In the Name of God

the Compassionate and the Merciful

H Reflex Inhibition During Muscular Fatigue in man

A Thesis Submitted for

the Degree of Doctor of Philosophy

in the Faculty of Medicine

by

Gholamreza-Olyaei

BSc and MSc in Physiotherapy

February 1995

Division of Neuroscience and Biomedical Systems,

Institute of Biomedical Life Sciences,

University of Glasgow

Thesis
10065
Copy 1

Dedicated to
my family

Contents   **Page number**

Figures:

Results:

Discussion:

Tables:

Discussion:

Abbreviations

Adenosine Triphosphate......................	**ATP**
Analogue to Digital...........................	**A/D**
Anterior Tibial Muscle......................	**TA**
Centimetre.....................................	**cm**
Electromyography.............................	**EMG**
Excitatory Post Synaptic Potentials.....	**EPSPs**
F Wave..	**F**
Functional Electrical Stimulation........	**FES**
Hertz...	**Hz**
Hoffmann Reflex..............................	**H**
Integrated Electromyography..............	**IEMG**
Maximal H Reflex............................	$\mathbf{H_{max}}$
Maximal M Wave.............................	$\mathbf{M_{max}}$
Maximal Voluntary Contraction..........	**MVC**
Millimetre Mercury Pressure.............	**mm. Hg**
Milli Second...................................	**msec**
Milli Volt......................................	**mV**
Motor Compound Action Potential......	**M**
Motor Threshold..............................	**T**
Personal Computer...........................	**PC**
Phosphoryl Creatine..........................	**PC**
Second...	**sec**
Volt...	**V**

Acknowledgements

I would like to express my specific appreciation to my supervisor Dr Ronald. H. Baxendale for his advice, helpfulness and composure in guiding me throughout this project.

I would greatly like to acknowledge the Ministry of Health and Medical Education of Iran for awarding me a scholarship to carry out this study.

I extend my gratitude to Professor McGrath, Dr Ferrell and Dr Pollock for giving me the opportunity to carry out this research in the department of Physiology.

It is also a great pleasure to acknowledge the assistance of the following persons:

To Dr Lucas my auditor, for his scientific and friendly chats during the course of my study.

To technician supports of the physiology department especially Mr Sinclair and Mr McCall in Electronic laboratories.

To Medical Illustration staff who also provided great help to prepare the illustrations for congresses.

To Mrs Collin and Mr Wallace for their help in the laboratory.

This project would not have been completed without volunteers from students and staff of the Institute of Physiology who generously gave their time on several occasions and hours. I am indebted to all of them.

I would like to express the inestimable help of my parents during the whole period of my studies, to animate, help and motivate me toward the completion of my meditation.

Lastly, and certainly not least, I have to thank my wife for her constant support throughout this project.

Declaration and list of publications

The experimental work and other research which make up this thesis were carried out entirely by myself. No part of the material has previously been presented for any other degree.

Part of work contained in this thesis has been, or will be published as follows:

1. Olyaei, G. R. and Baxendale, R. H. (1993). The effects of fatiguing electrical activity of the anterior tibial muscles on its own H reflex excitability. Proceeding XXXIInd Congress. I.U.P.S, Glasgow 170.40/p.

2. Olyaei, G. R. and Baxendale, R. H. (1994). The effects of fatiguing voluntary activity on the H reflex excitability of the anterior tibial muscles in Man. Journal of Physiology 477, 58-59P. (Oral communication).

3. Olyaei, G. R. and Baxendale, R. H. (1994). The effects of fatiguing voluntary activity of the anterior tibial muscle on the soleus H reflex excitability in Man. Journal of Physiology 479, 160-161P.

4. Olyaei, G. R. and Baxendale, R. H. (1994). The effects of muscles fatigue on H reflex excitability in Man. International symposium of Alpha and Gamma Motor Systems. Sherrington School of Physiology, London (in press).

5. Olyaei, G. R. and Baxendale, R. H. (1994). The effects of fatiguing voluntary activity of the quadriceps muscle on the soleus H reflex excitability. Journal of Physiology 483, 81-82P. (Oral communication).

Summary

It is well known that the motoneurone firing rates associated with muscle fatigue are reduced during sustained voluntary contraction and it has been suggested that one reason for this decline might lie in reflex inhibition of motoneurone pools by muscle afferents sensitised by the fatiguing contraction. Garland and McComas (1990) demonstrated that fatigue of soleus causes a depression of its H reflex excitability. Soleus is difficult to fatigue and so the objective of the present study was to extend this work by examining the reflex effects of fatiguing contractions in other muscles. The effects of fatiguing activity of the anterior tibial muscles on their own H reflex excitability and on the H reflex of their antagonist muscle, soleus also were examined. Alternatively quadriceps femoris muscle was fatigued to see how extensive the effect is. The main aim of this research was to determine the effects of fatiguing activity on the excitability of anterior tibial and soleus H reflexes. In addition, the differences between voluntary fatiguing activity and involuntary exercise by direct muscle stimulation were investigated.

