angle in a random order which was preserved for the remainder of the testing session. Readings were taken only after the subject had relaxed his/her muscle completely. Passive tension data collection began by releasing the foot plate and observing the natural resting position of the ankle joint (0 tension). Passive tension measurements were then recorded at the 10 joint angles in the predetermined order for that subject. However, with each joint angle change the foot plate was set back to the resting position and the system was zeroed in order to avoid any changes in the oscilloscope readings due to the passing of time.

Subsequent to the collection of the passive tension surrounding each joint angle, the foot-plate was then readjusted to 15°P in order to determine the voltage required for maximum torque production, after which isometric twitches were collected at each joint angle. Initially, reevaluation of the voltage required for maximum torque production by an evoked twitch was performed at each joint angle prior to collection of the twitch response. However, since no apparent change was observed in the required voltage for maximal torque production, the procedure for subsequent subjects was to simply evoke twitches at each of the joint angles at the same voltage required for maximal torque production at 15°P. The active torque was calculated by subtracting the passive tension generated from the total twitch torque achieved at the same angle. In cases where the total twitch torque was zero, the active torque was also taken to be zero, regardless of the amount of passive tension, as in these instances the passive tension was in the plantar- as opposed to dorsi-flexion direction.

Upon completion of the evoked single twitch data collection, subjects performed 2 MVCs at the ascribed joint angles with sufficient time (2-3 min) being allotted in between the two contractions to avoid any fatigue effects. As mentioned previously, the maximal voluntary contractions were interpolated to assess the degree of motor unit activation.

The last step in the experimental protocol involved 1 sec tetanic contractions at three frequencies, 20,50, and 80 Hz at each of the joint angles. Once again, the order in which the 3 tetanic frequencies were received was varied to accommodate any systematic effects. For each joint angle, a preserved random order of 20, 50, and 80 Hz tetanic pulses were delivered to the peroneal nerve at one minute intervals. Throughout the tetanic stimulation protocol, subjects were instructed to remain relaxed, despite the ensuing muscle activation, and to restrain from any natural tendencies to resist the working muscle.

Thus, the sequence of events for the 10 joint angles were as follows:

(1) determination of the resting joint angle,

(2) collection of the passive tension surrounding the ankle joint in the prescribed joint angle order,

(3) determination of the voltage at which peak isometric twitch torque is achieved by the dorsiflexors at 15°P,

(4) collection of the resting isometric twitch torque produced by the dorsiflexors at each joint angle

(order as assigned above) by the voltage previously determined to produce peak twitch torque at 15°P,

(5) collection of maximal voluntary contractions (MVCs) at each joint angle, including assessment of the extent of motor unit activation by use of the interpolated twitch procedure (order as assigned above),

(6) collection of evoked tetanic torque (20, 50, and 80 Hz at 1 min intervals) at each of the joint angles (order as assigned above).

2.4 STATISTICAL TREATMENT: A 3-way (age x gender x joint angle) between (age, gender)-within (joint angle) analysis of variance was used to test for significant differences between ages, genders, and joint angles in passive tension, single twitch, and MVC dependent variables. The maximal voluntary contraction which achieved greatest torque was used for statistical analysis. For the 1 sec evoked tetanic pulses, a 4-way (age x gender x joint angle x frequency) mixed analysis of variance was used to determine the level of significance in dependent variables. In both cases, a level of 0.05 was considered statistically significant. A Tukey A post-hoc was employed to examine significant differences between means. Unless otherwise indicated, throughout the text values are stated as means ± standard error of the mean.

CHAPTER 3

RESULTS

3.1 Effect of Age on Resting Joint Angle: All subjects, regardless of gender or age, were able to have their ankle joint comfortably moved from 30°P through to 15°D. The present investigation found the resting joint angle for the ankle dorsiflexors to be similar between elderly and young adults, regardless of gender. On average, the resting position for the ankle joint was approximately 13°P (SE=0.88; range 05°P-21°P).

3.2 Effect of Joint Position on Passive Tension: Although passive tension measurements were made in the present study, several methodological difficulties were encountered which resulted in the passive tension values being inaccurate. For example, one particularly disturbing finding was at the more plantarflexed joint angles the passive torque values were actually greater than the maximum evoked total twitch torques. Due to the design of the leg-holder foot plate apparatus, the pressure exerted by the clamp stabilizing the upper leg (refer to Figure 4), which was set to prevent movement of the lower leg, greatly contributed to the passive torque measurements in the more plantarflexed positions (i.e. positions more plantarflexed than the resting joint angle). In reassessing the passive tension results at the highest plantarflexed angle (30°P), it was later found that by only securing the foot in the 2 velcro straps and eliminating the clamp stabilizing the upper leg, the passive tension torques were reduced to approximately one-half the previous value. In the more dorsiflexed positions, a different problem was encountered which also affected the passive tension recordings, the heal of the foot raised off the foot-plate at extreme dorsiflexion. For these reasons, the passive tension measurements of the present research cannot be used in any statistical analysis. Furthermore, the active tension values which were to be generated by mathematical subtraction of the passive torque from the total peak torque would also be inaccurate, and hence are not reported in this research.

3.3 Effect of Joint Position on Single Twitch Characteristics: The effect of joint position on the time course of the twitch revealed gradually shorter time to peak torques (TPT) and one half relaxation times (1/2 RT) when moving from the extreme range of plantarflexion to dorsiflexion in both age groups. In agreement with previous literature, the measurement of evoked contractile properties revealed significantly slower twitches in the elderly versus young adults at all joint angles, as can be seen from the increased time to peak torque (TPT) and one half relaxation time (1/2 RT) (Table 1).

The peak evoked twitch torque systematically varied across joint angles; a continuous decline was observed from extreme plantarflexion through to extreme dorsiflexion (Figure 5)(Table 1). It can be seen that while males produced significantly larger torque values than females in both age groups, there was no effect of age on dorsiflexor twitch torque at any of the joint angles investigated.

3.4 Effect of Joint Position on Maximal Voluntary Contractions (MVCs): The maximal voluntary contraction (MVC) torque of the ankle dorsiflexors was significantly different across joint angles; maximal torque plateaued at 15°P and progressively declined as the joint angle became more dorsiflexed. There was a main effect of both age and gender for MVC torque, such that young adults generated significantly greater torque than the elderly adults, and males consistently achieved greater torque values than females (Figure 6).

Table 1:

Group means (± standard error of the mean) for time to peak torque (TPT), half-relaxation time (1/2 RT), and total peak torques at the ten joint angles in females and males of different ages.

TABLE I

	TPT (msec)	1/2 RT (msec)	TWITCH TORQUE (Nm)		TPT (msec)	1/2 RT (msec)	TWITCH TORQUE (Nm)
Young Adults (20–40yrs)							
Female				**Male**			
30P	79.3 ± 3.2	85.7 ± 3.3	3.5 ± 0.3	30P	73.8 ± 2.3	76.8 ± 4.3	5.3 ± 0.4
25P	75.4 ± 3.5	81.9 ± 3.2	2.9 ± 0.3	25P	73.4 ± 2.3	72.0 ± 4.9	4.4 ± 0.4
20P	71.9 ± 4.0	70.5 ± 4.8	2.4 ± 0.3	20P	71.9 ± 1.7	65.8 ± 6.0	3.7 ± 0.4
15P	71.6 ± 5.3	68.7 ± 5.1	2.0 ± 0.3	15P	70.2 ± 2.8	57.9 ± 3.9	2.9 ± 0.4
10P	54.6 ± 8.6	55.0 ± 8.4	1.4 ± 0.3	10P	61.7 ± 4.1	53.1 ± 6.1	2.0 ± 0.4
05P	44.6 ± 9.0	40.4 ± 8.6	0.9 ± 0.2	05P	49.6 ± 7.3	44.9 ± 8.4	1.4 ± 0.3
000	27.7 ± 8.7	26.0 ± 8.8	0.5 ± 0.2	000	35.0 ± 7.4	37.4 ± 8.8	0.7 ± 0.2
05D	11.9 ± 6.5	15.0 ± 9.1	0.2 ± 0.1	05D	17.8 ± 6.0	19.5 ± 8.3	0.3 ± 0.1
10D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	10D	6.2 ± 4.7	5.0 ± 4.0	0.2 ± 0.1
15D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	15D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Elderly Adults (60–80yrs)							
Female				**Male**			
30P	90.5 ± 2.7	99.9 ± 6.6	3.5 ± 0.2	30P	92.6 ± 2.5	100.7 ± 3.6	5.6 ± 0.5
25P	88.8 ± 3.6	89.4 ± 5.1	2.9 ± 0.1	25P	90.1 ± 2.2	92.3 ± 3.9	4.8 ± 0.6
20P	85.9 ± 2.5	85.2 ± 4.5	2.4 ± 0.1	20P	81.4 ± 6.1	78.7 ± 6.9	4.0 ± 0.5
15P	81.3 ± 3.9	75.5 ± 5.7	1.9 ± 0.2	15P	77.1 ± 6.1	73.6 ± 6.1	3.4 ± 0.5
10P	72.9 ± 5.0	62.8 ± 6.3	1.5 ± 0.2	10P	73.7 ± 5.8	72.1 ± 8.9	2.8 ± 0.5
05P	60.1 ± 5.3	54.3 ± 6.7	1.0 ± 0.1	05P	55.9 ± 9.3	47.8 ± 8.1	2.0 ± 0.4
000	40.0 ± 8.2	27.4 ± 6.4	0.5 ± 0.1	000	45.3 ± 8.9	39.7 ± 7.8	1.3 ± 0.3
05D	18.0 ± 8.0	12.3 ± 6.2	0.3 ± 0.1	05D	31.4 ± 8.7	22.8 ± 6.8	0.7 ± 0.3
10D	22.6 ± 13.8	9.4 ± 5.1	0.2 ± 0.1	10D	22.6 ± 8.6	13.7 ± 5.4	0.5 ± 0.2
15D	17.9 ± 12.3	8.0 ± 6.0	0.1 ± 0.1	15D	12.4 ± 5.9	9.9 ± 4.7	0.2 ± 0.1

Figure 5:

The effect of joint angle on peak twitch torque in females and males of different ages. Values are means ± standard error of the mean (n=15 in each group).

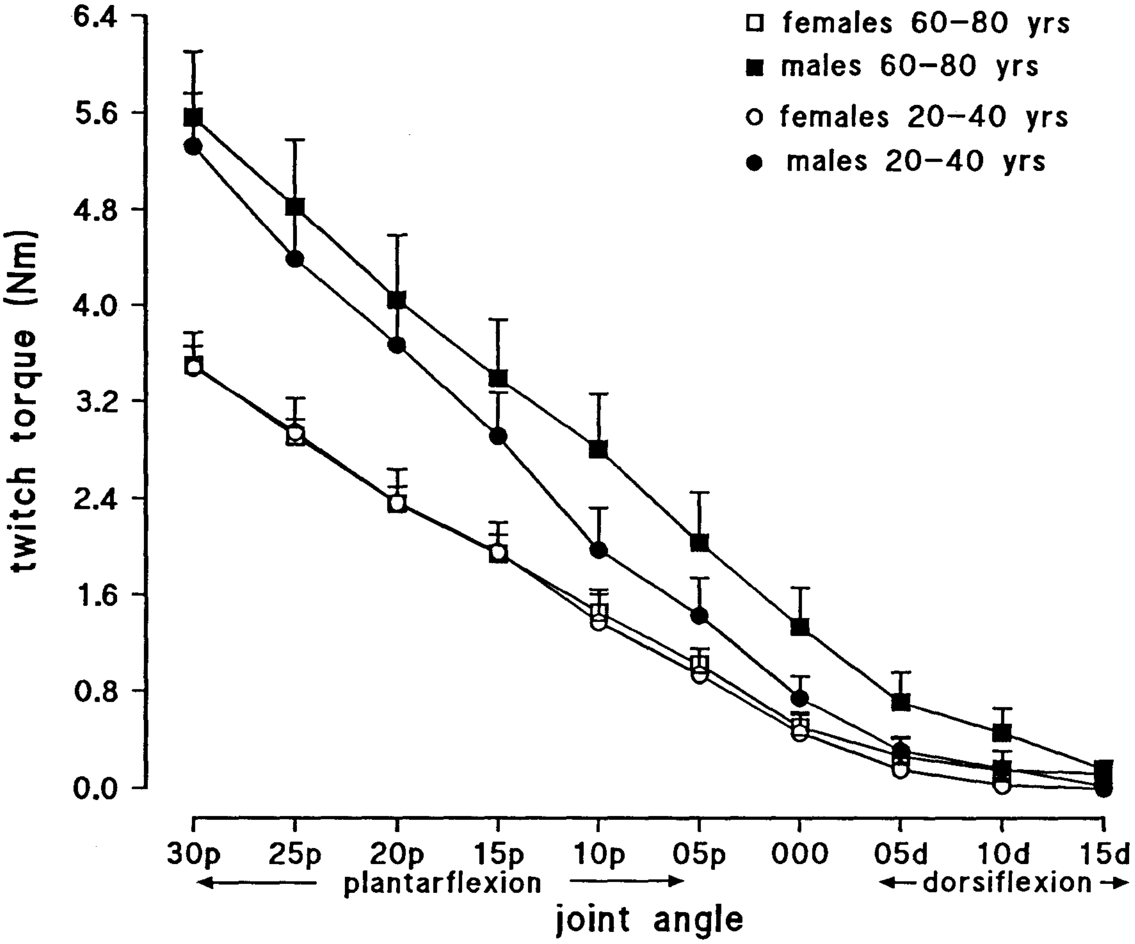
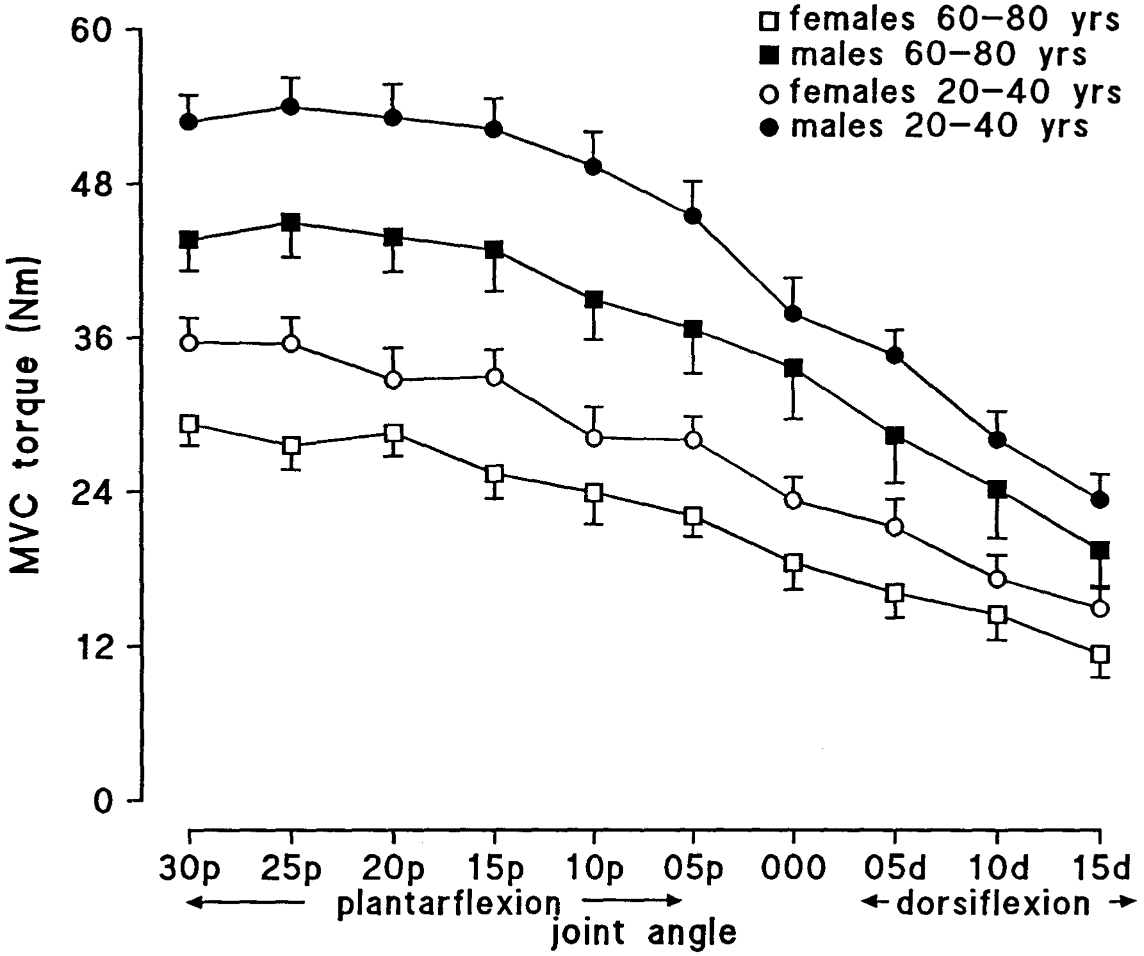

□ females 60−80 yrs
■ males 60−80 yrs
○ females 20−40 yrs
● males 20−40 yrs
twitch torque (Nm)
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
30p
25p
20p
15p
10p
05p
000
05d
10d
15d
plantarflexion
dorsiflexion
joint angle

Figure 6:

The effect of joint angle on the torque produced during the brief maximal voluntary contractions (MVCs) in females and males of different ages. Values are means ± standard error of the mean (n=15 in each group).

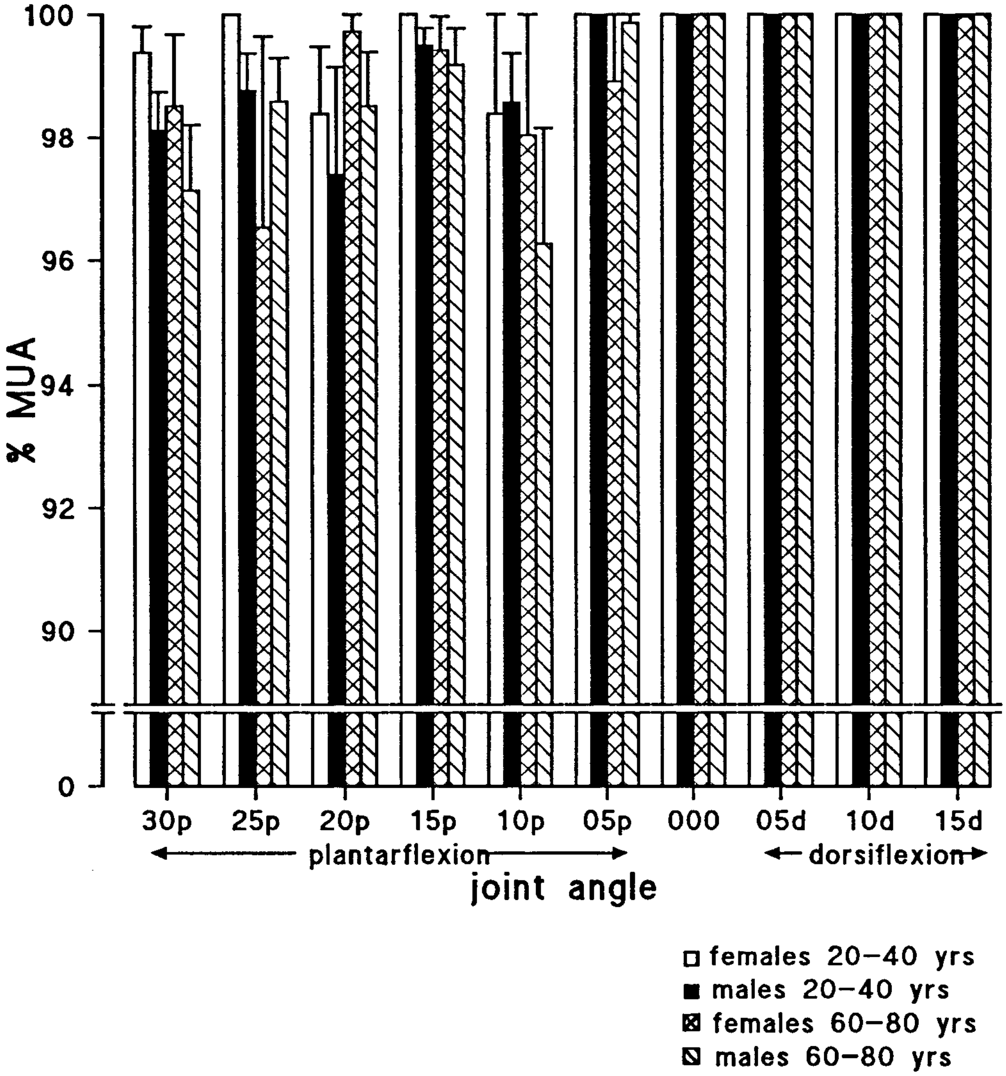

☐ females 60–80 yrs
■ males 60–80 yrs
○ females 20–40 yrs
● males 20–40 yrs
60
48
36
24
12
0
MVC torque (Nm)
30p
25p
20p
15p
10p
05p
000
05d
10d
15d
plantarflexion
dorsiflexion
joint angle

3.4.1 Effect of Joint Position on Percent Motor Unit Activation (% MUA): Joint angle had a significant effect on the degree of motor unit activation across all subjects: full activation was more frequently attained at the dorsiflexed angles, as illustrated in Figure 7. However, even at the more difficult joint angles for obtaining full activation, subjects achieved no less than 96 % MUA. Among the genders and different age groups however, there was no effect for joint angle on % MUA.

3.5 Effect of Joint Position on Tetanic Torque at Different Frequencies: There was a main effect of joint angle on the torque produced by the 1 sec tetanic trains. As was the case with the single twitch and MVC torques, the 1 sec peak tetanic torques declined from 30°P through to 15°D for all subjects. Also, in keeping with the MVC torque results, elderly adults obtained significantly lower tetanic torques than young adults and males greater torques than females. There was also a significant interaction between gender and age in evaluating the effect of joint angle on tetanic torque production. Compared to their younger counterparts, the older males showed a significantly greater reduction in tetanic torque than the older females at the plantarflexed joint angles (24% VS 9%

Figure 7:

The effect of joint angle on the percent motor unit activation (% MUA) achieved by females and males of different ages. Values are means ± standard error of the mean (n=15 in each group).


100
98
96
94
92
90
0
% MUA
30p
25p
20p
15p
10p
05p
000
05d
10d
15d
plantarflexion
dorsiflexion
joint angle
□ females 20–40 yrs
■ males 20–40 yrs
⊠ females 60–80 yrs
▧ males 60–80 yrs

reduction respectively in 80 Hz torque at 30°P), while the opposite was true for the dorsiflexed angles (23% VS 54% reduction respectively in 80 Hz torque at 15°D). Therefore aging effects were similar across joint angles in males (approximately 23% reduction in torque), however, for females the effects became progressively more pronounced towards extreme dorsiflexion (Figure 8).

As expected, there was also a significant effect of the frequency of tetanic stimulation on torque production of tibialis anterior. During the 20 Hz trial, the evoked torque was significantly lower as compared to the 50 and/or 80 Hz trial (Figure 9). This finding was typical of all subjects, however, the reduction was considerably reduced in extreme dorsiflexion (77% VS 28% for 30°P and 15°D respectively).

3.5.1 Effect of Joint Position on the Rise of Tetanic Torque: The duration of time for which 10-90% of the torque is developed (rise) during the 1 sec tetanic trains was the same for young and elderly adults with no significant difference between males and females. Conversely, time between 10-90% torque development during the different tetanic trains was significantly affected by joint angle, as

Figure 8:

The effect of joint angle on the normalized torque produced by the 80 Hz train in males and females aged 60-80 years.

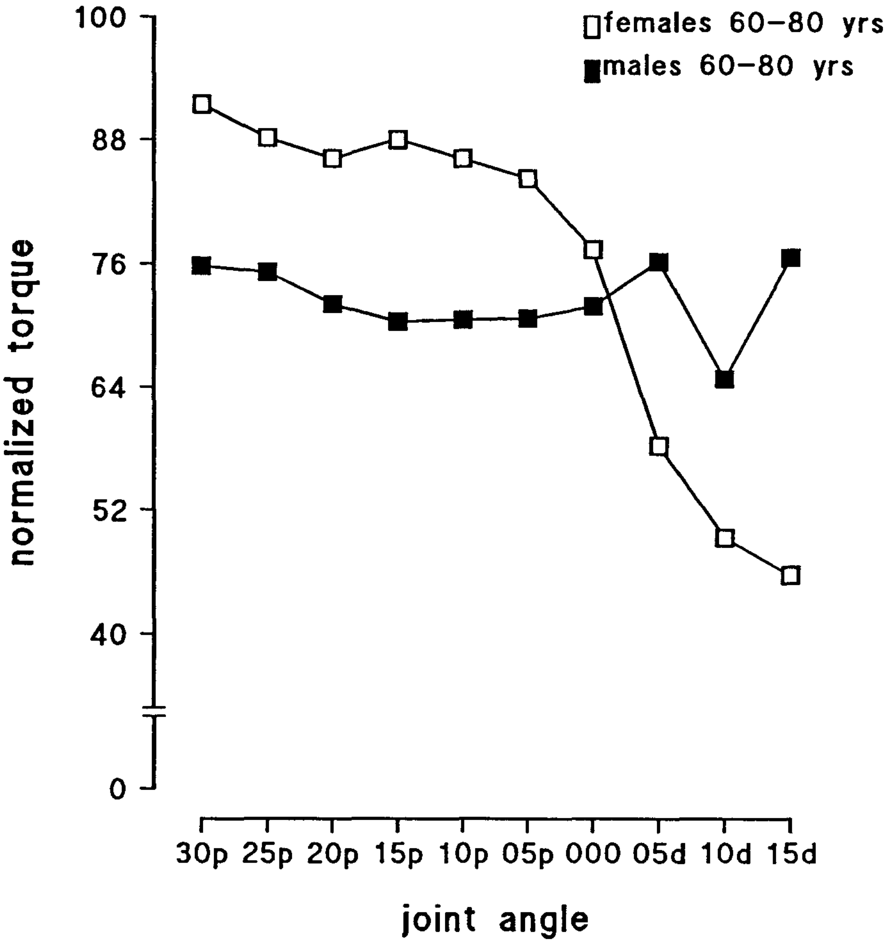
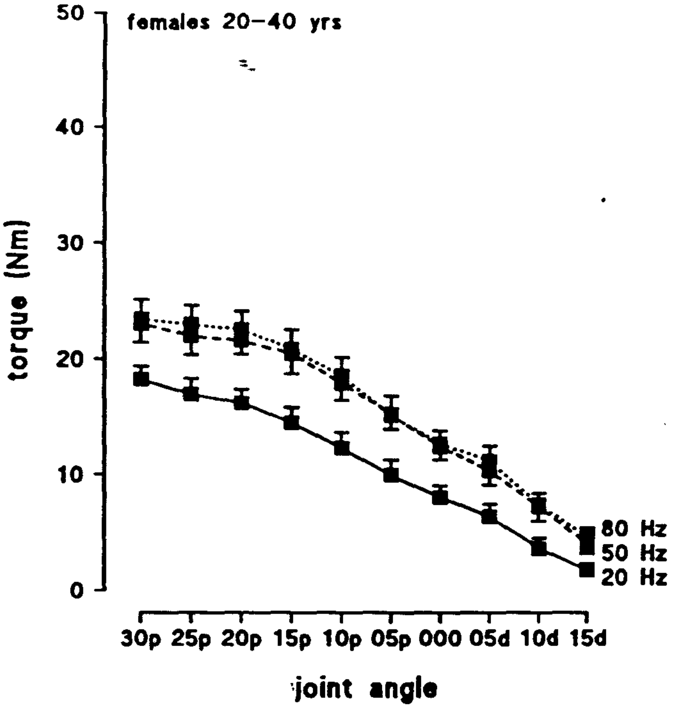
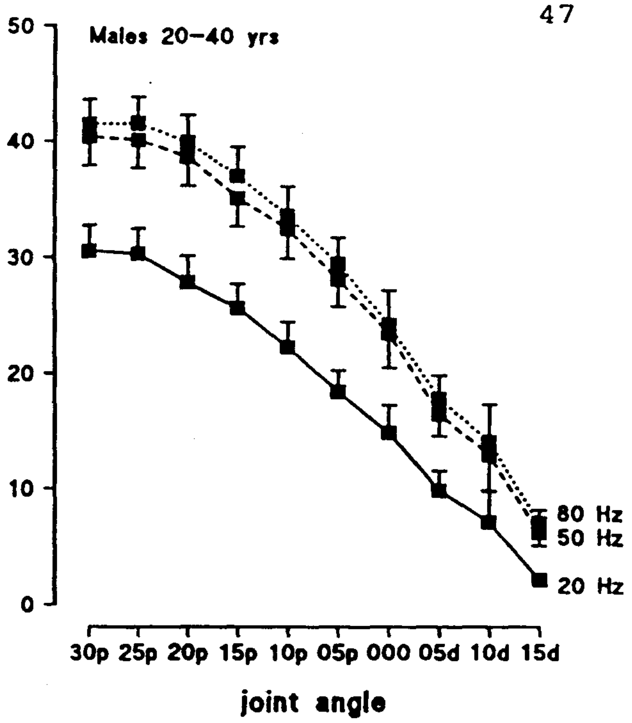
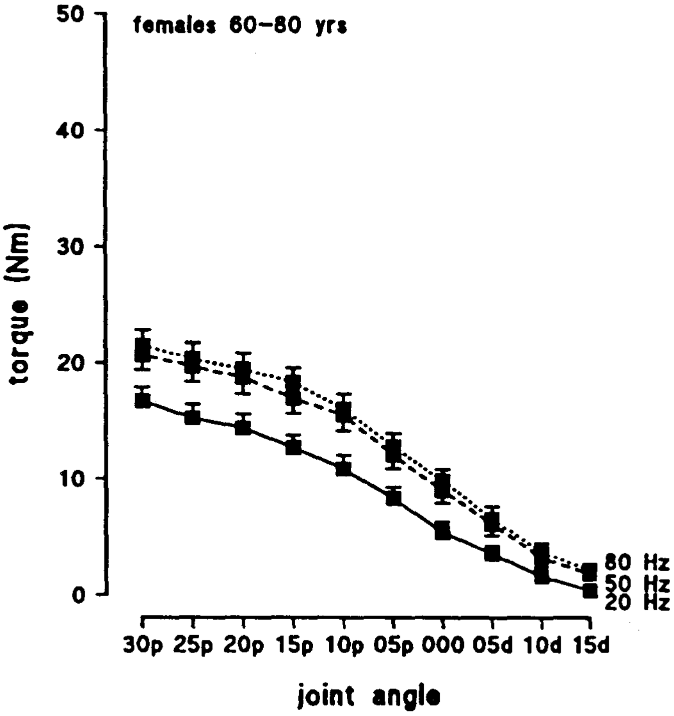

□females 60–80 yrs
■males 60–80 yrs
100
88
76
64
52
40
0
normalized torque
30p
25p
20p
15p
10p
05p
000
05d
10d
15d
joint angle

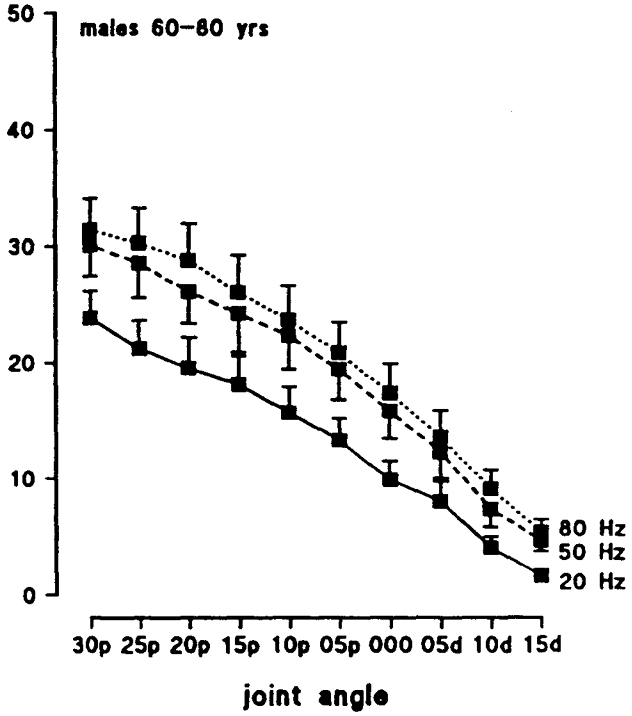
Figure 9:

The effect of joint angle on maximal tetanic torques produced by 20, 50, and 80 Hz trains in females and males of different ages. Values are group means ± standard error of the mean (n=15 in each group).


females 20-40 yrs
torque (Nm)
0
10
20
30
40
50
30p 25p 20p 15p 10p 05p 000 05d 10d 15d
joint angle
80 Hz
50 Hz
20 Hz


Males 20-40 yrs
0
10
20
30
40
50
30p 25p 20p 15p 10p 05p 000 05d 10d 15d
joint angle
80 Hz
50 Hz
20 Hz


females 60-80 yrs
torque (Nm)
0
10
20
30
40
50
30p 25p 20p 15p 10p 05p 000 05d 10d 15d
joint angle
80 Hz
50 Hz
20 Hz


males 60-80 yrs
0
10
20
30
40
50
30p 25p 20p 15p 10p 05p 000 05d 10d 15d
joint angle
80 Hz
50 Hz
20 Hz

illustrated in Figure 10. At the plantarflexed angles, the 20 Hz trial produced significantly slower duration of torque development than the 50 or 80 Hz trials, whereas the same was not true at the dorsiflexed angles; 80 Hz trains produced the slowest rate of torque development.

3.5.2 Effect of Joint Position on the Twitch/Tetanus and Twitch/MVC Ratios: Evaluation of the twitch:tetanus ratio was performed at 30°P since maximum twitch torque occurred at 30°P. The twitch/tetanus ratio was greater in elderly, as compared to young adults at 30°P, regardless of gender. As expected, stimulus frequency significantly influenced the twitch/tetanus ratio; the greater the frequency of stimulation, the smaller the twitch/tetanus ratio (Figure 11). The twitch/tetanus ratios for low frequency stimulation (20 Hz) were significantly larger when compared to the medium (50 Hz) or high (80 Hz) frequency, however, there was no apparent difference in the ratios between the 50 and 80 Hz stimulation frequencies.

Figure 10:

The effect of joint angle on the rise time in tetanic torque at 3 frequencies (20, 50, & 80 Hz) in females and males of different ages. Values are means, collapsed across age and gender, ± standard error of the mean (n=60 at each frequency).