Experiments were performed on 50 neurologically normal subjects. Their ages ranged from 17 to 42 years. Subjects were seated in a semi-reclined position with their knee and ankle supported at 110° and 90°. Maximal voluntary dorsiflexions were recorded at intervals through the experiment. EMG was recorded with surface electrodes placed over the anterior tibial muscles or over soleus. H reflexes of about half maximal amplitude were elicited by stimulation of the tibial nerve in the popliteal

fossa or common peroneal nerve on the head of fibula with single pulses, 0.1-0.5 ms duration, at intervals of 5 sec. The intensities of the stimulus were adjusted to deliver approximately half maximal H reflex amplitudes. In most experiments it was necessary for subjects to make a weak voluntary contraction of the anterior tibial muscles before an H reflex could be elicited. However, consistent H reflexes were recorded in relaxed soleus in all subjects. The mean of 10-15 successive tests was compared before and after anterior tibial muscle activity. At least 30 seconds elapsed after the end of contraction before the first test was made. In addition, a wider range of stimulus intensities was employed to identify maximal M and H waves. Fatigue was induced by intermittent voluntary isometric contractions at 30% of MVC, 7 sec on, 3 sec off, sustained for up to 9 minutes. These periods of muscle activity were performed with and without an arterial occlusion cuff round the midthigh inflated at least 150 mmHg to obstruct the circulation. Alternatively, the anterior tibial muscles were fatigued by transcutaneous electrical stimulation of the muscle belly at 20 Hz at the highest intensity the volunteer found tolerable. Stimulation was delivered for 7 seconds and then turned off for 3 seconds. This stimulation cycle was repeated until the tetanic force had fallen to about half its original value. Approximately equivalent fatigues, as judged by reductions in MVC were produced by electrical and voluntary exercise.

H reflexes in anterior tibial muscles were depressed significantly by fatiguing activity of anterior tibial muscles. Soleus H reflexes were depressed significantly by fatiguing activity of anterior tibial and quadriceps muscles. No significant difference was observed between the

reflex changes accompanying voluntary and electrically induced muscle activity. The result does not depend on the nature of exercise but the extent of the depression of H reflexes increases as the fatigue increases. All the changes in H reflexes, forces were restored progressively to control values after a 10 minute recovery period. The fatigue developed during experiments was relatively severe, particularly when the blood flow was occluded. In experiments using direct muscle stimulation, the mean force was reduced by approximately 40% and the half relaxation time increased by more than 70%.

It seems that a reflex inhibitory system is active during fatigue, which decreases the motoneurone excitability in conjunction with the reduction in force. This reflex is mediated, due to metabolic or chemical changes which could be substantially projected by small diameter afferent fibres from fatigued muscles. This agree with Garland and McComas (1990) who stated that the relative stability of the M and M_{max} waves and the H and H_{max} reflexes were decrease, suggests that this reduction could be a reflex phenomenon rather than neuromuscular junction failure.

1. Introduction

The Hoffmann (H) reflex is a monosynaptic reflex which can be used to assess the motoneurone pool excitability noninvasively. The amplitude of the H reflex can be altered by many factors from supra spinal influences to segmental reflex actions.

It is known that H reflex changes with short term activity such as the Jendrassik manoeuvre which potentiates motoneurone excitability. In addition, many studies have been done on H reflex excitability where agonist contraction increases whilst antagonist activity decreases the amplitude of H reflex. Thus, the excitability of motoneurone can easily be measured which is established as the H_{max}/M_{max} ratio.

In the longer term activity associated with fatigue has been shown to produce a reduction in H reflex amplitudes. This was first shown by Garland and McComas (1990) whereby soleus muscle was chosen as a fatigue resistant muscle during their experiments. Fatigued induced electrically excluded central factors in their experiments.

The present study used, the anterior tibial muscles which are predominantly used in phasic movements (Garland et al., 1988a). To find out the relationship between the ankle plantarflexor to dorsiflexor muscles. It is clear that soleus is a slow, postural muscle used during standing. The soleus motoneurone pool receives strong inputs from Ia afferents and shows strong monosynaptic and H reflexes. The anterior tibial motoneurones receive weaker inputs from Ia afferents and so show weaker H reflexes. In addition, anterior tibial motoneurones are

subjected to stronger descending influences (Belanger and McComas, 1981). On the other hand there is some activity in terms of linear gravity from pretibial muscles to interact with soleus muscle.

To compare the central and peripheral factors during experiments, anterior tibial muscles are exercised either voluntary or electrically. The H reflex and M wave amplitudes are compared to distinguish the influence of peripheral and central fatigue, or the existence of reflex phenomena.

These changes will be investigated on anterior tibial muscles. The effect of activity in the anterior tibial muscles will be studied on the anterior tibial H reflex and the H reflex of the antagonist muscle soleus. The next aim of study is to find out the effect of quadriceps group muscles activity and looking on soleus H reflex changes. The quadriceps group muscles are synergist and located more proximal than soleus and the size of this muscle is quiet bigger than anterior tibial muscles. Thus, another pair of muscles are employed to see how the extensive of effect is.

1.1. General history

The modern analysis of reflex physiology began with Charles Sherrington in the nineteenth century. He developed an experimental preparation of cats whose brain stems had been transected.

Decerebrated cats show increased reflexes and muscle tone in the extensor muscles of ·their limbs, and can be used to study postural control. In examining the reflexes in hind limbs of decerebrated cats Sherrington and Liddell (1924) showed that when they attempted to flex a rigidly extended limb, the limb resisted by active muscle contraction. This action is called the stretch or myotatic reflex (myotatic consists of two Greek words meaning extended muscle).

B. H. C. Matthews recorded from spindle afferents in 1933 and showed that they were stretch sensitive.

The afferent fibres which mediated the stretch reflex were investigated by David Lloyd in 1940s. He demonstrated that the Ia afferents were activated in the stretch reflex.

Conduction velocity of nerve fibres

In mammals, axons subserving different functions have different conduction velocity whereby motor fibres conduct more slowly than cutaneous fibres.

Nerve fibres may be divided into three main groups, A, B and C. According to axonal diameter (including the myelin sheath if present) and to the speed of conduction. Group A, is subdivided into α, β, γ and δ. Group C contains somatic afferents and visceral efferents. The

Erlanger/ Gasser and the Lloyd/ Hunt classifications of nerves fibres are shown in the tables 1a and b.

Table 1a. The Erlanger/ Gasser classification of nerve fibres.

Fibre type	Function	Diameter	Velocity (m/s)
Aα	Primary muscle spindle afferents, motor to skeletal muscle	8-20	50-120
Aβ	Cutaneous touch and pressure afferents	5-12	30-70
Aγ	Motor to muscle spindles	2-8	10-50
Aδ	Cutaneous temperature and pain afferents	1-5	3-30
B	Sympathetic preganglionic	1-3	3-15
C	Cutaneous pain and temperature afferents, sympathetic postganglionic	<1	<2

Table 1b. The Lloyd/ Hunt classification of nerve fibres.

Group	Function	Diameter	Velocity (m/s)
I	Primary muscle spindle afferents and afferents from tendon organs	12-20	70-120
II	Joint mechanoreceptors and afferents from spindle secondary endings	4-12	24-70
III	Deep pressure sensors in muscle	1-4	3-24
IV	Unmyelinated pain fibres	<1	<2

Table 1. These tables illustrate group, function, diameter and velocity of nerve fibres in cat. Table 1a shows the Erlanger/ Gasser and table 1b shows the Lloyd/ Hunt classifications of nerve fibres.

However, in human studies the results are different from animals. Macefield, Gandevia and Burke in 1989 reported that the mean conduction velocities of the lowest threshold muscle and cutaneous afferents were respectively, 74.7 ± 6.5 m/sec and 80.3 ± 6.7 m/sec for median nerve, 67.2 ± 10.2 m/sec and 67.5 ± 10.5 m/sec for the ulnar nerve, and 54.7 ± 3.4 m/sec and 52.8 ± 3.2 m/sec for the tibial nerve. For upper and lower limb nerves the conduction velocities of low-threshold muscle and cutaneous afferents were not significantly different when measured over the same proximal segment. In previous studies (Burke et al., 1983), had found that in human lower limb, muscles afferents conduct about 5-10 m/sec faster than cutaneous afferents.

Shefner and Logigan (1994) also investigated the motor and sensory conduction velocity of the isolated fibre populations in human sciatic nerve. The mean conduction velocity was 57.6 m/sec for muscle afferent fibre (Ia afferents), 55.1 m/sec for cutaneous afferent (II afferents) and 52.4 for motor (α efferents) and 56.3 m/sec for mixed nerve. There was significantly different between Ia afferent fibres and motor axons conduction velocities.