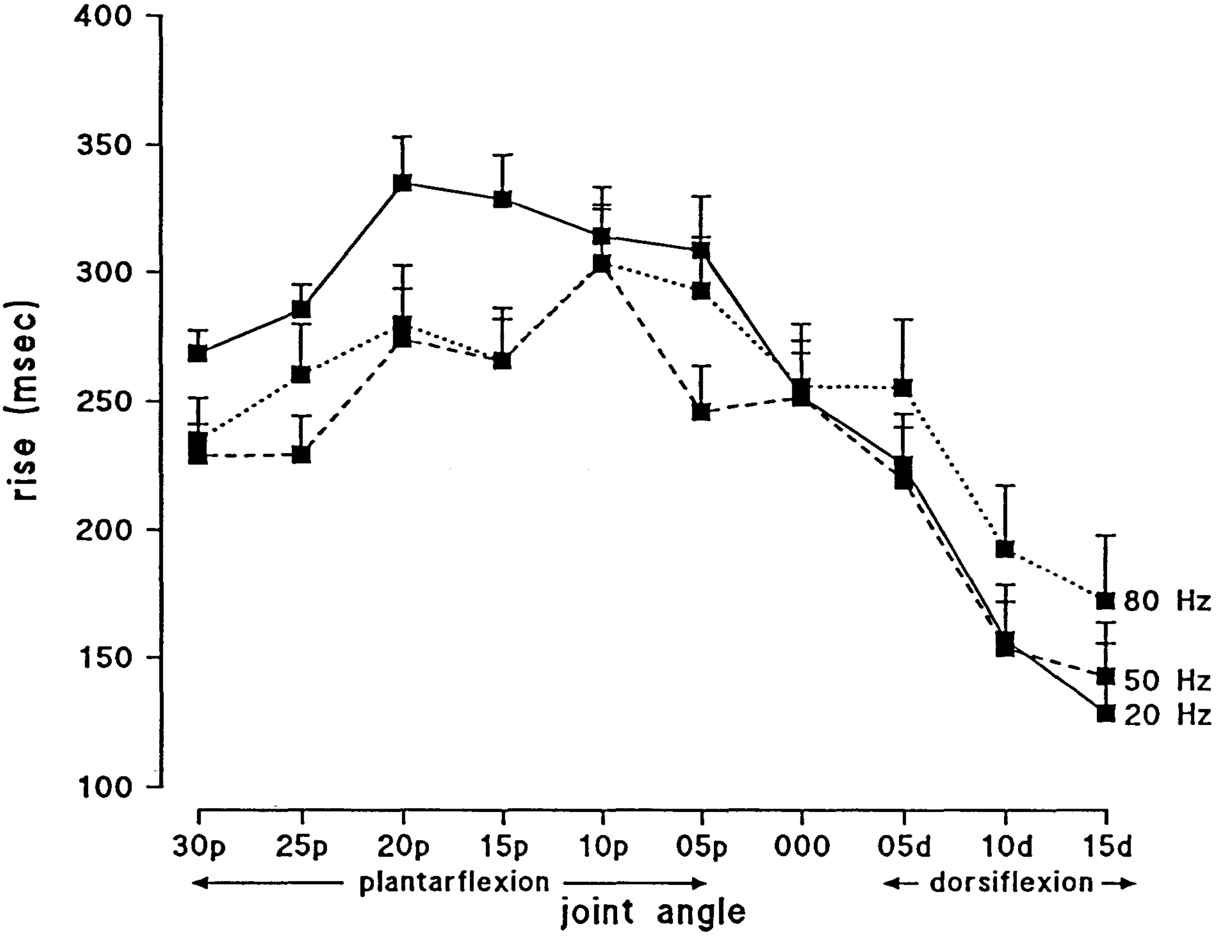
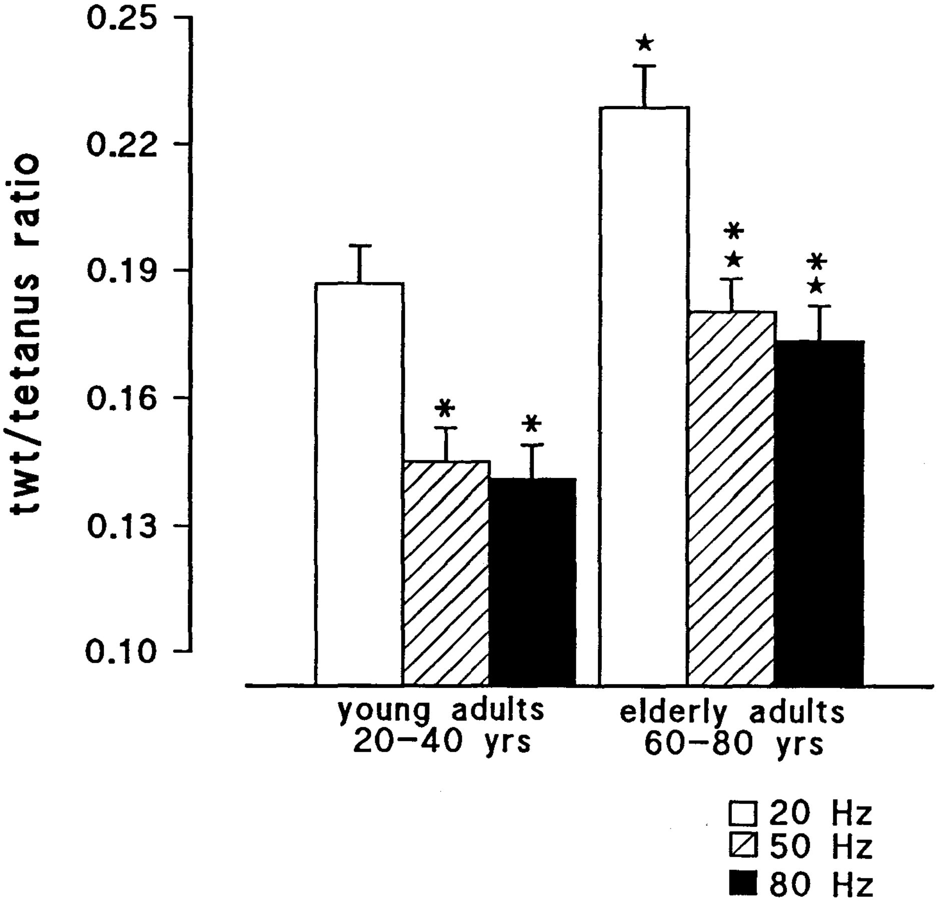

400
350
300
250
200
150
100
rise (msec)
30p
25p
20p
15p
10p
05p
000
05d
10d
15d
plantarflexion
dorsiflexion
joint angle
80 Hz
50 Hz
20 Hz

Figure 11:

The effect of age on the twitch/tetanus at 30°P. Values are means ± standard error of the mean (n=30 at each frequency).

* indicates 80 or 50 Hz is significantly ($p<0.05$) different from 20 Hz frequency.

✱ indicates elderly are significantly ($p<0.05$) different from young adults.


0.25
0.22
0.19
0.16
0.13
0.10
twt/tetanus ratio
young adults 20-40 yrs
elderly adults 60-80 yrs
*
*
*
*
*
*
*
*
□ 20 Hz
▨ 50 Hz
■ 80 Hz

CHAPTER 4

DISCUSSION

Few studies have considered the possibility of the length-tension relationship being affected by the natural skeletal muscle changes (i.e. contractile, morphological etc...) which accompany the aging process. The aim of the current investigation was to provide a better understanding of muscle function in elderly adults by considering the influence of muscle length on tension development in an aged population. The influence of joint position on the contractile properties of aged skeletal muscle was evaluated under the following conditions: isometric single twitches, voluntary contractions, and 20, 50, and 80 Hz stimulation of the ankle dorsiflexors.

4.1 <u>The Influence of Joint Position on Single Twitch Characteristics</u>: In the present study significant differences in the contractile properties of the tibialis anterior muscle (TA) were observed when the ankle joint was positioned at different joint angles; the 1/2 RT and TPT were shorter at the more dorsiflexed as compared to the plantarflexed angles, as well as the twitch torques being greatly reduced at extreme dorsiflexion. These differences were expected in view of the appreciably shorter muscle lengths at the dorsiflexed positions. At short muscle lengths (i.e. shorter than resting length) there is a considerable amount of added slack to be taken up before the active force generating mechanisms of muscle can be initiated. This slack, largely manifested in the SEC of the muscle, therefore demands more time to be absorbed at short muscle lengths, as compared to muscle lengths greater than resting length. Thus, the greater time demanded to take up the SEC results in less time for the generation of force, as depicted by the reduced peak torque of the resulting twitch. Hence, the resulting twitch is diminished not only in peak torque obtained, but also in its time factors, TPT and 1/2 RT.

Similar changes in the contraction and half-relaxation times at extreme dorsiflexion have been reported elsewhere (Marsh et al., 1981). In young male subjects (19-37 yrs) Marsh and colleagues found the mean contraction and half-relaxation times of maximal isometric twitches of TA were significantly reduced at full dorsiflexion compared to full plantarflexion. In as much as the decline in TPT and 1/2 RT with increased dorsiflexion in the current report supports the findings of Marsh and colleagues, there still remains sizable differences in the abruptness of the decline between the studies. At the extreme dorsiflexed position (15°D) the present investigation found a total loss of the twitch, while

Marsh and colleagues only report a 15% and 25% decline in TPT and 1/2 RT respectively, at extreme dorsiflexion. Overall, the present study supports the notion of reduced contractile speed with increasing dorsiflexion, however, the findings herein suggest that progressive shortening of the dorsiflexor muscles results in an extreme loss of contractile ability for the TA.

Despite the dissimilar reports in the human literature, the present study indirectly supports some of the existing animal research (Blinks et al., 1978; Stevenson & Williams, 1982). As discussed in Section 1.4, the amount of time required for tension development reflects either the process of calcium activation of the contractile filaments and/or the effectiveness of the tension-generating mechanisms. As was first suggested by Close, (1972), and since supported by others (Blinks et al., 1978; Stevenson & Williams, 1982), fibre length does influence the release and/or binding of the activator, calcium. Moreover, Taylor & Rudel, (1970) using frog muscle fibres, claim that incomplete activation of fibres stimulated at short muscle lengths is not due to contractile element dysfunction. Rather, they suggest T-tubular collapse and increased intracellular pressure may result in impaired transmission of the T-tubular action potential. Therefore, despite the fact that the present study did not measure calcium levels, the observed decrease in active state duration of the twitch at short muscle lengths offers support to those who have demonstrated an interdependence between fibre length and the release and/or binding of calcium.

The demonstration in the present study of an increased total twitch torque in all subjects as the TA muscle was lengthened, with peak torque in males aged 20-40 yrs (~5.3 ± .04 Nm) being recorded at an angle of 30°P, is comparable to the values obtained by Marsh et al., 1981, where males aged 19-37 yrs achieved maximum torque (~4.0 Nm) at 30°P. Since the twitch torque had still increased exponentially between 20 and 30°P, it is possible that an increase in twitch torque may even occur at joint angles beyond 30°P.

4.2 <u>The Effect of Age on Single Twitch Characteristics</u>: The slower contraction time of the ankle dorsiflexors in the elderly as compared to young adults in the current study is in agreement with previous findings of increased TPT and 1/2 RT for the TA of adults aged 60-100 yrs (Vandervoort & McComas, 1986; Cupido et al., 1992). Furthermore, increases in TPT and 1/2 RT of elderly muscle have also been demonstrated for the triceps surae (Davies & White, 1983; McDonagh et al., 1984; Klein et al., 1988), elbow flexors (McDonagh et al., 1984), first dorsal interosseous (Newton et al., 1988), and plantarflexors (Vandervoort & McComas, 1986). This age-related slowing of the contractile properties of elderly skeletal muscle could be speculated to involve the same mechanisms suggested to account for the muscle atrophy which has been shown to occur with age. For example, a reduction in Type II fibres (Lexell et al., 1983; Aniansson, 1986), with a subsequent increase in the proportion of Type I fibres (Larson 1978; Sjostrom et al., 1980; Lexell et al., 1983; Poggi et al., 1987), could possibly result in retarding the muscle's contractile capabilities. The same argument would be true for a type II to type I conversion, deinnervation/reinnervation process (Cavanagh, 1964; Campbell et al., 1973; Sabin, 1982), and decreased percentage of functioning motor units (Sica & McComas, 1971; Campbell et al., 1973; McComas, 1977).

Despite the TA muscle of elderly adults in the present study exhibiting slower contractile tendencies, there was no effect of age on the peak total twitch torque. Elderly individuals produced similar torque values at all joint angles compared to young adults. Similar torque values between elderly and young adults is in agreement with previous research from our lab where no observable changes in twitch torque were apparent between adults of different ages. Hicks et al., 1991, reported peak twitch torque values of 3.2 and 3.7 Nm at 20°P for the ankle dorsiflexors of young and elderly adults respectively, closely paralleling the 3.1 and 3.2 Nm respectively, reported in the present research. Thus, it appears that any age-related changes in muscle morphology, contractile properties, etc. does not appear to affect the torque-angle relationship of the ankle dorsiflexors. However, similar twitch torques between elderly and young adults is not a unanimous finding. Vandervoort & McComas, 1986, and more recent research from our lab (Cupido et al., 1992) have documented decreases and increases respectively, in the twitch torque of elderly TA muscle.

Under identical stimulation procedures to the present investigation, Cupido and co-workers reported peak twitch torques of 4.6 and 3.2 Nm at 20°P for the ankle dorsiflexors of elderly and young adults, respectively. The current research reports similar values for young adults (3.1 ±.35 Nm) however, the peak twitch torque of elderly dorsiflexors is sizably reduced (3.2 ±.3 Nm) compared to the work of Cupido and associates. These authors suggest that their unique finding of an increase in elderly twitch torque may be attributed to an alteration in the length-tension relationship with age. However, since the present research does not support the possibility of an altered length-tension relationship in the ankle dorsiflexors of elderly adults, the greater twitch torque observed by Cupido & Co-workers could not be due to the TA of elderly subjects being at a more optimal length for the uptake of the series elastic component within the muscle or the effects of increased muscle stiffness and connective tissue. Therefore, we can only speculate that this disparity in elderly twitch torque values between the present research and that of Cupido & Co-workers, 1990, may reside in differences among the subject populations. The elderly group of Cupido and co-workers consisted of 7 males and 2 females with a mean age of 67.7 ±1.2 years. While the mean age of the present study's elderly population is comparable (68.8 yrs), the distribution of the male and female genders is dissimilar. The present research fairly represents both genders in its elderly group (n=15♂, n=15♀), compared to the already mentioned 7:2, male:female ratio of Cupido and co-workers' elderly population. It was previously stated that gender significantly influenced the amount of torque generated by the ankle dorsiflexors; with males consistently producing higher twitch torques than females. In keeping with these findings, it seems possible that the elevated elderly torque values of Cupido and co-workers research may reflect their biased representation of the male population amongst the elderly group.

In contrast to the findings of Cupido and coworkers, Vandervoort and McComas (1986) found reduced twitch torque values in elderly (2.6, 1.7 Nm, ♂ & ♀ respectively), as compared to young adults (4.2, 2.7 Nm, ♂ & ♀ respectively) at 30°P. Once again, the twitch torque values for young adults are similar to those reported in the current study, however, the values reported for elderly individuals are sizably reduced compared to those of the present investigation. Unlike Cupido and co-workers, Vandervoort and McComas's population was not as biased towards a particular gender. Rather, their elderly population was well represented, both in relation to gender, and to the size of their young adult population; they cited twenty-three 60-69 yr-olds (13♂,10♀), twenty-five 70-79 yr-olds (16♂,9♀), and twenty-one 80-100 yr-olds (13♂,8♀). Therefore, there must be an alternate explanation for the incongruent findings between the reported twitch torque results in the present research and those of Vandervoort & McComas. These discordant results may be accounted for by the fact that the conclusions of Vandervoort and McComas, 1986, seem to have been made primarily by comparison of their 20-32 yr-old and 80-100 yr-old groups. Since the oldest individual in the current study was 78 years, and the elderly group as a whole had a mean of 68.8 yrs, it is conceivable that the aging process is further advanced in individuals 80 years and older. The peak torque values for the 20-32 yr-olds and 80-100 yr-olds from Vandervoort and McComas's research were 3.445 and 2.26 Nm, respectively. However, regrouping of their 60-69 yr-olds and 70-79 yr-olds into one 60-79 yr-old group results in an average peak twitch torque of 2.91 Nm, which is not much different from the 3.2 Nm reported in the present study. In fact, the data from

Vandervoort and McComas' subject population is within one standard deviation of the mean from the current study, with a slightly stronger young adult group (3.1 vs 3.4 Nm, respectively) and slightly weaker old adult group (3.2 vs 2.9 Nm, respectively). Therefore, while the present study finds no support for reduced twitch torque values in elderly individuals 60-80 yrs ($\bar{x}$=68.8yrs), further aging (i.e. 80+ yrs) may result in reduced evoked strength characteristics.

4.3 <u>The Influence of Joint Position on Maximal Voluntary Contractions</u>: In the present study, the influence of joint position greatly affected the generation of maximal voluntary contraction torque. All subjects were able to achieve much greater torque values in the more plantarflexed angles as compared to the dorsiflexed angles when asked to perform an MVC. In addition, the results of the present study indicate the influence of tendon elasticity by a marked levelling of the MVC torque at the more plantarflexed joint angles (15-20°P). Tendon elasticity reflects force utilized in taking up of the series elastic component (SEC) residing in the long TA tendon. Upon maximal tendon stretch, the SEC is fully taut and therefore limits the amount of cross-bridge interaction between the actin and myosin filaments. This effect results in a marked flattening of the length-tension curve upon extreme stretching of the TA tendon. An additional argument for the lack of an optimal angle for MVC torque produced, may be that the long extensors of the toes may have rather different length-tension curves as compared to TA (i.e. with an optimal length greater than that of TA)(Marsh et al., 1981).

As predicted, there was an effect of aging on MVC torque. Elderly subjects produced much reduced torque values at all joint angles as compared to the young adults. Thus, while twitch torque was unaffected by age, maximal voluntary torque is influenced by the aging process. These apparently contradictory results might be explained by the difference in contractile properties in elderly versus young muscle; elderly muscle is slower to contract. The prolonged contraction time of elderly muscle has significant implications when analyzing the amount of torque generated during evoked single twitches as compared to voluntary contractions. As summarized in Section 1.3, each cross-bridge contributes a fixed amount of tension to the total, thus the greater the number of cross-bridges formed the greater the amount of tension produced. Additionally, increased cross-bridge cycling also plays a significant role in tension generation. The turnover between the formation and disengagement of cross-bridges can increase tension production if the duration for which cycling occurs increases. Thus, the increased duration of evoked twitches in elderly TA muscle may allow more time for cross-bridge cycling, thereby permitting evoked torque values to approach that of young adults. However, under maximum voluntary efforts, the dorsiflexors of elderly individuals were unable to generate torque values comparable to the young adults, which may be due to the muscle fibre atrophy and/or fibre type conversions that is thought to accompany the aging process. The possibility of the lower MVC torques in the elderly being due to incomplete muscle activation is unlikely, as the results from the interpolated twitch data revealed at least 96% motor unit activation across all joint angles, with no significant age effect apparent.

4.4 The Influence of Joint Position on Tetanic Torque at Different Frequencies: The present study also evaluated the effect of joint angle on tetanic torque at different frequencies. In agreement with the findings of Marsh et al., 1981, the present study found that joint position directly influenced the force-frequency curve. For a given joint angle, the force-frequency curve is typically characterized as torque increasing rapidly in the low-frequency range and more slowly as higher frequencies are employed (Marsh et al., 1981). Upon manipulation of dorsiflexor muscle length in the present research, the force-frequency curve was altered; with increased stretching beyond resting length (5°P) the relationship became more steep in the low-medium frequency range, whereas the force-frequency curve developed more slowly upon shortening (refer to Appendix M). However, while these authors found maximal torque for TA was obtained in the resting position (05-10°P) for stimulus frequencies above 30 Hz, our findings suggest that maximal torque is achieved at 30°P, regardless of stimulus frequency. This dissimilar finding between the present research and that of Marsh and colleagues may be attributed to methodological differences. The tetanic stimulation results in the current study are based on dorsiflexor activation via supramaximal stimulation of the peroneal nerve. In contrast, Marsh and colleagues employed direct motor point stimulation of the tibialis anterior muscle by the cathodal electrode being applied directly over the tibialis anterior muscle. Therefore, the results of Marsh et al., 1981, were not influenced by other muscles which are coinnervated by the peroneal nerve; extensor digitorum longus, peroneus tertius, brevis, and longus. Under the present study's methodology, the influence of some of the plantarflexor muscles (peroneus brevis & peroneus longus) cannot be avoided. Therefore, the undefined maximum joint angle for tetanic frequencies greater than 30 Hz in the current report may reflect the possibility that with increased plantarflexion the reduced influence of the plantarflexor muscles contribution is greater than the natural decrease in dorsiflexor torque. An alternative possibility, as previously mentioned, may be that the action of the other dorsiflexor muscles activated by peroneal nerve stimulation have a different length-tension relationship than the TA.