1.2   Anatomy

Soleus muscle

It arises by tendinous fibres from the back of the head and from the upper one-forth of the posterior surface of the shaft of the fibula; from the popliteal line and the middle one-third of the medial border of tibia. The muscular fibres end in a flat tendon which covers the posterior

surface of the muscle, and finally joins with the tendon of the gastrocnemius, and forms with it the tendon calcaneus. This muscle innervated by the tibial nerve, the nerve roots are mainly S_1 and S_2. Its action is plantar flexion of the foot.

Anterior tibial muscle

Anterior tibial is the first muscle located on the anterior border of the tibia 1cm to 2 cm to this border on the lateral side of the tibia, adjacent to extensor hallucis longus and extensor digitorum longus muscles. It originates from the lateral condyle and upper one-half or two-thirds of the lateral surface of the shaft of the tibia. The fibres run vertically down wards and end in a tendon which is apparent on the anterior surface of the muscle at the lower third of the leg. It passes through the superior and inferior extensor retinacula, and is inserted into the medial and under surfaces of the medial cuneiform bone, and the base of the first metatarsal bone. This muscle is innervated by deep common peroneal nerve, the nerve roots are L_4 and L_5, mainly L_5. Its action is dorsiflexion and inversion of the foot.

Quadriceps femoris muscle

This is the most powerful muscle of the human body. It consists of four muscles: Rectus femoris, vastus lateralis, vastus medialis and vastus intermedius. They arise from anterior inferior iliac spine and posterior brim of acetabulum, intertrochanteric line, medial and lateral lip of linea aspera, anterior and lateral surfaces of the shaft of the femur and joining together to produce the common patellar tendon which inserts on the

tibial tuberosity. These muscles are innervated by femoral nerve, the nerve roots are L_2, L_3 and mainly L_4. Quadriceps femoris is a powerful extensor of the knee joint during standing, walking and running actions. In addition, rectus femoris contributes in hip flexion.

1.3   Monosynaptic reflexes

The tendon jerk

The tendon jerk is a reflex elicited by a brief stretch of the muscles. Almost every doctor elicits this reflex when he performs a physical examination. This test has two major purposes. First, if the reflex can be elicited, it shows that both the sensory and motor nerve connections are intact between the muscle and spinal cord. Second, it can help determine the degree of excitability of the motoneurone pool. The tendon reflex is a phasic stretch reflex which can be evoked by a tendon tap direct on the tendon of a muscle. During the stroke of a hammer on the tendon of a muscle, the muscle will be briefly stretched. Then primary muscle spindle endings are activated, and after a short latency excitatory post synaptic potentials (EPSPs) are produced in the homonymous motoneurones. Some of these EPSPs were above threshold, and induced motor fibre activity which produced a slight twitch of that muscle. Figure 1 shows a monosynaptic stretch reflex pathway.

The Monosynaptic Reflex Arc
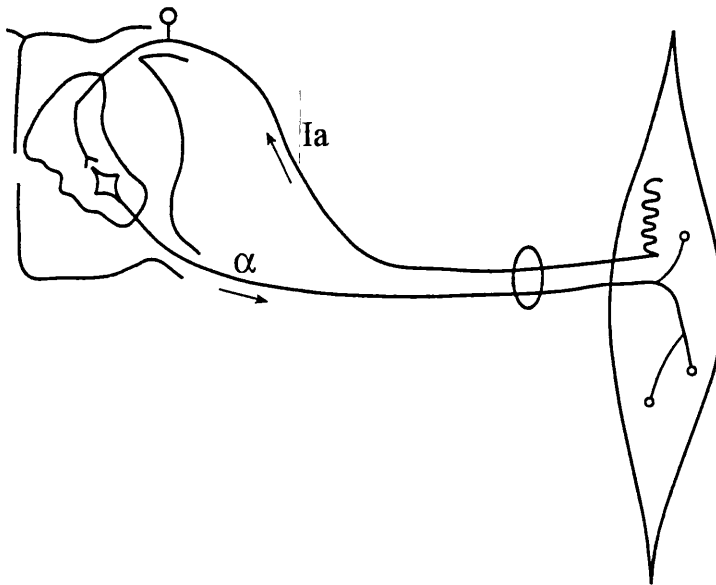
Figure 1. This picture shows reflex arc of the monosynaptic reflex. This arc consists of the Ia afferent fibres originating from muscle spindles to motoneurone and back to the muscle via α motor axon.