It was apparent in this research that aging does affect the amount of torque produced during a 1-sec tetanic burst, regardless of the frequency of stimulation. An unusual and perhaps surprising finding was that the magnitude of the aging effect was more pronounced in the dorsiflexed positions and less pronounced in the plantarflexed positions for females despite a uniform magnitude across all joint angles for males. This finding may be explained by the fact that females possess a more elastic musculature. Therefore, at short muscle lengths more time would be required to take up the elasticity of female muscle before actual tension could be generated. The greater energy and time expended to take up this elasticity, may leave less time available, as compared to males, for active torque production.

In comparing the torques achieved by the 80 Hz stimulation and maximal voluntary contractions several notable observations became apparent. Firstly, the present study found that the maximum torque developed by the dorsiflexors during the 80 Hz stimulation was on average 72.5% of MVC dorsiflexor torque. This is almost 2-fold the value (42%) reported by Marsh et al., 1981 for the percentage of torque generated during a 100 Hz tetanus compared to the torque generated by the ankle dorsiflexors during maximum voluntary effort. In view of the different methods of stimulation employed in the two studies (peroneal nerve VS percutaneous stimulation over TA motor point), these apparently discrepant results can be easily explained by the greater contribution of the other dorsiflexor muscles to torque production with peroneal nerve versus motor point stimulation. The fact that the 80 Hz stimulation in the present study was not able to generate torque equal to that of the MVC likely reflects the antagonistic effects of the peroneus muscles which act to plantarflex, rather than dorsiflex the foot.

In addition, the present research found no differences in the rate of rise of tetanic torque between elderly and young adults regardless of frequency, thereby suggesting that the elastic properties of elderly dorsiflexor muscles are similar to young adults.

Not surprisingly, the current study found an elevated twitch/tetanus ratio at 30°P in elderly adults. Since the present investigation revealed similar twitch torques and rate of rise of tetanic torques between elderly and young adults, there is really no evidence for a reduction in elastic properties in elderly versus young dorsiflexor muscle. As explained on page 58, the increased contraction time of the ankle dorsiflexors in elderly individuals probably contributes to the increased twitch torque, and hence, elevated twitch/tetanus ratio observed in this population as compared to young adults. The observation of an increased twitch/tetanus ratio in elderly adults in the current study is in agreement with previous literature (Botelho et al., 1956). However, Botelho and Co-workers attributed their results to an increased stiffness or rigidity of the non-muscular structures of elderly women between 45-61 years of age.

4.5 Summary: In summary, the results of the present research offers considerable insight into the contractile characteristics of elderly muscle.

1. As previously demonstrated in existing literature, the time course of the twitch declines with increasing dorsiflexion, as evidenced by shorter TPT and 1/2 RT times, and the contractile capabilities of elderly adults are substantially slower, as compared to young adults.

2. Peak total twitch torque occurs at the extreme of plantarflexion (30°P) in both elderly and young adults.

3. Elderly individuals produced similar torque values at all joint angles compared to young adults.

4. In performing maximal voluntary contractions, all subjects, regardless of age, were stronger at the more plantarflexed compared to the dorsiflexed angles. Furthermore, the relationship between joint angle and MVC torque was similar between elderly and young adults.

5. MVC torque was found to be influenced by the aging process. Elderly subjects demonstrated much reduced torque values compared to young adults at all joint angles.

6. In the evaluation of joint position on tetanic torque of different frequencies, stretching of the ankle dorsiflexors beyond resting length resulted in an increased steepness of the force-frequency curve, in contrast to a more slowly developing curve upon shortening.

7. Elderly adults produced significantly less torque at all joint angles compared to young adults.

8. There was no difference in the rate at which the rise in tetanic torque was developed at all joint angles between elderly and young adults.

9. Finally, the twitch/tetanus ratio was greater in elderly, as compared to young adults, at 30°P. Combined with the similar total twitch torque and rate of rise of tetanic torque results in elderly and young adults, the twitch/tetanus results herein ultimately indicate that the elastic properties of elderly ankle dorsiflexors are similar to those of young adults.

Overall, the present study demonstrates that the optimal length at which maximal force of ankle dorsiflexors is developed is similar between elderly and young adults, independent of the mode of contraction. Therefore, despite the age-related changes that occur in skeletal muscle morphology, contractile properties, influences of tendon length, etc..., the present research suggests that the length-tension relationship, as estimated by joint angle, for the ankle dorsiflexors is unaffected by the aging process.

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Appendix A

Table A1. Individual Data for Passive Tension Measurements at Joint Angles of 30°P-15°D.

			PASSIVE TORQUE (Nm)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	4.98	3.49	1.95	0.61	-1.37	-2.42	-3.22	-5.13	-6.84	-9.64
2	F	71	5.98	4.35	0.02	-2.61	-7.57	-7.89	-10.33	-11.89	-11.82	-11.95
3	F	68	13.16	7.40	4.03	1.34	-0.66	-3.74	-3.74	-3.37	-4.13	-6.01
4	F	67	4.98	2.69	1.51	0.63	-0.29	-1.98	-3.13	-3.22	-5.15	-5.98
5	F	72	3.49	1.25	2.44	-0.05	-0.51	-2.00	-2.49	-5.13	-4.88	-6.98
6	F	62	8.03	1.95	3.52	1.93	1.15	-0.90	-1.66	-3.32	-4.64	-7.01
7	F	72	5.27	3.34	1.17	0.00	-1.83	-3.00	-5.57	-8.25	-11.08	-15.38
8	F	67	5.40	3.25	1.71	0.68	-1.10	-2.34	-3.61	-3.69	-6.03	-8.30
9	F	68	3.56	2.10	1.12	-0.20	-1.44	-2.78	-4.64	-6.03	-5.74	-9.74
10	F	65	5.93	4.44	2.59	1.27	0.00	-2.03	-2.78	-3.86	-6.32	-8.23
11	F	73	13.92	8.06	5.91	3.64	1.83	-0.34	-2.34	-3.25	-5.15	-8.69
12	F	62	6.54	3.86	2.47	1.15	-0.22	-1.88	-2.86	-5.32	-5.66	-9.25
13	F	72	6.71	5.27	3.27	2.25	0.00	-2.25	-2.91	-3.61	-4.25	-7.74
14	F	70	3.74	3.20	2.12	0.20	-1.27	-2.64	-5.10	-5.66	-8.50	-10.64
15	F	70	3.64	2.47	0.59	-1.49	-2.66	-4.74	-6.47	-9.18	-12.77	-16.16
16	M	65	2.81	1.64	0.00	-0.95	-3.20	-5.08	-6.23	-9.71	-15.41	-22.63
17	M	62	2.25	-0.95	3.17	-1.00	0.90	-2.49	-5.00	-6.69	-5.98	-12.13
18	M	69	6.62	4.39	2.43	1.78	-0.90	-7.28	-5.18	-7.20	-7.35	-12.45
19	M	68	10.52	6.64	5.96	2.34	0.00	-1.76	-4.32	-4.79	-6.62	-9.89
20	M	78	4.30	3.64	1.25	0.68	-0.78	-2.29	-4.30	-5.59	-9.18	-11.13
21	M	73	3.64	2.69	1.78	0.78	-0.76	-1.34	-2.59	-4.71	-5.25	-6.96
22	M	62	3.56	2.12	1.56	0.27	-1.22	-2.29	-3.42	-5.18	-5.25	-10.86
23	M	64	5.47	3.91	2.00	0.00	-0.68	-4.64	-8.03	-12.11	-15.33	-22.09
24	M	70	8.86	5.93	3.66	2.05	-0.22	-2.08	-4.25	-6.57	-8.96	-13.31
25	M	70	5.79	3.52	2.22	1.34	0.00	-1.22	-2.56	-4.59	-6.45	-9.55
26	M	73	6.35	4.49	2.51	1.12	-0.07	-2.25	-4.37	-8.33	-10.74	-15.89
27	M	72	6.05	4.35	2.27	1.17	0.00	-1.93	-3.93	-5.37	-7.45	-10.35
28	M	71	4.42	2.56	-0.29	1.37	-2.10	-4.25	-5.35	-9.52	-13.40	-22.68
29	M	64	3.34	2.22	1.17	-0.46	-1.86	-3.71	-5.64	-8.35	-12.11	-17.65
30	M	68	2.95	1.71	1.68	-0.83	-2.32	-4.10	-6.25	-9.38	-12.87	-18.19
31	F	25	7.71	4.27	3.00	1.93	-0.37	-2.32	-4.44	-5.13	-8.13	-12.72
32	F	35	5.98	4.39	2.66	1.05	-0.56	-2.22	-3.76	-6.08	-6.98	-9.23
33	F	23	5.83	4.52	2.00	0.54	-3.10	-4.96	-8.15	-8.47	-7.96	-8.96
34	F	36	6.42	3.91	2.59	1.29	0.27	-0.93	-2.47	-4.44	-6.71	-9.77
35	F	22	5.54	3.61	2.44	1.81	1.12	-0.39	-1.05	-2.00	-3.03	-4.25
36	F	26	4.52	2.27	0.88	-0.73	-0.90	-4.37	-5.37	-8.01	-10.84	-14.01
37	F	24	5.35	5.15	1.66	0.37	-1.73	-2.33	-5.23	-8.50	-12.18	-15.60
38	F	25	4.69	3.03	1.93	-0.22	-2.71	-3.61	-6.54	-8.74	-14.14	-14.16
39	F	23	8.50	5.10	3.15	2.27	-0.20	-1.73	-3.56	-5.40	-7.76	-9.94
40	F	26	5.66	3.88	2.25	0.83	0.78	-1.49	-2.93	-5.10	-6.69	-8.78
41	F	24	6.96	4.76	2.47	-0.54	-2.49	-5.15	-8.45	-13.06	-18.80	-25.85
42	F	20	6.42	4.59	2.15	0.63	-0.95	-2.49	-4.64	-6.74	-9.72	-14.84
43	F	21	8.33	5.25	3.03	1.42	0.00	-3.37	-2.03	-2.86	-4.64	-6.15
44	F	23	4.05	2.27	0.34	-1.54	-2.29	-4.10	-6.40	-7.45	-10.50	-14.33
45	F	22	4.39	3.42	2.32	0.85	-0.76	-1.73	-3.03	-5.35	-7.50	-8.91
46	M	25	3.27	1.10	-0.17	-0.49	-0.98	-6.05	-7.23	-11.01	-15.33	-20.75
47	M	23	12.01	7.08	3.54	-1.07	-3.37	-6.74	-8.94	-12.50	-14.89	-17.02
48	M	23	3.37	2.61	1.76	0.27	-1.71	-3.52	-6.08	-9.13	-14.09	-20.95
49	M	27	5.96	5.40	3.54	2.47	0.73	-1.76	-3.64	-5.22	-8.79	-11.91
50	M	23	5.44	4.27	2.81	-0.37	-3.44	-5.49	-9.84	-13.38	-19.95	-25.17
51	M	25	7.45	5.96	3.52	0.93	-1.37	-4.30	-5.57	-8.91	-11.55	-18.63
52	M	25	5.08	4.03	2.42	1.15	0.22	-1.93	-5.18	-4.66	-7.40	-10.33
53	M	38	5.15	3.20	1.98	0.98	-0.68	-2.05	-3.27	-5.81	-7.86	-10.89
54	M	24	5.05	3.20	1.98	0.59	-0.98	-2.39	-4.29	-6.23	-8.15	-11.69
55	M	25	4.27	3.59	1.29	-2.00	-1.03	-2.49	-12.55	-12.77	-17.16	-23.00
56	M	25	7.13	5.62	3.54	1.86	0.00	-0.20	-4.15	-5.42	-8.13	-10.89
57	M	20	8.64	5.81	3.69	1.86	-0.12	-2.59	-4.59	-7.06	-10.82	-14.28
58	M	26	8.59	7.71	5.40	3.49	1.46	-1.32	-3.37	-5.83	-11.33	-17.58
59	M	35	9.30	6.71	3.56	0.39	-1.93	-4.57	-6.96	-10.01	-13.99	-18.73
60	M	22	6.45	5.35	1.29	0.00	-2.20	-5.37	-5.64	-6.47	-5.00	-11.99

Appendix B

Table A2. Individual Data for Total Peak Twitch Torque at Joint Angles of 30°P-15°D.

			PEAK TOTAL TORQUE (Nm)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	3.96	3.49	2.78	2.34	1.90	1.17	0.63	0.00	1.04	1.45
2	F	71	4.37	3.39	2.81	2.17	1.73	1.20	0.76	0.00	0.00	0.00
3	F	68	3.52	3.20	2.17	1.86	1.29	0.46	0.98	0.00	0.00	0.00
4	F	67	4.17	3.47	3.00	2.66	1.90	1.37	0.85	1.25	0.61	0.00
5	F	72	2.49	2.22	1.68	1.34	0.61	0.73	0.27	0.00	0.00	0.00
6	F	62	3.39	2.73	2.49	1.78	1.39	0.90	0.34	0.00	0.00	0.00
7	F	72	3.61	2.95	2.51	1.76	1.49	0.51	0.39	0.00	0.00	0.00
8	F	67	3.74	3.15	2.61	2.37	1.93	0.95	0.00	0.00	0.00	0.00
9	F	68	4.52	3.96	3.52	3.17	2.54	1.68	1.39	1.76	0.54	0.42
10	F	65	3.64	2.54	1.71	2.54	2.10	1.73	0.90	0.29	0.00	0.00
11	F	73	2.61	2.59	2.34	1.68	1.10	1.73	0.78	0.00	0.00	0.00
12	F	62	3.52	2.95	2.22	1.66	1.03	1.07	0.00	0.66	0.00	0.00
13	F	72	3.00	2.34	1.83	1.49	1.25	1.17	0.00	0.00	0.00	0.00
14	F	70	2.93	2.54	1.95	1.59	1.25	0.61	0.00	0.00	0.00	0.00
15	F	70	3.05	2.12	1.68	0.66	0.27	0.00	0.00	0.00	0.00	0.00
16	M	65	4.25	3.17	2.42	1.76	1.20	0.68	0.00	0.00	0.00	0.00
17	M	62	3.93	3.39	2.29	1.90	1.15	0.00	0.00	0.00	0.00	0.00
18	M	69	6.05	5.15	4.20	3.49	2.64	2.47	0.95	0.00	0.00	0.00
19	M	68	5.25	4.79	3.91	3.42	2.69	1.86	1.56	0.00	0.00	0.00
20	M	78	7.50	5.98	5.40	4.39	3.86	3.39	2.00	1.37	1.61	0.61
21	M	73	7.62	6.54	6.13	5.27	4.93	3.98	2.91	1.59	1.12	0.61
22	M	62	5.44	4.76	4.05	3.61	3.17	2.05	1.39	0.61	0.00	0.00
23	M	64	2.59	1.51	1.10	0.39	0.29	0.00	0.00	0.00	0.00	0.00
24	M	70	7.79	7.71	6.64	5.71	4.98	3.86	3.37	1.88	0.88	0.78
25	M	70	6.91	6.30	5.40	4.54	3.44	2.64	1.64	0.88	0.00	0.00
26	M	73	7.20	6.45	5.40	4.66	3.69	2.78	1.07	0.22	0.00	0.00
27	M	72	4.27	3.61	2.83	2.12	1.66	0.00	0.00	0.00	0.00	0.00
28	M	71	5.00	4.49	3.42	3.08	2.29	1.86	1.46	0.76	0.61	0.32
29	M	64	1.17	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	M	68	8.45	8.08	7.45	6.49	6.05	4.86	3.64	3.27	2.59	0.00
31	F	25	5.83	5.27	4.20	3.56	2.95	1.71	0.93	0.00	0.00	0.00
32	F	35	5.52	4.64	4.20	4.00	3.17	2.59	1.71	0.00	0.42	0.00
33	F	23	4.13	3.49	2.98	2.20	1.46	1.37	0.00	0.00	0.00	0.00
34	F	36	2.27	1.88	1.71	1.51	0.83	0.54	0.59	0.00	0.00	0.00
35	F	22	3.93	3.52	2.93	2.64	2.27	1.64	1.27	1.34	0.00	0.00
36	F	26	2.98	2.71	2.32	1.76	1.44	1.12	0.00	0.00	0.00	0.00
37	F	24	3.05	2.81	2.54	1.51	1.51	0.00	0.00	0.00	0.00	0.00
38	F	25	3.64	2.98	2.00	1.20	0.00	0.00	0.00	0.00	0.00	0.00
39	F	23	4.35	3.91	3.39	2.71	2.37	2.00	1.05	0.63	0.00	0.00
40	F	26	2.86	1.98	0.83	1.64	0.34	0.20	0.00	0.00	0.00	0.00
41	F	24	3.25	2.56	2.00	1.49	1.07	0.83	0.29	0.00	0.00	0.00
42	F	20	2.27	1.59	1.00	0.63	0.24	0.00	0.00	0.00	0.00	0.00
43	F	21	2.83	2.37	1.78	1.68	1.05	0.54	0.00	0.00	0.00	0.00
44	F	23	2.05	1.54	1.03	0.68	0.00	0.00	0.00	0.32	0.00	0.00
45	F	22	3.25	2.88	2.54	2.08	2.00	1.46	0.93	0.00	0.00	0.00
46	M	25	6.42	3.96	5.52	3.61	1.51	2.15	0.00	1.03	0.00	0.00
47	M	23	3.49	2.73	2.12	1.37	0.66	0.61	0.00	0.00	0.00	0.00
48	M	23	5.22	4.49	3.42	2.32	1.39	0.61	0.00	0.00	0.00	0.00
49	M	27	4.54	3.96	3.17	2.66	2.03	1.78	1.29	0.49	2.00	0.00
50	M	23	5.18	3.88	3.00	2.32	2.05	1.29	0.63	0.78	0.37	0.29
51	M	25	4.79	3.86	2.95	2.10	0.44	0.00	0.27	0.00	0.00	0.00
52	M	25	6.74	6.23	5.69	4.86	3.96	3.66	1.86	1.15	0.00	0.00
53	M	38	8.37	7.69	6.71	5.71	5.22	3.20	1.56	0.00	0.00	0.00
54	M	24	5.20	4.10	3.37	2.81	1.51	0.00	0.88	0.00	0.00	0.00
55	M	25	7.06	5.35	3.66	3.20	2.59	1.88	1.39	0.54	0.00	0.00
56	M	25	3.39	2.98	2.39	1.78	1.32	0.63	0.56	0.00	0.00	0.00
57	M	20	2.69	2.15	1.68	1.44	0.68	0.68	0.00	0.00	0.00	0.00
58	M	26	7.59	6.91	5.64	4.86	3.08	2.98	1.78	0.59	0.00	0.00
59	M	25	3.54	2.49	1.66	1.05	0.44	0.00	0.00	0.00	0.00	0.00
60	M	22	5.69	4.96	4.05	3.54	2.66	1.90	0.88	0.00	0.00	0.00

Appendix C

Table A3. Individual Data for Time to Peak Torque (TPT) at Joint Angles of 30°P-15°D.

			TIME TO PEAK TORQUE (TPT) (ms)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	96.54	105.86	91.88	86.55	95.21	69.91	67.24	0.00	202.40	179.76
2	F	71	82.56	94.54	81.56	69.57	78.89	80.89	56.92	0.00	0.00	0.00
3	F	68	79.23	76.56	86.55	90.55	73.24	38.62	0.98	0.00	0.00	0.00
4	F	67	98.54	100.53	93.87	95.87	83.89	73.90	67.91	88.55	57.26	0.00
5	F	72	81.23	83.22	75.90	74.57	54.59	59.92	31.29	0.00	0.00	0.00
6	F	62	87.22	96.54	88.55	89.88	82.56	73.24	42.61	0.00	0.00	0.00
7	F	72	102.53	91.21	90.55	83.22	89.88	43.94	61.92	0.00	0.00	0.00
8	F	67	107.19	109.85	103.20	105.19	92.54	63.25	0.00	0.00	0.00	0.00
9	F	68	111.85	109.19	105.19	103.20	76.56	67.24	84.55	79.23	51.93	49.27
10	F	65	84.55	76.56	71.90	83.89	86.55	82.56	55.26	34.62	0.00	0.00
11	F	73	84.55	87.22	79.23	64.58	45.94	65.25	65.25	0.00	0.00	0.00
12	F	62	83.89	77.23	79.89	65.91	68.58	57.92	0.00	50.60	0.00	0.00
13	F	72	92.54	85.22	85.22	85.22	79.89	71.24	0.00	0.00	0.00	0.00
14	F	70	80.56	67.91	75.90	68.58	66.58	53.26	0.00	0.00	0.00	0.00
15	F	70	84.55	69.91	78.56	49.93	22.64	0.00	0.00	0.00	0.00	0.00
16	M	65	91.21	85.89	84.55	85.22	79.89	59.25	0.00	0.00	0.00	0.00
17	M	62	117.18	101.20	88.55	83.89	75.23	0.00	0.00	0.00	0.00	0.00
18	M	69	87.88	81.89	85.22	77.23	69.24	68.58	53.26	0.00	0.00	0.00
19	M	68	88.55	81.23	79.23	89.21	85.22	63.25	75.90	0.00	0.00	0.00
20	M	78	103.20	98.54	87.88	89.88	86.55	89.21	68.58	74.57	79.23	39.95
21	M	73	94.54	91.88	85.89	80.56	79.89	86.55	71.24	67.24	55.26	35.29
22	M	62	72.57	79.23	78.56	81.23	72.57	62.58	49.27	40.61	0.00	0.00
23	M	64	95.21	101.20	101.86	50.60	53.26	0.00	0.00	0.00	0.00	0.00
24	M	70	89.21	93.21	83.22	90.55	90.55	87.88	86.55	79.23	63.25	71.90
25	M	70	83.22	83.22	78.56	73.24	76.56	73.90	70.57	61.92	0.00	0.00
26	M	73	88.55	99.87	85.89	86.55	92.54	88.55	51.26	19.97	0.00	0.00
27	M	72	91.88	91.88	93.87	87.88	80.56	0.00	0.00	0.00	0.00	0.00
28	M	71	97.87	95.87	99.87	95.21	85.89	79.89	73.24	55.26	73.90	38.62
29	M	64	93.21	75.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	M	68	95.21	90.55	88.55	84.55	77.90	79.23	79.23	72.57	67.24	0.00
31	F	25	85.22	77.23	78.56	76.56	75.90	67.24	60.59	0.00	0.00	0.00
32	F	35	88.55	89.88	81.89	116.51	90.55	75.23	67.24	0.00	31.29	0.00
33	F	23	79.23	77.90	81.89	80.56	68.58	69.91	0.00	0.00	0.00	0.00
34	F	36	93.21	78.56	89.21	85.22	57.92	49.27	51.93	0.00	0.00	0.00
35	F	22	87.88	85.22	75.23	81.23	79.89	73.24	67.24	71.24	0.00	0.00
36	F	26	82.56	65.25	79.89	76.56	65.91	63.91	0.00	0.00	0.00	0.00
37	F	24	79.23	82.56	79.23	71.24	66.58	0.00	0.00	0.00	0.00	0.00
38	F	25	70.57	69.24	61.25	48.60	0.00	0.00	0.00	0.00	0.00	0.00
39	F	23	107.86	107.19	98.54	99.87	110.52	109.85	90.55	63.91	0.00	0.00
40	F	26	68.33	61.67	40.00	55.26	10.00	8.33	0.00	0.00	0.00	0.00
41	F	24	62.58	66.58	57.26	54.59	51.93	44.61	17.98	0.00	0.00	0.00
42	F	20	59.25	52.60	46.60	41.28	15.98	0.00	0.00	0.00	0.00	0.00
43	F	21	73.24	72.57	75.23	73.24	53.93	50.60	0.00	0.00	0.00	0.00
44	F	23	71.90	61.25	65.25	45.27	0.00	0.00	0.00	43.94	0.00	0.00
45	F	22	79.23	82.56	67.91	67.91	70.57	56.59	59.25	0.00	0.00	0.00
46	M	25	79.89	77.23	79.89	63.91	68.58	49.93	0.00	42.61	0.00	0.00
47	M	23	60.00	68.33	71.67	61.67	36.67	43.33	0.00	0.00	0.00	0.00
48	M	23	71.90	75.23	71.24	66.58	51.93	40.61	0.00	0.00	0.00	0.00
49	M	27	68.33	68.33	66.67	65.00	66.67	60.00	56.67	30.67	66.67	0.00
50	M	23	72.57	72.57	73.24	70.57	71.90	59.25	30.63	42.27	25.97	25.97
51	M	25	69.24	71.24	72.57	58.59	43.28	0.00	25.30	0.00	0.00	0.00
52	M	25	82.56	69.91	75.23	69.91	75.90	73.90	63.91	53.26	0.00	0.00
53	M	28	77.23	73.90	75.23	79.89	81.89	79.23	61.92	0.00	0.00	0.00
54	M	24	67.24	72.57	67.91	79.23	57.92	0.00	41.94	0.00	0.00	0.00
55	M	25	93.87	84.55	72.57	82.56	77.23	78.56	71.90	39.28	0.00	0.00
56	M	25	69.91	72.57	67.91	73.24	61.92	51.26	52.60	0.00	0.00	0.00
57	M	20	66.58	61.25	66.58	68.58	53.93	61.25	0.00	0.00	0.00	0.00
58	M	26	79.23	92.54	78.56	88.55	69.91	77.23	70.57	58.59	0.00	0.00
59	M	35	65.25	57.26	56.59	45.27	29.96	0.00	0.00	0.00	0.00	0.00
60	M	22	82.56	83.89	82.56	79.23	77.90	69.24	49.93	0.00	0.00	0.00

Appendix D

Table A4. Individual Data for Half-Relaxation Time (1/2 RT) at Joint Angles of 30°P-15°D.

			HALF - RELAXATION TIME (1/2/ RT) (ms)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	117.84	96.54	93.87	89.88	71.24	69.24	39.28	0.00	54.49	85.22
2	F	71	106.86	88.88	108.85	116.51	95.54	87.55	53.93	0.00	0.00	0.00
3	F	68	105.19	101.86	85.89	70.57	63.25	29.29	45.94	0.00	0.00	0.00
4	F	67	107.19	89.88	82.56	71.24	69.91	59.92	43.28	40.61	36.62	0.00
5	F	72	77.23	68.58	61.92	51.93	29.29	29.96	19.31	0.00	0.00	0.00
6	F	62	99.20	74.57	80.56	62.58	69.24	57.26	25.31	0.00	0.00	0.00
7	F	72	73.90	79.23	67.91	62.58	52.60	50.60	23.97	0.00	0.00	0.00
8	F	67	149.80	12317.00	109.85	109.19	100.53	105.86	0.00	0.00	0.00	0.00
9	F	68	132.49	113.85	108.52	103.20	88.55	62.58	81.23	81.89	49.93	34.62
10	F	65	85.89	75.23	89.88	67.24	59.92	54.59	50.60	21.97	0.00	0.00
11	F	73	85.22	81.89	73.90	65.91	61.92	61.25	27.96	0.00	0.00	0.00
12	F	62	90.55	80.56	74.57	57.91	52.60	41.94	0.00	39.28	0.00	0.00
13	F	72	129.93	123.17	105.86	95.87	77.90	74.57	0.00	0.00	0.00	0.00
14	F	70	51.26	54.49	55.93	55.26	41.94	29.29	0.00	0.00	0.00	0.00
15	F	70	85.22	88.55	77.23	42.61	7.32	0.00	0.00	0.00	0.00	0.00
16	M	65	100.53	86.55	72.57	56.59	51.26	45.94	0.00	0.00	0.00	0.00
17	M	62	141.15	125.17	105.19	96.54	105.86	0.00	0.00	0.00	0.00	0.00
18	M	69	97.20	93.87	77.90	91.21	62.58	67.91	49.27	0.00	0.00	0.00
19	M	68	97.20	95.21	51.93	78.56	78.56	83.22	52.60	0.00	0.00	0.00
20	M	78	99.87	95.21	83.22	83.22	63.25	57.92	61.25	41.94	42.61	29.96
21	M	73	95.21	97.20	91.20	78.56	75.23	61.92	61.25	51.93	41.94	35.29
22	M	62	97.87	89.88	84.55	73.90	77.23	67.91	63.25	34.62	0.00	0.00
23	M	64	98.54	77.90	64.58	56.59	38.62	0.00	0.00	0.00	0.00	0.00
24	M	70	102.53	101.86	103.86	94.54	86.55	83.22	80.56	73.90	55.26	58.59
25	M	70	74.57	69.24	65.25	67.91	53.26	49.27	45.27	29.96	0.00	0.00
26	M	73	112.52	98.54	99.87	87.22	82.56	63.91	59.25	7.32	0.00	0.00
27	M	72	98.54	89.88	93.21	81.23	161.12	0.00	0.00	0.00	0.00	0.00
28	M	71	101.20	94.54	95.87	72.57	74.57	67.24	65.25	41.94	23.97	23.97
29	M	64	87.88	59.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	M	68	105.86	101.20	91.21	85.22	70.57	67.91	57.92	59.92	41.28	0.00
31	F	25	72.57	75.90	65.25	65.25	66.58	57.92	47.27	0.00	0.00	0.00
32	F	35	90.55	84.55	81.23	77.90	58.59	69.24	61.25	0.00	31.92	0.00
33	F	23	93.21	88.55	85.89	69.24	56.59	49.27	0.00	0.00	0.00	0.00
34	F	36	76.56	80.56	65.91	67.91	60.59	47.27	43.94	0.00	0.00	0.00
35	F	22	91.88	91.88	97.87	91.21	92.54	89.21	87.88	85.22	0.00	0.00
36	F	26	87.22	95.87	85.89	75.56	89.88	69.91	0.00	0.00	0.00	0.00
37	F	24	85.22	87.22	75.90	88.55	71.90	0.00	0.00	0.00	0.00	0.00
38	F	25	74.57	70.57	49.93	49.93	0.00	0.00	0.00	0.00	0.00	0.00
39	F	23	121.84	112.52	107.19	116.51	110.52	89.21	96.54	112.52	0.00	0.00
40	F	26	91.67	80.00	40.00	61.25	23.33	1.67	0.00	0.00	0.00	0.00
41	F	24	82.56	62.58	60.59	51.26	38.62	33.95	18.64	0.00	0.00	0.00
42	F	20	95.21	78.56	55.26	35.29	23.97	0.00	0.00	0.00	0.00	0.00
43	F	21	74.57	74.57	61.92	63.91	73.90	35.95	0.00	0.00	0.00	0.00
44	F	23	71.90	77.23	51.93	55.93	0.00	0.00	0.00	27.30	0.00	0.00
45	F	22	75.90	68.58	72.57	61.25	57.26	62.58	34.62	0.00	0.00	0.00
46	M	25	71.24	58.59	65.25	65.91	53.93	41.94	0.00	33.29	0.00	0.00
47	M	23	58.33	58.33	53.33	50.00	56.67	40.00	0.00	0.00	0.00	0.00
48	M	23	76.56	63.91	50.60	41.28	35.29	18.64	0.00	0.00	0.00	0.00
49	M	27	73.33	73.33	65.00	58.33	48.33	56.67	48.33	26.67	58.33	0.00
50	M	23	68.58	55.93	47.94	40.61	33.29	32.62	23.30	19.31	16.64	10.65
51	M	25	71.24	62.58	53.93	53.93	17.98	0.00	20.64	0.00	0.00	0.00
52	M	25	79.89	90.55	79.23	79.23	70.57	64.58	66.58	70.57	0.00	0.00
53	M	38	84.55	84.55	78.56	67.24	65.91	66.58	63.91	0.00	0.00	0.00
54	M	34	81.23	72.57	67.91	53.93	71.24	0.00	43.28	0.00	0.00	0.00
55	M	25	121.17	125.17	132.49	84.55	95.87	102.53	102.53	33.95	0.00	0.00
56	M	25	71.90	71.90	63.25	55.93	62.58	89.21	51.26	0.00	0.00	0.00
57	M	20	57.26	57.92	44.61	45.27	37.95	27.30	0.00	0.00	0.00	0.00
58	M	26	101.86	87.88	89.88	80.56	89.21	82.56	81.89	108.52	0.00	0.00
59	M	35	61.25	49.93	37.28	33.29	15.98	0.00	0.00	0.00	0.00	0.00
60	M	22	73.24	67.24	57.26	57.92	42.27	51.26	59.92	0.00	0.00	0.00

Appendix E

Table A5. Individual Data for Maximal Voluntary Contractions (MVCs) at Joint Angles of 30°P-15°D.

			M V C TORQUE (Nm)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	37.23	35.87	35.95	38.81	35.25	25.68	18.81	17.35	13.16	11.36
2	F	71	45.00	42.80	47.79	40.75	41.02	35.83	38.96	34.93	35.12	30.68
3	F	68	29.37	28.50	24.93	21.89	18.74	18.67	14.17	9.81	15.44	8.62
4	F	67	25.92	25.05	23.96	22.18	20.29	24.32	16.26	13.57	18.57	17.62
5	F	72	29.05	25.61	29.30	23.08	19.13	19.90	20.95	16.92	13.83	10.32
6	F	62	32.06	30.36	33.47	31.29	36.02	26.17	22.96	2.71	13.35	16.12
7	F	72	34.17	32.48	30.97	27.48	27.82	24.27	21.55	17.86	11.33	8.96
8	F	67	16.04	10.87	18.81	19.39	12.67	19.32	11.94	11.94	8.06	3.37
9	F	68	27.96	26.00	27.33	14.13	11.14	20.83	16.07	13.96	24.47	7.84
10	F	65	31.63	32.09	31.50	31.89	29.83	27.45	24.17	22.03	14.32	13.59
11	F	73	26.70	21.74	27.60	26.53	31.65	27.29	29.08	21.87	19.42	16.77
12	F	62	27.57	28.40	25.32	22.82	26.41	18.76	13.50	13.18	7.43	6.33
13	F	72	24.03	24.54	23.52	19.00	17.57	16.82	12.89	11.60	9.21	8.01
14	F	70	22.04	20.49	20.68	17.89	11.04	10.05	4.95	3.08	3.98	3.33
15	F	70	30.92	29.10	27.77	23.69	20.07	16.29	11.41	9.42	9.13	7.01
16	M	65	50.19	52.38	48.52	44.05	37.55	29.22	20.00	16.75	10.83	7.69
17	M	62	49.22	53.52	49.80	46.00	41.94	40.73	36.99	32.11	25.00	20.97
18	M	69	43.64	44.05	43.30	48.57	43.45	43.37	45.36	35.83	28.52	24.71
19	M	68	40.46	40.49	40.34	41.01	37.77	37.45	37.23	34.25	33.42	28.86
20	M	78	37.14	35.70	37.35	33.74	31.94	29.95	24.76	24.85	21.50	18.06
21	M	73	42.11	43.03	41.07	42.09	34.32	36.99	37.94	35.10	30.58	26.04
22	M	62	56.70	57.57	56.41	55.15	54.71	49.17	44.27	38.42	31.53	27.77
23	M	64	45.19	41.82	35.41	29.95	26.02	20.44	11.94	11.41	8.11	9.42
24	M	70	54.71	55.97	56.70	56.60	50.53	49.76	47.33	35.61	36.87	30.27
25	M	70	50.85	54.78	53.28	62.91	59.30	58.37	57.86	58.52	58.01	40.49
26	M	73	42.28	43.88	41.80	36.89	37.23	37.57	28.54	27.23	20.46	14.08
27	M	72	34.22	35.24	33.59	30.27	28.57	23.01	17.52	14.49	10.78	7.91
28	M	71	38.88	41.46	43.71	38.46	31.17	25.15	20.49	9.49	6.26	5.10
29	M	64	19.71	18.91	18.74	17.18	15.22	12.48	9.15	7.30	4.90	5.00
30	M	68	49.22	56.04	58.13	59.85	54.49	55.87	54.83	44.22	36.24	26.26
31	F	25	52.77	53.54	53.30	50.95	49.90	48.83	43.88	42.89	38.35	35.46
32	F	35	42.11	41.55	37.45	39.83	37.45	34.83	26.99	21.84	14.95	13.64
33	F	23	39.34	38.88	37.38	39.10	34.17	31.43	22.23	25.53	15.92	13.83
34	F	36	24.47	23.76	24.44	23.64	21.02	19.36	18.64	13.06	11.60	11.92
35	F	22	29.95	26.67	26.90	24.13	24.20	23.59	21.04	18.74	16.12	12.60
36	F	26	33.83	36.26	32.06	30.85	30.34	23.13	24.15	21.29	26.34	15.58
37	F	24	45.83	46.72	44.70	47.50	36.92	32.94	27.84	24.76	22.55	18.73
38	F	25	36.07	35.39	34.17	31.72	29.03	23.64	17.48	15.15	13.54	12.74
39	F	23	30.78	30.95	30.92	29.76	27.97	26.12	21.20	18.16	15.41	12.43
40	F	26	38.11	38.42	33.79	31.12	32.31	26.55	21.60	17.09	13.11	10.34
41	F	24	34.71	34.15	36.60	33.52	31.87	27.31	24.32	17.91	12.22	12.33
42	F	20	24.85	26.75	10.80	24.08	18.67	26.60	13.52	11.72	16.31	14.02
43	F	21	32.92	35.53	26.12	30.95	27.43	29.30	27.79	24.71	19.83	12.77
44	F	23	36.60	34.81	32.38	29.51	24.10	22.18	18.45	15.80	10.07	11.07
45	F	22	32.14	29.47	29.34	27.04	27.09	24.15	20.49	17.45	11.97	16.31
46	M	25	56.48	56.80	57.01	54.05	47.65	42.97	37.21	26.53	16.46	13.97
47	M	23	48.96	48.30	46.16	47.31	46.53	37.94	34.47	27.43	21.12	17.38
48	M	23	46.65	46.63	43.91	41.29	35.27	32.96	20.95	29.54	12.01	11.14
49	M	27	50.19	53.54	54.49	52.80	53.81	49.00	43.50	39.81	32.10	28.08
50	M	23	57.21	59.25	59.26	62.43	60.32	50.29	49.08	42.74	36.50	29.71
51	M	25	55.29	56.65	57.99	58.01	56.21	45.34	35.46	30.32	24.37	19.22
52	M	25	41.92	43.93	39.03	44.37	38.35	39.78	38.69	34.08	31.72	30.02
53	M	38	70.27	72.62	72.67	71.89	71.38	68.33	60.56	55.83	47.65	40.68
54	M	24	52.11	53.52	52.30	50.97	49.22	52.04	39.30	37.94	32.74	24.42
55	M	25	63.23	63.62	69.15	60.73	62.72	51.55	44.93	30.41	30.46	17.40
56	M	25	43.93	43.45	42.52	42.14	39.13	32.21	35.97	30.87	26.21	24.30
57	M	20	48.50	50.44	49.81	46.00	39.34	36.41	13.59	28.30	25.27	22.26
58	M	26	63.25	66.02	62.79	61.77	55.80	62.79	40.05	37.57	23.52	17.35
59	M	35	49.59	45.27	43.28	40.49	40.44	38.50	35.24	31.14	27.35	25.46
60	M	22	44.34	49.76	46.46	48.93	43.35	42.09	38.69	36.12	32.99	29.27

Appendix F

Table A6. Individual Data for 20 Hz Tetanic Torque at Joint Angles of 30°P-15°D.