The differences between the Achilles tendon jerk and soleus H reflex were investigated by Burke et al. (1983). They found that the response of soleus muscle afferents to mechanical stimuli consisted of a dispersed volley, beginning 3.5-7.0 msec after percussion of tendon, increasing to a peak over 6.5-11.0 msec, and lasting 25-30 msec, depending on the strength of percussion. Electrical stimuli to the tibial nerve near motor threshold produced a synchronised volley, the conduction velocity in fastest fibres was 62-67 m/sec, and in the slowest fibres was 36-45 m/sec.

H reflex

This response is usually elicited in the calf muscles by using electrical stimulation of the posterior tibial nerve in the popliteal fossa, as originally shown by Piper (1912) and then clearly described by Hoffmann (1918; 1922). He demonstrated that after stimulation there were two components, the former which was named the M response was due to direct activation of the axons of the alpha motoneurones. It has a constant latency of about 5 msec.

The latter, which has a latency of about 35 msec is a monosynaptic reflex which could be elicited in isolation, i.e. without evoking the M response. This was called the Hoffmann-reflex, or "H" reflex by (Magladery and McDougal, 1950). In many nerves, the very largest diameter fibres are Ia afferents. Sub motor threshold current activates the large, fast-conducting group Ia afferent fibres from muscle spindles. The slower fibres within the soleus are mainly responsible for the reflex evoked twitch (Buchtal and Schmalbruch, 1970).

1.4   Literature review

Methodology of eliciting H reflex

This has been described in detail in the classical paper by Hugon (1973). The H reflex can be elicited with the subject lying on a bed in the prone position, or in the supine position, or more easily with the subject sitting in a suitable chair. Each position has some advantages and disadvantages. For example the prone position with a foot suspended over the end of the bed, seems to offer an easier approach to the popliteal fossa for using electrical stimulation and to the calf muscles for recording. However, to keep the knee and ankle joints at a standard position requires some support of the limbs.

The prone position is not easily tolerated if the experiments take a long time especially for fat people or older patients with respiratory problems. The sitting position is more comfortable for the subject and it permits the investigators do their experiments more conveniently. However, it needs some supporting frame to hold the leg in specified positions (Hugon, 1973).

During experiments, a general requirement is that the subject should be relaxed and the limb position should be kept passively by the equipment rather than by postural muscle activity of the subject. It is essential that the subject be given time to adapt to the apparatus before recording starts. The head and neck position should be supported in order to prevent vestibular influences (Desmedt, 1973).

Physiology and characteristics of H reflex

Motorneurone pool

The cell bodies of motoneurones that innervate each muscle are located in motoneurone pools. According to the proximal-distal rule, the motoneurones innervating the most proximal muscles are located medially, while those innervating more distal muscles are located progressively more laterally. In addition, according to the flexor-extensor rule, motoneurones that innervate extensor muscles lie ventral to those innervating flexor muscles. The motoneurones of soleus muscle consist of S_1 and S_2 segments, the anterior tibial of L_4 and L_5 segments and quadriceps femoris of L_2, L_3 and L_4 segments.

These anatomical relationships account for an important functional difference whereby proximal muscles (especially the extensor muscles of the legs) are mostly used to maintain equilibrium and posture, while distal muscles (especially the upper limbs) are used for fine delicate movements (Gordon and Ghez, 1994).

Motor unit

In 1925 Liddell and Sherrington introduced the term 'motor unit" to designate the basic unit of motor function. The motor unit includes, the cell body of the alpha motoneurone, the axon of the motoneurone, the neuromuscular junction and the muscle fibres innervated by that neurone. Disorders of motor unit function have recently been reviewed by Rowland (1994).

Each motoneurone innervates a number of skeletal muscle fibres, but each muscle fibre is innervated by only one motoneurone. Therefore, all muscle fibres innervated by a single motoneurone contract simultaneously in response to an action potential in the motor axon. The number of muscle fibres innervated by a single motoneurone is called the innervation ratio. This ratio varies considerably from one muscle to another, approximately in proportion to the size of that muscle. In muscles that control fine movements for example, in human extraocular muscles, which are very small, the ratio is about 10 and in the hand muscles, which are somewhat larger, it is about 100. In contrast, in the gastrocnemius muscles used in walking, there are about 2000 muscle fibres in each motor unit (Gordon and Ghez, 1994).

A single muscle can comprise hundreds of motor unit, and for example the anterior tibial muscle in man is estimated to contain about 445 motor units (Enoka and Stuart, 1985).

Muscle receptors

For effective control of the muscle, the central nervous system needs extensive information about the lengths of the muscles and the forces they generate. The proprioceptive information is transmitted to the central nervous system by two types of muscle receptors e.g. muscle spindles and Golgi tendon organs. The former one signals changes in length while the latter one signal changes in tension. This information reaches the highest levels within the nervous system where it is responsible for perception of limb position and is used in planning and

controlling movements. At the segmental levels, muscle receptors control motor behaviour through reflexes.