			20 Hz PEAK TORQUE (Nm)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	17.92	11.79	8.72	6.25	3.34	3.34	1.90	0.00	0.00	0.00
2	F	71	25.56	26.17	25.00	21.78	17.02	12.01	7.47	3.20	0.00	2.75
3	F	68	18.24	16.75	15.43	14.36	10.18	9.23	5.74	2.64	0.85	0.00
4	F	67	19.21	15.53	17.04	15.65	13.57	11.91	8.79	6.59	3.20	0.00
5	F	72	12.70	11.33	10.79	9.47	8.01	5.20	2.81	1.17	0.00	0.00
6	F	62	20.78	18.70	20.61	15.70	16.38	13.45	10.52	6.54	2.88	0.34
7	F	72	20.04	18.41	18.33	14.87	13.84	9.89	8.25	4.10	6.25	0.71
8	F	67	16.04	15.50	14.43	13.04	12.99	10.47	3.13	6.25	1.81	0.00
9	F	68	20.58	19.48	18.58	17.11	16.31	14.11	10.33	7.40	4.74	0.00
10	F	65	13.48	14.87	12.21	12.55	14.16	9.52	8.89	7.71	2.71	1.44
11	F	73	8.28	8.40	7.15	6.27	3.30	3.88	2.49	1.46	0.00	0.00
12	F	62	14.26	13.96	12.87	13.13	10.64	6.64	3.78	1.93	0.00	0.00
13	F	72	13.99	12.11	11.74	12.21	9.55	7.86	5.52	2.83	0.93	0.00
14	F	70	8.86	7.13	8.74	7.10	5.66	3.47	0.93	0.00	0.00	0.00
15	F	70	20.02	18.07	13.89	10.60	7.28	3.13	0.00	0.00	0.00	0.00
16	M	65	25.15	25.22	21.14	19.14	18.24	12.30	7.37	3.05	0.00	0.00
17	M	62	17.07	10.60	11.30	14.67	14.97	16.77	6.30	4.79	2.49	0.00
18	M	69	25.44	20.73	18.12	22.78	19.19	14.99	14.28	9.62	4.88	2.15
19	M	68	21.24	19.46	20.68	17.46	14.23	13.67	9.18	7.10	4.20	0.00
20	M	78	24.78	22.58	20.85	13.87	16.41	11.60	9.20	7.01	5.91	3.39
21	M	73	37.11	31.45	33.98	32.23	27.93	23.63	20.51	18.70	10.96	5.15
22	M	62	28.37	26.83	26.27	22.97	21.00	18.48	12.40	9.59	4.08	0.85
23	M	64	15.31	8.15	4.69	2.29	0.00	0.00	0.00	0.00	0.00	0.00
24	M	70	34.89	34.79	32.76	25.88	27.76	17.77	19.97	11.74	9.67	3.08
25	M	70	40.67	38.45	36.52	38.09	24.95	28.05	17.53	23.97	9.57	3.69
26	M	73	25.39	22.19	21.95	19.34	16.70	12.08	8.11	6.84	0.00	1.17
27	M	72	14.50	14.72	7.42	14.06	5.51	9.47	2.66	0.88	0.00	0.00
28	M	71	16.11	14.11	11.77	10.55	9.23	7.62	10.72	4.59	2.44	1.25
29	M	64	7.06	5.59	4.25	2.98	1.66	0.00	0.00	0.00	0.00	0.00
30	M	68	25.15	23.44	21.73	15.63	17.87	12.92	10.03	12.28	6.20	3.66
31	F	25	28.25	27.88	28.66	27.81	26.73	22.85	16.72	17.63	7.28	3.81
32	F	35	17.60	13.60	12.60	13.01	9.42	9.03	5.91	4.42	13.09	1.42
33	F	23	20.85	19.78	19.43	15.31	12.74	11.45	14.11	3.37	0.78	0.00
34	F	36	14.65	13.99	13.40	12.13	10.11	9.47	5.86	4.08	1.86	1.07
35	F	22	19.90	18.68	16.94	16.26	14.70	13.26	10.60	8.57	5.96	2.39
36	F	26	20.61	19.70	17.53	15.87	13.45	9.59	7.13	4.54	1.81	0.85
37	F	24	22.14	24.00	15.31	18.73	11.47	10.40	5.76	2.95	1.22	0.00
38	F	25	15.72	8.54	17.58	6.76	5.49	0.00	3.59	1.56	1.51	0.00
39	F	23	16.55	17.58	18.48	16.48	16.58	14.11	11.99	9.01	6.03	3.37
40	F	26	19.38	18.85	16.82	15.50	13.72	11.89	9.47	6.15	3.78	2.27
41	F	24	20.73	19.31	17.38	14.79	11.45	8.11	4.47	0.63	0.00	0.00
42	F	20	7.47	7.30	6.64	5.83	5.13	5.25	2.81	2.03	0.71	0.00
43	F	21	15.92	14.94	13.45	12.96	12.60	5.52	7.86	6.64	3.08	1.22
44	F	23	17.70	14.79	13.04	10.42	6.79	6.40	4.32	5.13	2.76	1.78
45	F	22	16.06	17.48	15.89	15.43	13.01	11.45	9.25	6.18	4.15	2.08
46	M	25	31.93	32.74	28.05	29.93	24.22	20.31	13.31	7.20	2.95	0.00
47	M	23	23.32	24.85	22.73	20.14	15.04	11.67	7.57	3.54	0.00	0.00
48	M	23	31.96	29.03	27.08	22.34	16.50	13.57	6.59	1.44	0.00	0.00
49	M	27	33.45	31.15	30.98	29.91	27.32	23.63	19.75	14.58	7.81	4.00
50	M	23	26.25	34.67	25.73	29.93	20.75	21.14	15.04	12.84	4.32	2.47
51	M	25	28.86	25.61	20.63	21.63	19.53	14.70	11.25	6.54	2.69	0.59
52	M	25	30.49	29.17	30.32	26.00	26.29	21.53	20.56	13.67	10.25	5.08
53	M	38	50.51	49.15	47.49	42.33	40.99	34.86	25.20	25.88	11.87	5.27
54	M	24	21.34	24.17	20.17	16.46	17.87	16.97	10.55	12.72	2.37	1.90
55	M	25	38.96	37.06	35.03	29.57	27.03	19.63	15.04	5.98	3.98	0.00
56	M	25	30.66	29.71	28.03	28.25	24.61	19.85	17.24	13.45	9.08	6.05
57	M	20	13.26	11.16	10.74	9.52	6.79	5.59	3.91	2.69	1.20	0.00
58	M	26	40.19	40.09	41.58	32.42	31.57	25.32	40.70	14.11	42.70	2.81
59	M	35	25.22	22.44	19.31	16.63	11.43	7.81	2.95	1.12	0.00	0.00
60	M	22	31.47	33.18	29.10	29.30	23.71	19.56	12.99	11.47	7.81	3.44

Appendix G

Table A7. Individual Data for 50 Hz Tetanic Torque at Joint Angles of 30°P-15°D.

			50 Hz PEAK TORQUE (Nm)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	22.44	14.92	14.36	9.84	9.33	7.79	5.13	4.27	2.20	1.46
2	F	71	31.18	32.23	31.01	28.32	22.27	18.14	7.96	4.05	0.00	2.97
3	F	68	20.00	19.24	18.33	17.53	14.99	11.62	8.11	4.79	1.93	0.00
4	F	67	21.92	20.39	20.02	18.31	16.41	14.84	11.96	8.62	5.32	2.64
5	F	72	16.31	15.84	14.79	13.48	12.33	8.52	5.52	2.93	0.00	0.00
6	F	62	26.25	25.93	28.52	21.85	23.78	20.11	16.43	11.52	7.64	4.25
7	F	72	25.98	24.07	24.27	21.29	19.70	15.45	14.58	8.69	8.69	4.54
8	F	67	18.53	18.04	17.87	16.97	14.89	13.09	9.81	7.76	4.61	2.93
9	F	68	22.31	21.78	21.00	19.97	18.46	16.02	12.43	9.18	6.03	2.59
10	F	65	16.36	19.21	15.33	17.29	23.02	14.55	13.33	13.60	4.91	3.76
11	F	73	15.19	14.84	13.60	10.33	7.67	6.64	6.30	5.27	2.73	0.49
12	F	62	17.87	17.31	17.53	17.94	15.84	10.23	7.28	4.15	0.00	0.00
13	F	72	17.43	17.16	16.70	17.38	14.23	12.45	9.64	6.37	3.22	1.00
14	F	70	13.33	11.77	10.82	9.47	8.54	4.91	2.78	0.00	0.00	0.00
15	F	70	24.12	22.36	17.90	14.31	10.74	5.96	2.86	0.00	0.00	0.00
16	M	65	33.91	33.72	33.11	28.22	25.10	19.85	11.18	6.23	1.66	0.00
17	M	62	25.07	22.63	25.42	16.97	15.38	20.85	15.53	7.13	4.57	2.29
18	M	69	32.03	30.52	30.32	27.88	29.86	26.29	24.12	18.29	13.04	7.42
19	M	68	33.11	33.15	32.06	30.44	27.20	23.58	22.88	16.26	12.21	6.88
20	M	78	28.37	24.07	24.27	20.36	19.82	17.04	11.99	9.40	7.84	5.83
21	M	73	43.29	38.40	41.75	40.65	32.76	32.79	27.20	25.39	16.31	9.99
22	M	62	35.94	35.62	33.62	30.27	27.76	23.05	16.14	12.60	6.40	3.22
23	M	64	21.17	11.60	10.13	2.59	3.52	0.00	0.00	0.00	0.00	0.00
24	M	70	42.60	44.48	42.36	40.28	37.82	32.35	28.66	19.80	15.53	7.13
25	M	70	46.39	46.44	45.02	45.07	32.93	30.27	25.17	27.56	14.36	9.42
26	M	73	31.23	30.81	28.66	26.17	25.27	21.17	14.87	12.62	2.88	5.86
27	M	72	17.85	17.87	12.01	7.47	5.83	11.67	4.61	1.34	0.00	0.00
28	M	71	22.88	19.58	19.53	15.36	17.21	13.94	16.65	9.03	5.49	3.74
29	M	64	8.30	6.76	5.27	4.64	3.34	0.00	0.00	0.00	0.00	0.00
30	M	68	29.52	32.37	28.98	27.64	31.20	18.70	18.46	18.31	9.91	7.67
31	F	25	33.98	35.69	35.64	35.55	34.03	30.20	24.10	21.24	13.45	8.01
32	F	35	23.34	19.09	18.92	17.65	17.19	12.72	11.18	8.74	21.26	3.93
33	F	23	28.20	27.08	26.34	25.29	20.04	18.12	14.11	8.45	4.47	1.00
34	F	36	17.72	17.43	16.80	15.82	13.62	12.45	9.11	6.18	4.57	3.27
35	F	22	23.49	22.39	21.58	20.48	18.73	16.97	14.63	11.87	7.67	4.30
36	F	26	26.27	22.00	23.29	21.88	18.43	15.16	11.35	8.25	4.76	3.22
37	F	24	31.84	32.18	27.29	27.73	22.90	17.68	11.62	7.89	5.52	2.47
38	F	25	15.72	12.89	18.19	10.96	12.84	10.18	9.84	7.45	5.05	1.22
39	F	23	22.27	22.44	23.07	27.59	20.12	17.77	17.26	13.06	9.69	3.37
40	F	26	24.44	21.90	20.95	19.75	18.14	14.70	12.79	10.74	6.74	4.42
41	F	24	25.63	24.56	23.46	20.56	16.54	12.52	8.35	3.32	1.71	0.00
42	F	20	8.28	11.04	10.13	9.62	8.84	14.06	7.18	5.32	3.27	1.83
43	F	21	21.53	19.70	19.73	19.34	18.55	10.57	13.77	11.33	6.49	3.93
44	F	23	22.09	20.24	17.77	14.38	10.82	9.06	7.18	6.67	5.49	4.71
45	F	22	21.19	21.36	20.63	20.09	18.14	16.28	13.23	10.45	7.62	4.71
46	M	25	42.21	39.67	35.21	35.52	31.86	28.64	20.12	11.28	6.71	2.88
47	M	23	36.45	34.99	32.50	30.08	26.90	21.66	17.04	11.35	5.64	0.73
48	M	23	44.85	42.99	40.06	36.55	25.95	21.41	14.53	8.98	3.61	3.08
49	M	27	41.02	41.26	40.04	39.87	35.45	32.91	27.15	20.75	12.65	8.54
50	M	23	40.58	39.28	42.19	35.72	37.40	31.27	25.17	18.41	11.79	6.05
51	M	25	38.09	41.14	34.42	37.35	30.32	26.61	21.85	16.28	11.57	7.13
52	M	25	41.80	42.97	42.99	41.36	39.53	35.89	29.42	21.61	17.80	12.55
53	M	38	59.42	59.25	58.20	55.59	53.10	46.88	36.94	33.40	19.07	12.18
54	M	24	28.22	32.74	30.22	23.61	21.46	20.95	13.53	17.26	4.10	2.86
55	M	25	50.81	49.98	49.34	43.38	41.16	31.01	23.12	12.72	9.20	2.78
56	M	25	37.82	37.67	36.74	36.96	34.77	31.52	28.81	22.95	18.65	13.48
57	M	20	23.00	20.95	21.73	17.53	16.06	13.13	9.94	7.01	4.59	1.29
58	M	26	52.86	51.49	52.42	43.09	40.84	35.45	51.95	19.21	51.95	6.79
59	M	35	29.27	27.76	25.49	21.36	16.75	12.28	6.57	4.47	3.74	2.27
60	M	22	39.36	39.62	38.48	37.35	35.33	31.98	25.07	21.66	12.94	10.64

Appendix H

Table A8. Individual Data for 80 Hz Tetanic Torque at Joint Angles of 30°P-15°D.