Muscle spindles are innervated by group I (large myelinated) and group II (smaller myelinated) afferent fibres, Golgi tendon organs are innervated only by group I afferent fibres. The group I afferents innervating muscle spindles are called group Ia afferents and those innervating tendon organs have slightly smaller diameters and are called group Ib afferents (Hunt, 1954). Muscle spindles are encapsulated structures, each one has a group of specialised muscle fibres called intrafusal fibres with sensory and motor innervation (Gordon and Ghez, 1994).

The motor and sensory nerve conduction velocities of the isolated fibre populations in human sciatic nerve were investigated by Shefner and Logigan (1994). The mean conduction velocity was 57.6 m/sec for muscle afferent fibres, 55.1 m/sec for cutaneous afferents and 52.4 for motor and 56.3 m/sec for mixed nerve. The conduction velocities of Ia afferent fibres and motor axons were significantly different.

The connections between afferents and motoneurones

Generally, intrafusal and extrafusal fibres receive separate motor supplies. This was first described by Leksell (1945), who established that the intrafusal fibres are innervated by small gamma motoneurones while the extrafusal fibres are innervated by larger alpha motoneurones. Thus, the discharge rate of muscle spindle afferents can be modulated by the gamma motoneurones.

The monosynaptic connection between α motoneurones and Ia afferents was confirmed in the 1950s by Eccles and his coworkers through intracellular recordings from motoneurones. When muscles are stretched the muscle spindle primary and secondary sensory endings increase their firing rate. The activity in Ia fibres excites motoneurones to both homonymous and synergist muscles and inhibits antagonist motoneurones.

Although group II spindle afferents have monosynaptic excitatory connections with homonymous motoneurones this is relatively weak (Gordon and Ghez, 1994). The main connections of group II afferents to motoneurones are polysynaptic (Eccles and Lundberg, 1959). Group Ib afferents from Golgi tendon organs also make polysynaptic connections to motoneurones (Gordon and Ghez, 1994).

Most reflex actions between sensory nerves and motoneurone pools are mediated via polysynaptic pathways. The very special connectivity leading to the H reflex where a peripheral nerve is stimulated by a weak stimulus intensity just near threshold. The H reflex occurs preferentially in small motor units and so probably follows the classical size principle for motoneurone recruitment. Hugon (1973), showed that stimulation strong enough to elicit near maximal M waves is needed to occlude the H-reflex completely. Thus the reflex is hardest to occlude in motoneurones with the highest thresholds to electrical stimulation. These are almost certainly the smallest members of the motoneurone pool. Hugon estimated that up to 75% of the soleus motoneurone pool may be activated in H reflexes, though the mean excitability is lower at about 52%.

H reflexes can be used to measure the excitability of the motoneurone pool. Changes in stimulus intensity induce specific effects upon the size of the M and H waves. As the stimulus intensity increases, the H reflex amplitude grows to a maximum and then decreases progressively. The M wave amplitude rises along a sigmoid curve and levels off when all motor fibres had been recruited (Angel and Hofmann, 1963).

The amplitude of the H reflex, when it first appears, is larger than of the direct M response. This occurs because afferent thresholds are generally lower than motor fibre thresholds. This provides an input to the motoneurone pool sufficiently strong to elicit reflex firing of the most excitable motoneurones before the most excitable motor axons are active. The H reflex does not include muscle spindle receptor activation, but this reflex arc is similar to that for the spindle-dependent phasic myotatic (deep tendon reflex) which is produced by muscle stretch. The appearance of calf H and Achilles tendon reflexes are highly correlated (Katirji and Weissman, 1988; Weintraub et al., 1988).

The H reflex is reduced as the intensity of the stimulus is increased. This inhibition has been attributed to "collision" of orthodromic impulses by antidromic conduction in motor axons (Magladery and McDougal, 1950). In addition, it is known that Renshaw cells are activated by antidromic activation of motor roots (Renshaw, 1941) and discharge more strongly and with shorter latency by increasing stimulus intensity (Renshaw, 1946). Thus, H reflex could be inhibited through Renshaw cells. Direct motoneurone to motoneurone connections are also present and could be involved in H reflex inhibition (Gogan, 1977). Large H reflexes, however, are obtained from calf muscles even with

supramaximal stimulation if the stimuli are timed appropriately with phasic contractions of the muscles (Gottlieb and Agarawal, 1976).

The relationship of H reflex to longer latency F wave

The H reflex is a monosynaptic reflex obtained with low intensity stimulation close to the motor threshold. The upper limit of normal latencies for calf H reflexes is 35 ms, and for flexor carpi radialis H reflexes is 20 ms (Fisher, 1992). The F wave is a late muscle potential response, which is obtained by high intensity antidromic stimulation of anterior horn cells and therefore is always preceded by an M response (Magladery and McDougal, 1950). Motoneurones are activated by depolarisation at low thresholds following invasion of the soma (Eccles, 1955). This occurs whether the resultant action potentials is orthodromic or antidromic. Upper limits of normal for minimal F latencies are 31, 36, and 61 ms when recording from hand, calf, and foot muscles, respectively (Fisher, 1992).

The amplitude of the H reflex when it first appears is larger than of the direct M response. The amplitude decreases as the intensity of the stimulus is increased (Andrews and Bruyninckx, 1986). However, F waves appear at a certain stimulus intensity and then tend to increase in amplitude with stronger nerve volleys (Magladery and McDougal, 1950). A conventional stimulus intensity for F waves is 25% above supramaximal (Fisher, 1992). The amplitude of the F wave is usually only about 1% that of the M response (Andrews and Bruyninckx, 1986).

The shape of the H reflex obtained from the soleus muscle is usually triphasic, with an initial and terminal positivity and a central negativity,

but the F response appears smaller in amplitude. Its major deflection is usually negative, although it may be preceded by a small positive wave (Andrews and Bruyninckx, 1986).

The H reflex is constant in latency owing to activation of the same motoneurone pool. However, the F wave has a variable latency and is inconsistent in its appearance. This is due to activation of different groups of motoneurones (Andrews and Bruyninckx, 1986). The shortest F wave latencies are usually 1 to 2 ms longer than H reflex latencies (Burke et al., 1989 and Fisher, 1992). The mean F wave latency on human normal subjects was 42.7 ± 4 msec for common peroneal nerve and 52.3 ± 4.3 for tibial nerve (Kimura, 1983). There is little chance of confusing H and F reflexes.

Comparison between H reflex and tendon jerk

The Hoffmann reflex elicited by electrical stimulation of a muscle nerve which has simple input and output. The tendon reflex is a monosynaptic stretch reflex which can be evoked by a mechanical stimuli such as a tendon tap direct on the tendon of a muscle. Many spindles primary, secondary endings as well as tendon organ endings could be involved in the stretch reflex. It is not exclusively monosynaptic and also has polysynaptic components.

The afferent volleys responsible for the Achilles tendon jerk and soleus H reflex were investigated by Burke et al. (1983). They found that the response of soleus muscle afferents to tendon tap consisted of a dispersed volley, beginning 3.5-7.0 msec after percussion of the tendon, increasing to a peak over 6.5-11.0 msec, and lasting 25-30 msec,

depending on the strength of percussion. Electrical stimuli to the tibial nerve near motor threshold produced a synchronised volley, the conduction velocity in fastest fibres was 62-67 m/sec, and in the slowest fibres was 36-45 m/sec. The wave of acceleration produced by percussion subthreshold for the ankle jerk spread along the skin surface at over 150 m/sec. In their experiments, tendon percussion elicited single discharge from two Golgi tendon organs, and altered the discharge pattern of a single secondary spindle ending. Percussion on the Achilles tendon evoked crisp afferent volleys in recording from nerve fascicles innervating flexor hallucis longus, tibialis posterior, the intrinsic muscles of the foot and the skin of the foot. Electrical stimuli which elicited soleus H reflexes produced either a volley in muscle afferents from the intrinsic muscles of the foot or a volley in cutaneous afferent from the foot. The H reflex was inhibited but the Achilles tendon jerk enhanced when the ankle was dorsiflexed. The mean excitatory post-synaptic potential rise times were 1.9 msec for electrical stimulation and 6.6 msec for mechanical stimuli. They suggested that neither mechanical nor electrical stimulation produces homogeneous Ia afferent volleys from triceps surae. It addition, neither reflex can be considered to be purely monosynaptic in origin.

H reflexes in muscles other than soleus

Although the techniques of evoking the H reflex in the soleus muscle is the one most commonly used, because of the easy accessibility of the posterior tibial nerve and the relative selectivity of stimulation, similar H

reflexes can be elicited in other muscles. This has been reviewed recently by Schieppati (1987).

Pinelli and Valle (1960) evoked a H reflex in the flexor digitorum muscle. The H reflex can be recorded in hypothenar muscles (Johns et al., 1957), though this is consistently successful only in very young children i.e. under age of 2 years (Thomas and Lambert, 1960; Hodes et al., 1962; Mayer and Mosser, 1973). In older patients the reflex may appear in hypothenar muscles, though most commonly in subjects affected by central nervous system disorders (Hodes et al., 1962; Ioku, 1984).