			80 Hz PEAK TORQUE (Nm)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	22.12	13.53	15.63	20.26	8.59	7.67	6.05	5.15	3.00	1.54
2	F	71	34.03	33.33	32.08	28.78	24.98	18.87	10.69	4.05	1.20	2.38
3	F	68	20.34	20.17	16.87	17.63	13.21	12.48	8.30	4.57	1.76	0.73
4	F	67	21.92	20.65	20.48	18.51	17.09	14.94	12.11	8.74	5.66	2.71
5	F	72	17.09	15.92	16.21	14.18	13.35	9.18	9.38	3.54	0.63	0.00
6	F	62	27.10	26.46	27.61	24.34	23.32	20.12	16.92	12.70	8.18	5.27
7	F	72	25.27	25.76	22.63	21.85	19.87	14.55	12.23	8.67	6.54	5.35
8	F	67	18.73	18.26	17.46	16.63	15.33	3.35	9.99	7.79	4.52	2.98
9	F	68	23.36	23.32	23.27	21.39	20.17	17.77	14.01	10.47	9.03	2.61
10	F	65	17.92	18.75	18.60	18.85	21.63	16.31	14.28	15.01	6.32	4.15
11	F	73	17.77	15.70	13.43	10.11	9.55	8.50	1.93	5.03	3.54	1.93
12	F	62	18.92	18.14	17.63	18.51	16.82	10.89	8.54	5.20	0.88	0.00
13	F	72	18.21	17.97	16.99	16.63	14.45	12.96	10.06	6.47	3.52	1.76
14	F	70	12.67	12.50	12.87	11.18	10.03	6.67	3.42	0.00	0.00	0.00
15	F	70	26.15	24.02	20.17	16.26	11.94	7.25	4.08	0.00	0.00	0.00
16	M	65	37.96	38.67	37.04	29.08	24.58	21.41	12.77	8.57	3.10	0.00
17	M	62	26.54	26.00	26.95	17.70	14.16	19.19	13.43	8.01	4.74	2.51
18	M	69	33.45	30.86	31.30	29.44	27.03	25.24	25.22	17.75	12.06	7.50
19	M	68	34.28	34.74	33.03	30.96	28.13	22.34	23.34	17.87	13.55	8.28
20	M	78	26.39	28.17	21.73	21.58	19.41	16.65	12.55	12.11	8.69	8.08
21	M	73	44.51	41.43	42.04	40.06	37.08	32.30	29.64	29.59	19.95	12.96
22	M	62	36.74	37.13	35.77	32.89	30.03	25.56	17.75	13.84	7.81	4.05
23	M	64	23.10	11.55	10.69	7.57	5.42	2.00	0.00	0.00	0.00	0.00
24	M	70	45.14	44.46	44.38	42.46	39.77	33.67	30.20	19.46	15.65	7.71
25	M	70	47.22	47.12	46.14	46.51	33.76	38.82	29.64	27.71	19.12	10.52
26	M	73	32.71	30.79	29.79	26.73	24.71	20.61	16.55	13.43	5.08	5.96
27	M	72	21.95	20.65	15.53	13.72	12.18	17.02	7.91	3.13	5.10	0.00
28	M	71	22.90	21.17	21.68	16.70	18.60	15.16	17.09	10.08	6.18	4.03
29	M	64	8.25	6.86	5.52	4.71	3.25	1.39	0.00	0.00	0.00	0.00
30	M	68	30.10	34.62	30.76	31.01	37.99	21.73	24.83	22.02	15.33	9.28
31	F	25	34.81	34.91	36.45	36.62	35.23	30.79	24.90	23.63	14.33	8.89
32	F	35	24.46	21.83	20.36	20.14	15.94	16.06	11.33	9.52	16.97	4.10
33	F	23	28.08	27.93	27.64	27.47	23.19	19.31	14.04	8.72	3.74	0.00
34	F	36	18.21	17.90	17.43	16.31	13.96	12.74	9.25	6.71	4.66	3.54
35	F	22	24.17	23.88	22.58	22.24	20.26	18.60	15.55	12.60	8.81	5.54
36	F	26	26.78	26.64	24.73	22.44	19.38	15.70	12.28	9.03	5.57	3.81
37	F	24	35.30	34.28	31.74	28.66	24.02	18.55	13.13	9.06	6.93	3.56
38	F	25	16.99	16.31	15.04	12.48	13.77	9.28	9.03	8.52	4.79	2.47
39	F	23	19.19	21.85	23.44	18.63	18.97	19.12	14.62	12.70	9.40	5.71
40	F	26	23.22	22.27	21.56	20.21	18.31	15.60	13.35	10.47	7.67	4.76
41	F	24	25.83	24.61	23.00	20.80	16.80	12.79	8.45	4.52	2.71	1.44
42	F	30	8.94	10.45	12.92	10.77	9.52	0.00	7.37	5.71	5.93	2.81
43	F	21	22.29	19.34	28.14	20.24	18.53	10.21	13.84	10.94	6.23	4.69
44	F	23	22.05	20.63	19.14	14.38	10.62	10.72	7.79	7.47	5.98	4.88
45	F	22	21.48	22.34	22.12	21.22	19.92	17.53	15.01	11.55	8.11	5.74
46	M	25	42.41	41.28	35.62	38.23	33.08	27.59	19.58	11.16	6.05	3.64
47	M	23	38.35	36.57	34.11	31.71	27.93	23.27	17.08	14.45	6.84	3.15
48	M	23	44.02	42.26	40.50	36.87	25.78	21.73	13.99	7.98	3.37	0.00
49	M	27	43.90	43.58	43.48	42.26	37.82	35.50	28.78	22.17	14.23	10.21
50	M	23	41.28	45.14	42.92	37.82	38.77	33.69	26.51	21.29	13.13	8.67
51	M	25	34.89	41.38	36.91	34.13	34.50	28.39	18.80	17.53	13.33	9.18
52	M	25	42.14	43.07	42.60	41.89	39.14	36.08	29.61	23.00	19.63	11.62
53	M	38	60.11	59.67	58.37	56.88	53.91	46.85	37.65	33.50	20.17	13.84
54	M	24	37.08	35.01	34.16	29.37	25.59	24.56	18.16	20.75	5.64	3.83
55	M	25	51.15	50.20	48.41	44.34	40.43	31.30	23.39	11.87	10.30	3.27
56	M	25	38.96	41.97	38.01	37.23	34.47	34.67	29.96	26.64	18.12	14.16
57	M	20	25.78	23.29	23.93	16.72	15.92	14.97	11.11	7.54	4.57	2.10
58	M	26	50.59	50.59	52.91	47.17	42.41	36.72	53.49	20.87	54.03	7.08
59	M	35	30.76	28.56	25.93	21.85	17.49	1.50	7.13	6.47	5.81	3.56
60	M	22	40.82	40.87	41.14	38.67	36.47	32.56	27.27	21.95	16.31	11.28

Appendix I

Table A9. Individual Data for 20 Hz Rise Time for Tetanic Torque at Joint Angles of 30°P-15°D.

Subject (#)	Gender	Age (yr)	20 Hz RISE TIME (ms) 30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	480	280	890	830	100	790	90	270	400	0
2	F	71	280	310	280	320	280	240	250	190	0	55
3	F	68	250	270	580	360	700	270	260	230	190	0
4	F	67	280	290	280	300	260	300	260	250	180	0
5	F	72	340	370	400	390	380	490	350	630	0	0
6	F	62	270	270	340	320	320	340	360	240	180	60
7	F	72	250	310	370	310	450	390	510	590	700	660
8	F	67	300	310	340	370	320	300	130	270	250	0
9	F	68	300	310	340	550	600	580	640	460	180	0
10	F	65	190	230	170	180	240	140	150	270	120	140
11	F	73	130	130	100	110	90	110	60	60	0	0
12	F	62	230	260	270	270	230	250	240	130	0	0
13	F	72	340	370	340	360	420	410	360	420	910	0
14	F	70	210	220	280	220	240	210	150	0	0	0
15	F	70	380	370	440	420	400	380	0	0	0	0
16	M	65	390	380	420	260	240	240	180	160	0	0
17	M	62	230	230	270	280	290	330	190	210	120	0
18	M	69	200	200	240	270	200	220	220	180	170	150
19	M	68	240	240	230	230	220	210	230	230	200	0
20	M	78	450	520	540	540	530	590	550	520	190	130
21	M	73	280	230	340	340	240	670	480	180	270	490
22	M	62	330	300	320	280	290	230	220	210	150	90
23	M	64	420	230	360	240	0	0	0	0	0	0
24	M	70	320	380	430	610	420	520	450	430	460	910
25	M	70	290	320	370	340	500	600	440	410	330	110
26	M	73	300	250	340	330	340	250	280	150	0	40
27	M	72	200	200	200	210	190	280	320	100	0	0
28	M	71	190	190	200	810	180	650	360	150	130	100
29	M	64	290	310	370	360	530	0	0	0	0	0
30	M	68	310	230	410	180	220	200	150	150	210	110
31	F	25	220	240	240	260	230	220	210	210	210	130
32	F	35	190	400	110	450	100	700	90	780	140	100
33	F	23	300	330	300	430	460	460	460	190	100	0
34	F	36	300	310	320	310	290	220	250	230	150	120
35	F	22	240	270	270	280	280	260	260	260	190	150
36	F	26	280	380	330	30	400	220	200	150	110	90
37	F	24	280	370	450	420	440	350	220	160	120	0
38	F	25	150	140	290	110	860	0	110	180	60	0
39	F	23	240	260	310	310	310	360	310	350	360	270
40	F	26	220	230	200	220	170	200	250	180	220	210
41	F	24	280	300	310	280	260	240	210	60	0	0
42	F	20	290	290	810	220	220	250	240	200	50	0
43	F	21	280	270	320	280	260	210	220	220	160	120
44	F	23	240	290	240	210	280	210	240	250	260	810
45	F	22	210	230	250	270	240	240	220	240	180	150
46	M	25	300	300	230	260	360	280	250	150	80	0
47	M	23	300	320	360	350	310	260	220	170	0	0
48	M	23	290	380	380	370	320	380	210	290	0	0
49	M	27	270	280	400	300	250	250	240	210	170	140
50	M	23	250	330	390	430	610	450	390	290	140	100
51	M	25	230	220	230	220	210	200	170	140	110	50
52	M	25	240	260	290	330	310	330	340	200	210	150
53	M	38	240	240	260	270	280	260	300	240	200	160
54	M	24	140	500	660	390	270	220	200	200	130	90
55	M	25	260	290	390	500	460	360	210	150	120	0
56	M	25	280	260	310	340	300	270	420	370	470	340
57	M	20	140	150	140	150	120	130	90	110	50	0
58	M	26	240	260	260	280	230	220	240	170	270	80
59	M	35	260	260	260	260	260	250	210	70	0	0
60	M	22	270	250	320	290	320	310	250	250	210	140

Appendix J

Table A10. Individual Data for 50 Hz Rise Time for Tetanic Torque at Joint Angles of 30°P-15°D.

			80 Hz RISE TIME (ms)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	230	130	910	220	520	490	690	120	110	50
2	F	71	270	250	260	270	290	450	630	410	60	200
3	F	68	190	190	240	210	200	330	180	330	40	30
4	F	67	200	180	200	190	180	220	180	180	240	500
5	F	72	280	310	220	290	350	270	250	540	100	0
6	F	62	270	230	260	260	280	280	270	350	480	620
7	F	72	540	690	780	750	760	610	790	840	120	690
8	F	67	240	240	340	270	250	250	230	140	150	330
9	F	68	210	220	270	580	590	610	530	360	560	190
10	F	65	130	140	130	140	470	230	120	580	100	100
11	F	73	110	100	80	50	90	220	50	70	70	50
12	F	62	170	170	210	240	160	210	160	60	30	0
13	F	72	350	500	440	430	430	340	400	460	550	500
14	F	70	140	160	570	390	290	250	530	0	0	0
15	F	70	240	350	230	240	270	470	560	0	0	0
16	M	65	690	610	450	190	210	420	190	700	860	0
17	M	62	210	580	230	550	600	420	240	110	100	120
18	M	69	180	170	190	200	190	180	290	170	180	380
19	M	68	180	180	170	170	710	250	200	180	160	250
20	M	78	450	190	140	130	420	570	450	560	560	410
21	M	73	210	520	170	170	150	350	160	200	430	390
22	M	62	220	210	190	180	180	170	140	120	80	70
23	M	64	700	720	780	360	520	810	0	0	0	0
24	M	70	290	310	330	320	290	230	260	360	320	560
25	M	70	210	210	210	380	170	410	570	450	450	120
26	M	73	180	170	200	190	210	180	170	220	175	120
27	M	72	130	120	170	180	180	200	160	90	150	0
28	M	71	150	150	170	120	140	130	160	120	100	90
29	M	64	190	180	160	160	240	190	0	0	0	0
30	M	68	300	290	370	210	170	130	160	120	380	90
31	F	25	160	190	180	180	170	210	140	110	140	120
32	F	35	450	480	90	130	60	610	70	640	70	120
33	F	23	210	290	400	590	640	290	320	410	240	0
34	F	36	170	180	170	170	170	170	150	160	110	90
35	F	22	190	200	190	200	200	290	200	170	290	450
36	F	26	170	380	440	480	420	220	120	110	80	70
37	F	24	190	360	490	730	310	160	160	120	110	70
38	F	25	50	420	590	40	700	700	780	700	760	80
39	F	23	150	150	200	200	330	460	520	320	450	460
40	F	26	160	160	180	150	130	120	100	120	110	320
41	F	24	230	220	230	230	190	140	180	110	100	90
42	F	20	100	100	150	230	180	0	90	190	100	70
43	F	21	240	130	240	270	420	230	180	570	70	760
44	F	23	130	150	180	120	130	140	90	110	100	100
45	F	22	140	170	170	190	150	170	160	190	100	480
46	M	25	200	150	240	360	170	250	260	100	70	50
47	M	23	200	240	250	250	280	330	200	380	90	60
48	M	23	340	220	220	300	340	280	100	90	60	0
49	M	27	210	210	210	210	450	240	180	160	80	70
50	M	23	410	440	570	420	450	490	430	590	300	100
51	M	25	180	130	150	160	410	140	90	90	80	70
52	M	25	210	200	190	240	210	210	380	150	160	70
53	M	38	160	170	270	220	250	200	180	130	110	100
54	M	24	480	570	460	640	650	360	220	490	40	40
55	M	25	230	390	430	390	520	390	500	380	110	60
56	M	25	150	190	150	160	130	180	190	210	240	270
57	M	20	110	100	100	80	90	80	90	170	70	60
58	M	26	200	180	200	160	220	150	180	110	180	50
59	M	35	140	140	140	140	130	120	90	50	40	50
60	M	22	230	220	240	260	300	260	260	330	530	630

Appendix K

Table A11. Individual Data for 80 Hz Rise Time for Tetanic Torque at Joint Angles of 30°P-15°D.

			50 Hz RISE TIME (ms)									
Subject (#)	Gender	Age (yr)	30P	25P	20P	15P	10P	05P	000	05D	10D	15D
1	F	76	310	660	640	310	590	130	100	120	90	50
2	F	71	270	250	240	270	360	440	590	390	0	360
3	F	68	190	200	420	310	590	330	190	520	70	0
4	F	67	230	200	200	210	200	210	220	200	180	620
5	F	72	270	340	270	320	320	380	180	730	0	0
6	F	62	230	250	320	250	250	270	290	280	410	600
7	F	72	180	250	170	290	330	250	510	230	500	520
8	F	67	270	240	310	290	190	280	270	190	180	210
9	F	68	220	230	310	530	600	620	660	510	310	170
10	F	65	140	170	120	140	470	130	140	380	90	100
11	F	73	110	100	100	100	90	80	80	90	70	40
12	F	62	160	170	220	250	160	270	200	80	0	0
13	F	72	340	350	420	410	380	380	270	420	620	600
14	F	70	140	150	170	160	210	450	140	0	0	0
15	F	70	280	290	250	300	310	420	630	0	0	0
16	M	65	250	590	240	240	190	250	150	150	120	0
17	M	62	230	210	250	210	210	180	150	120	120	120
18	M	69	190	170	180	230	190	220	180	190	170	270
19	M	68	200	190	170	190	700	240	220	230	190	430
20	M	78	440	210	500	340	540	310	610	390	380	270
21	M	73	220	160	200	340	160	170	210	170	180	420
22	M	62	230	230	200	190	190	170	160	270	100	60
23	M	64	390	200	450	150	670	0	0	0	0	0
24	M	70	280	320	340	350	410	330	290	350	300	420
25	M	70	220	220	220	210	230	300	230	410	120	110
26	M	73	210	190	210	190	260	190	220	260	40	65
27	M	72	130	130	140	240	190	190	150	240	0	0
28	M	71	180	140	170	610	160	140	350	130	100	90
29	M	64	210	200	180	180	280	0	0	0	0	0
30	M	68	300	320	500	230	190	130	830	140	120	100
31	F	25	170	180	180	190	190	190	150	120	130	100
32	F	35	150	170	100	480	90	90	90	560	270	80
33	F	23	480	220	220	510	540	400	460	180	100	500
34	F	36	190	190	180	190	190	200	180	160	120	100
35	F	22	180	190	190	210	210	200	220	200	150	220
36	F	26	270	300	450	310	370	170	140	110	90	80
37	F	24	540	480	450	490	330	340	230	180	110	90
38	F	25	70	50	610	50	720	740	720	670	90	50
39	F	23	180	180	240	300	480	270	230	310	290	270
40	F	26	180	160	160	140	140	120	120	140	120	120
41	F	24	240	240	240	200	180	160	140	90	70	0
42	F	20	120	110	130	160	230	170	230	230	80	70
43	F	21	200	160	190	300	200	150	170	220	100	90
44	F	23	150	150	150	150	100	120	100	120	100	100
45	F	22	160	150	160	260	160	240	150	180	160	390
46	M	25	140	150	330	400	390	240	280	100	70	50
47	M	23	200	220	230	380	380	390	330	300	170	100
48	M	23	300	230	230	220	170	190	130	110	90	70
49	M	27	210	220	210	230	250	220	190	150	100	90
50	M	23	370	320	570	150	430	380	360	130	130	90
51	M	25	150	160	160	150	110	120	110	100	80	70
52	M	25	220	230	210	220	220	200	350	150	120	110
53	M	38	180	180	360	230	250	260	220	190	140	110
54	M	24	540	650	820	640	530	570	370	500	40	40
55	M	25	230	270	500	510	530	330	430	110	100	50
56	M	25	160	180	170	190	200	170	250	180	620	290
57	M	20	120	110	110	120	110	100	90	90	110	60
58	M	26	210	190	210	160	400	140	210	110	210	60
59	M	35	160	160	340	180	160	150	110	80	50	40
60	M	22	220	210	220	270	300	260	310	290	420	540

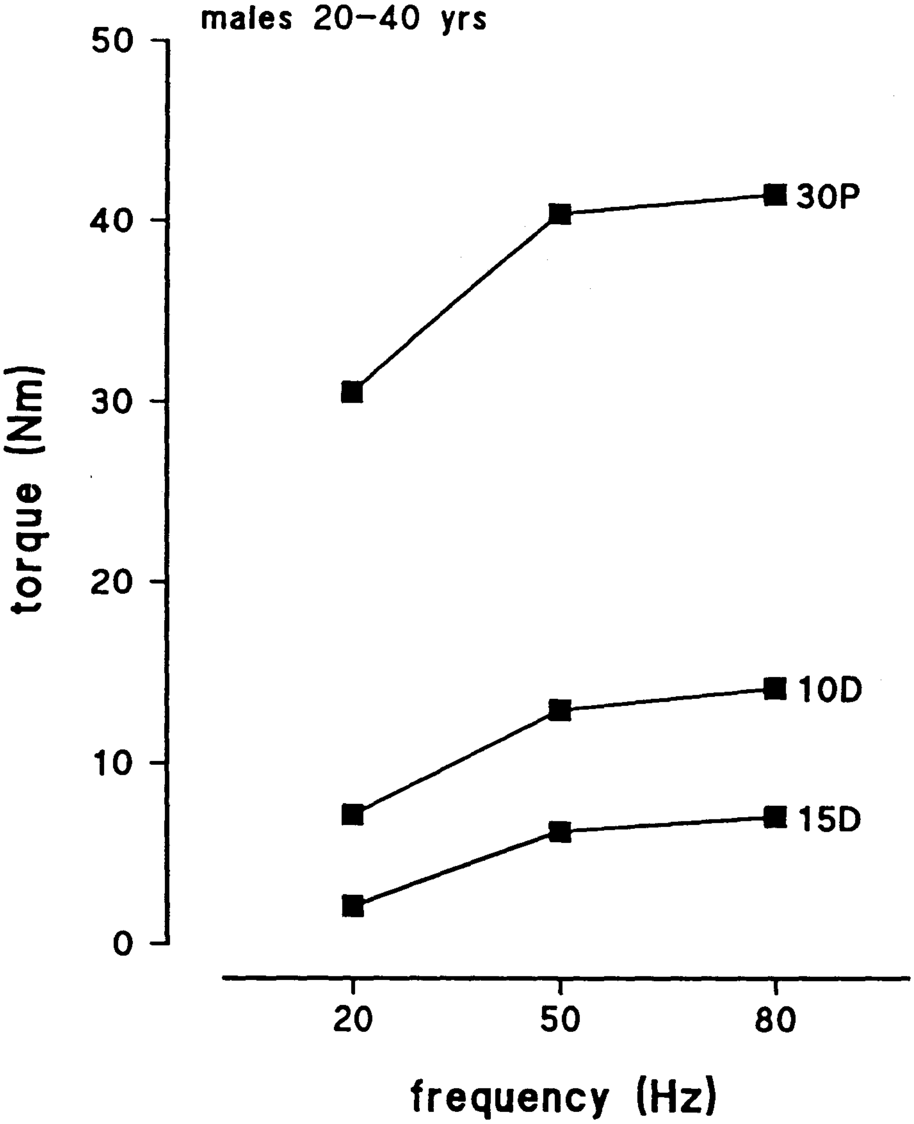
Appendix L

Table A12. Individual Data for the Twitch/Tetanus Ratios (20, 50, & 80 Hz) at 30°P and the Twitch/MVC Ratio at 15°P.

Subject (#)	Gender	Age (yr)	Twt/Tetanus ratio (30P) 20 Hz	 50 Hz	 80 Hz	Twt/MVC ratio (15P)
1	F	76	0.2210	0.1765	0.1790	0.0603
2	F	71	0.1710	0.1402	0.1284	0.0532
3	F	68	0.1930	0.1760	0.1731	0.0849
4	F	67	0.2171	0.1902	0.1902	0.1199
5	F	72	0.1960	0.1526	0.1457	0.0580
6	F	62	0.1631	0.1291	0.1251	0.0568
7	F	72	0.1801	0.1389	0.1429	0.0640
8	F	67	0.2332	0.2080	0.1997	0.1222
9	F	68	0.2196	0.2026	0.1935	0.2243
10	F	65	0.2700	0.2225	0.2031	0.0796
11	F	73	0.3152	0.1718	0.1469	0.0633
12	F	62	0.2468	0.1970	0.1860	0.0727
13	F	72	0.2144	0.1721	0.1647	0.0784
14	F	70	0.3307	0.2198	0.2313	0.0888
15	F	70	0.1523	0.1265	0.1166	0.0278
16	M	65	0.1689	0.1253	0.1120	0.0399
17	M	62	0.2302	0.1568	0.1481	0.0413
18	M	69	0.2378	0.1889	0.1809	0.0718
19	M	68	0.2472	0.1586	0.1532	0.0833
20	M	78	0.3027	0.2644	0.2842	0.1301
21	M	73	0.2053	0.1760	0.1712	0.1252
22	M	62	0.1918	0.1514	0.1481	0.0654
23	M	64	0.1692	0.1223	0.1121	0.0130
24	M	70	0.2233	0.1829	0.1726	0.1008
25	M	70	0.1699	0.1490	0.1463	0.0721
26	M	73	0.2836	0.2305	0.2201	0.1263
27	M	72	0.2945	0.2392	0.1945	0.0700
28	M	71	0.3104	0.2185	0.2183	0.0800
29	M	64	0.1657	0.1410	0.1418	0.0634
30	M	68	0.3360	0.2862	0.2807	0.1084
31	F	25	0.2064	0.1716	0.1675	0.0698
32	F	35	0.3136	0.2365	0.2257	0.1004
33	F	23	0.1980	0.1465	0.1457	0.0563
34	F	36	0.1549	0.1281	0.1246	0.0638
35	F	22	0.1975	0.1673	0.1626	0.1094
36	F	26	0.1446	0.1134	0.1113	0.0570
37	F	24	0.1378	0.0958	0.0864	0.0317
38	F	25	0.2316	0.2316	0.2142	0.0378
39	F	23	0.2628	0.1953	0.2267	0.0910
40	F	26	0.1475	0.1170	0.1232	0.0526
41	F	24	0.1568	0.1268	0.1258	0.0444
42	F	20	0.3039	0.2742	0.2539	0.0261
43	F	21	0.1778	0.1314	0.1269	0.0542
44	F	23	0.1158	0.0928	0.0930	0.0230
45	F	22	0.2024	0.1534	0.1513	0.0769
46	M	25	0.2011	0.1521	0.1514	0.0667
47	M	23	0.1497	0.0957	0.0910	0.0289
48	M	23	0.1633	0.1164	0.1186	0.0561
49	M	27	0.1357	0.1107	0.1034	0.0503
50	M	23	0.1973	0.1276	0.1255	0.0371
51	M	25	0.1659	0.1258	0.1373	0.0362
52	M	25	0.2210	0.1612	0.1600	0.1095
53	M	38	0.1657	0.1409	0.1392	0.0794
54	M	24	0.2437	0.1843	0.1402	0.0551
55	M	25	0.1854	0.1389	0.1380	0.0526
56	M	25	0.1106	0.0896	0.0870	0.0422
57	M	20	0.2029	0.1170	0.1043	0.0313
58	M	26	0.1889	0.1436	0.1500	0.0786
59	M	35	0.1404	0.1209	0.1151	0.0259
60	M	22	0.1808	0.1446	0.1394	0.0723

Appendix M

The Force-Frequency Curve for Males 20-40 years of age at Joint Angles 30°P, 10°, & 15°D.



Appendix N

ANOVA Table for Comparison of Total Torque Values for Females and Males Aged 20-40 Years and 60-80 Years at Joint Angles of 30°P - 15°D in 5° Increments.

```
ANALYSIS OF VARIANCE TABLE
2-Way Mixed Design - 2 Between Ss, 1 Within Ss

Source               Sum Sqr.       df        Mean Sqr.       F

Betw. Ss.             618.6771      59
age          -A       9.060547      1         9.060547       1.061153
gender       -B       125.9043      1         125.9043       14.74566
A x B                 5.562012      1         5.562012       .6514117
Error                 478.1503      56        8.538398

Within Ss.            1599.075      540
angle        -C       1328.449      9         147.6054       355.5495
A * C                 1.429932      9         .1588813       .3827106
B * C                 58.37671      9         6.486301       15.62409
A * B * C             1.584961      9         .1761068       .424203
Error                 209.2343      504       .4151473

F ( 1 , 56 ) = 1.061153   Probability = 0.30810
F ( 1 , 56 ) = 14.74566   Probability = 0.00057
F ( 1 , 56 ) = .6514117   Probability = 0.42855
F ( 9 , 504 ) = 355.5495   Probability = 0.00000
F ( 9 , 504 ) = .3827106   Probability = 0.94320
F ( 9 , 504 ) = 15.62409   Probability = 0.00000
F ( 9 , 504 ) = .424203   Probability = 0.92221
```

Appendix O

ANOVA Tables for Comparison of (a) TPT and (b) 1/2 RT for Females and Males Aged 20-40 Years and 60-80 Years at Joint Angles of 30°P - 15°D in 5° Increments.

(a)

Source		Sum Sqr.	df	Mean Sqr.	F
Betw. Ss.		168360.5	59		
age	-A	25410.25	1	25410.25	9.981852
gender	-B	274.75	1	274.75	.1079294
A x B		119.375	1	119.375	4.689381E-02
Error		142556.1	56	2545.645	
Within Ss.		675520	540		
angle	-C	479407.8	9	53267.53	140.3253
A * C		1286.75	9	142.9722	.3766387
B * C		2313.875	9	257.0972	.6772838
A * B * C		1193	9	132.5556	.3491976
Error		191318.6	504	379.6004	

F (1 , 56) = 9.981852 Probability = 0.00289
F (1 , 56) = .1079294 Probability = 0.73991
F (1 , 56) = 4.689381E-02 Probability = 0.81230
F (9 , 504) = 140.3253 Probability = 0.00000
F (9 , 504) = .3766387 Probability = 0.94597
F (9 , 504) = .6772838 Probability = 0.73131
F (9 , 504) = .3491976 Probability = 0.95748

(b)

Source		Sum Sqr.	df	Mean Sqr.	F
Betw. Ss.		172502.4	59		
age	-A	14498.88	1	14498.88	5.16057
gender	-B	84.125	1	84.125	2.994253E-02
A x B		584.625	1	584.625	.208085
Error		157334.8	56	2809.549	
Within Ss.		718500.3	540		
angle	-C	547966.1	9	60885.13	192.3705
A * C		4414.75	9	490.5278	1.549854
B * C		4824.625	9	536.0695	1.693746
A * B * C		1779.125	9	197.6806	.6245846
Error		159515.6	504	316.4993	

F (1 , 56) = 5.16057 Probability = 0.02538
F (1 , 56) = 2.994253E-02 Probability = 0.83942
F (1 , 56) = .208085 Probability = 0.65436
F (9 , 504) = 192.3705 Probability = 0.00000
F (9 , 504) = 1.549854 Probability = 0.12713
F (9 , 504) = 1.693746 Probability = 0.08719
F (9 , 504) = .6245846 Probability = 0.77766

Appendix P

ANOVA Table for Comparison of MVCs (Maximal Voluntary Contractions) for Females and Males Aged 20-40 Years and 60-80 Years at Joint Angles of 30°P - 15°D in 5° Increments.

```
ANALYSIS OF VARIANCE TABLE
-Way Mixed Design - 2 Between Ss, 1 Within Ss

Source                   Sum Sqr.        df       Mean Sqr.        F

Betw. Ss.                 79906.98       59
Age           -A          5993           1        5993             8.411206
Gender        -B          33836.25       1        33836.25         47.48935
A x B                     177.625        1        177.625          .2492976
Error                     39900.1        56       712.5018

Within Ss.                51737.02       540
Angle         -C          38948.13       9        4327.569         208.1863
A * C                     490.375        9        54.48611         2.621163
B * C                     1671.438       9        185.7153         8.934202
A * B * C                 150.4375       9        16.71528         .8041217
Error                     10476.65       504      20.787

F ( 1 , 56 ) = 8.411206   Probability = 0.00547
F ( 1 , 56 ) = 47.48935   Probability = 0.00000
F ( 1 , 56 ) = .2492976   Probability = 0.62522
F ( 9 , 504 ) = 208.1863   Probability = 0.00000
F ( 9 , 504 ) = 2.621163   Probability = 0.00598
F ( 9 , 504 ) = 8.934202   Probability = 0.00000
F ( 9 , 504 ) = .8041217   Probability = 0.61386
```

Appendix Q

ANOVA Table for Comparison of Tetanic Torque of Different Frequencies (20, 50, & 80 Hz) for Females and Males Aged 20-40 Years and 60-80 Years at Joint Angles of 30°P - 15°D in 5° Increments.

1= Age
2= Gender
3= Joint Angle
4= Frequency of Stimulation

```
    DESIGN  4 - way ANOVA, fixed effects
 DEPENDENT  1 variable (Repeated Measure)
   BETWEEN: 1-VAR1     ( 2):    1   2
            2-VAR2     ( 2):    1   2
    WITHIN: 3-RFACTOR1(10) x 4-RFACTOR2(3)

DDDDDDDDDDBDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD
css/3:    3      Summary of all Effects; design:
general   3      1-VAR1, 2-VAR2, 3-RFACTOR1, 4-RFACTOR2
manova    3
DDDDDDDDDDEDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDD4
          3   df     3    MS     3   df     3    MS     3          3
Effect    3 Effect   3  Effect   3 Error    3  Error    3    F     3 p-level
DDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDD4
:1        3        1 3 10842.90 3        56 3 1191.105 3   9.1032 3  .003834
:2        3        1 3 33528.32 3        56 3 1191.105 3  28.1489 3  .000001
:3        3        9 3 12297.94 3       504 3   36.217 3 339.5671 3 0.000000
:4        3        2 3  7460.54 3       112 3   15.296 3 487.7353 3 0.000000
 12       3        1 3  2356.21 3        56 3 1191.105 3   1.9782 3  .165[illegible]
:13       3        9 3   104.03 3       504 3   36.217 3   2.8723 3  .002575
:23       3        9 3   544.82 3       504 3   36.217 3  15.0434 3  .000000
:14       3        2 3   189.57 3       112 3   15.296 3  12.3933 3  .000014
:24       3        2 3   593.95 3       112 3   15.296 3  38.8299 3  .000001
 34       3       18 3    49.16 3      1008 3    1.975 3  24.8988 3 0.000000
 123      3        9 3   137.33 3       504 3   36.217 3   3.7919 3  [illegible]
 124      3        2 3    35.92 3       112 3   15.296 3   2.3483 3  .100221
 134      3       18 3     1.40 3      1008 3    1.975 3    .7080 3  .805[illegible]
 234      3       18 3     3.77 3      1008 3    1.975 3   1.9068 3  .012[illegible]
 1234     3       18 3     1.68 3      1008 3    1.975 3    .8487 3  .64[illegible]
DDDDDDDDDDADDDDDDDDDDDADDDDDDDDDDADDDDDDDDDDADDDDDDDDDDADDDDDDDDDDADDDDDDDDDD
arked effects significant at p≤.0500
```

Appendix R

ANOVA Table for Comparison of Rise Time of Tetanic Torque of Different Frequencies (20, 50, & 80 Hz) for Females and Males Aged 20-40 Years and 60-80 Years at Joint Angles of 30°P - 15°D in 5° Increments.

1= Age
2= Gender
3= Joint Angle
4= Frequency of Stimulation

```
     DESIGN: 4 - way ANOVA, fixed effects
  DEPENDENT: 1 variable (Repeated Measure)
    BETWEEN: 1-VAR1     ( 2):   1   2
             2-VAR2     ( 2):   1   2
     WITHIN: 3-RFACTOR1(10) x 4-RFACTOR2(3)
```

```
ZDDDDDDDDDDBDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD
3 css/3:    3      Summary of all Effects; design:
3 general   3      1-VAR1, 2-VAR2, 3-RFACTOR1, 4-RFACTOR2
3 manova    3
CDDDDDDDDDDEDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDDBDDDDDDDDDD
3           3    df    3    MS     3    df     3     MS     3           3
3 Effect    3  Effect  3  Effect   3  Error    3   Error    3     F     3 p-level
CDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDDEDDDDDDDDDD
3 1         3         1 3 325624.5 3        56 3 194256.4 3  1.67626 3  .200735
3 2         3         1 3  68820.5 3        56 3 194256.4 3   .35428 3  .554100
3*3         3         9 3 506410.4 3       504 3  32108.4 3 15.77191 3  .000000
3*4         3         2 3 131375.5 3       112 3  32675.3 3  4.02064 3  .020592
3 12        3         1 3  71064.5 3        56 3 194256.4 3   .36583 3  .547730
3 13        3         9 3   5930.7 3       504 3  32108.4 3   .18471 3  .995667
3 23        3         9 3  20430.5 3       504 3  32108.4 3   .63630 3  .766233
3 14        3         2 3  18984.9 3       112 3  32675.3 3   .58102 3  .561006
3 24        3         2 3   8437.5 3       112 3  32675.3 3   .25822 3  .772881
3*34        3        18 3  26316.5 3      1008 3  10232.9 3  2.57175 3  .000337
3 123       3         9 3  16764.7 3       504 3  32108.4 3   .52213 3  .858839
3 124       3         2 3  23812.6 3       112 3  32675.3 3   .72876 3  .484779
3 134       3        18 3   9422.9 3      1008 3  10232.9 3   .92084 3  .552802
3 234       3        18 3  12119.4 3      1008 3  10232.9 3  1.18435 3  .266358
3 1234      3        18 3  11419.0 3      1008 3  10232.9 3  1.11590 3  .330231
@DDDDDDDDDDADDDDDDDDDDADDDDDDDDDDADDDDDDDDDDDDADDDDDDDDDDADDDDDDDDDDADDDDDDDDDD
*Marked effects significant at ps.0500
```

Appendix S

ANOVA Table for Comparison of the Twitch/Tetanus Ratio at 30°P for Females and Males Aged 20-40 Years and 60-80 Years.

```
Source                    Sum Sqr.        df        Mean Sqr.       F

Betw. Ss.                 .4013127        59
age             A         5.984545E-02    1         5.984545E-02    10.36162
gender         -B         2.031326E-03    1         2.031326E-03    .351703
A x B                     1.599741E-02    1         1.599741E-02    2.769785
Error                     .3234385        56        5.775687E-03

Within Ss.                .1202423        120
frequency      -C         9.166813E-02    2         4.583406E-02    187.1146
A * C                     7.238388E-04    2         3.619194E-04    1.47775
B * C                     3.471375E-04    2         1.735687E-04    .7086967
A * B * C                 7.295609E-05    2         3.647804E-05    .1489431
Error                     2.743021E-02    112       2.449125E-04

F ( 1 , 56 ) = 10.36162   Probability = 0.00250
F ( 1 , 56 ) = .351703   Probability = 0.56249
F ( 1 , 56 ) = 2.769785   Probability = 0.09782
F ( 2 , 112 ) = 187.1146   Probability = 0.00000
F ( 2 , 112 ) = 1.47775   Probability = 0.23109
F ( 2 , 112 ) = .7086967   Probability = 0.49893
```

Post Hoc Test Used was Tukey's HSD Test

First Digit: Age 1= 20-40 Year-Olds, 2= 60-80 Year-Olds;
Second Digit: Gender 1= Female, 2= Male;
Third Digit: Frequency 1= 20 Hz, 2= 50 Hz, 3= 80 Hz.

```
SUMMARY OF TUKEY'S HSD TEST

    123 122 113 112 213 212 121 223 222 111 211
221 .01 .01 .01 .01 .01 .01 .01 .01 .01 .01 ...
211 .01 .01 .01 .01 .01 .01 .01 .01 .01 .01
111 .01 .01 .01 .01 .01 .05 .05 ... ...
222 .01 .01 .01 .01 ... ... ... ...
223 .01 .01 .01 .05 ... ... ...
121 .01 .01 .05 ... ... ...
212 .01 .01 ... ... ...
213 .01 .01 ... ...
112 .01 .01 ...
113 .01 .01
122 ...
```

Appendix T

ANOVA Table for Comparison of The Twitch/MVC Ratio at 15°P for Females and Males Aged 20-40 Years and 60-80 Years.

```
ANALYSIS OF VARIANCE TABLE

Source                Sum Sqr.      df      Mean Sqr.      F - value     Prob.
------------------------------------------------------------------------------
age                   7.36377E-03    1      7.36377E-03    6.007131      0.01651
gen                   6.606799E-04   1      6.606799E-04   .5389618      0.47264
gen*age               4.914152E-05   1      4.914152E-05   .0400881      0.82255
Error                 6.864693E-02   56     1.225838E-03
------------------------------------------------------------------------------
Total                 7.672052E-02   59
```