French et al. (1961) elicited H reflexes in peroneal muscles from stimulation of the lateral peroneal nerve in children with phenylketonuria, but this reflex was absent in normal control children, as it is usually in adults. H reflexes can also be obtained from extensor digitorum brevis muscle of the foot in normal men (Willer, 1975; Dehen et al., 1976; Willer and Dehen, 1977), from quadriceps (Gassel, 1963; Mongia, 1972; Bathien and Guiheunec, 1974; Bergmans et al., 1978; Pierrot-Deseilligny et al., 1981b; Aiello et al., 1983b), from the forearm flexor muscles (Deschuytere and Rosselle, 1974 and Deschuytere et al., 1983), and from the masseter muscle (Godaux and Desmedt, 1975).

In selected cases or during voluntary contraction, H reflexes can be evoked in other muscles, such as the anterior tibial muscles (Upon et al., 1971; Deschuytere and Rosselle, 1971; Pierrot-Deseilligny and Bussel, 1973; Pierrot-Deseilligny et al., 1981a; Schieppati and Crenna, 1985; Davies, 1985; Schieppati, 1987) and thenar muscles (Stanley, 1978;

Deuschl et al., 1985), the wrist extensors (Day et al., 1984; Cavallari et al., 1985) and occasionally in the abductor pollicis muscle (McComas et al., 1970; Person and Kozina, 1978).

1.5   Comparison of H reflexes in the anterior tibial and soleus muscles

It is known that soleus is a slow, postural muscle used during standing. The soleus motoneurone pool has strong inputs from Ia afferent fibres and develops strong H reflexes and strong stretch reflexes. The anterior tibial muscles receive weaker inputs from Ia afferent fibres and are under more control from descending pathways. This was shown by Belanger and McComas (1981). Thus, anterior tibial muscles need a weak background contraction to produce reliable H reflexes. Similar suggestion has been reported that anterior tibial H reflexes can only be elicited after precontraction (Upon et al., 1971).

The anterior tibial H reflex excitability during equally intense activity of the motoneurone pool produced by voluntary and polysynaptic reflex activity was investigated by Pierrot-Deseilligny and Bussel (1973). They showed that the anterior tibial H reflex amplitude was much greater at the onset of voluntary activity than the onset of a polysynaptic reflex.

Tanaka in 1980, reported that usually pretibial motoneurones have a low level of excitability. He also showed that H reflexes in pretibial muscles can be regularly elicited during dorsiflexion, which had been reported previously by Hoffmann (1934).

Belanger and McComas (1981) compared the mechanical properties of plantarflexor and dorsiflexor muscles in man. Their results showed that plantarflexor muscles have larger twitch torques and slower twitch speeds than dorsiflexors. This shows greater muscle bulk and a higher percentage of slow twitch fibres in plantarflexors like soleus. There have been other investigations of muscle fibre type distribution using samples of muscle obtained at autopsy (Johnson et al., 1973). Muscles with an almost exclusively postural function, such as soleus, have up to 87% slow fibres whilst the anterior tibial muscle, has up to 73% of type I fibres.

The differences between anterior tibial and soleus compositions are much greater in cats where, the percentages of slow fibres are much higher for soleus than for anterior tibial muscles (Ariano et al., 1973). Hensbergen and Kernell (1993) reported that cumulative activity times tended to be significantly higher for soleus than anterior tibial.

What is the main reason for the differences between slow and fast fibre types accordance with different species? Sargeant and Kernell (1993) pointed out that the percentage of slow fibres is much higher in heavy animals than light ones. They also suggest that with respect of increasing body dimensions, force would increase by the square of the linear dimension but weight by the third power of the linear dimension. Thus larger animals have less favourable power to weight ratios and this is associated with relatively higher densities of slow fibres. Therefore, the percentage of slow fibres in postural muscles is higher in man than in the cat.

1.6 H reflex in Human physiology

The H reflex has been widely used in the study of human neurophysiology in normal subjects and patients with neurological disease. The size of the H reflex provides a measure of motoneurone pool excitability. Under controlled conditions, variations in the size of H reflex provide a reliable measure of the net excitatory and inhibitory influences on the α- motoneurones pool (Granit, 1950).

The fraction of soleus motoneurone pool activated in an H reflex is usually about 50%, but can be as high as 100% (Taborikova and Sax, 1968). The ratio of the peak to peak amplitude of maximum H reflex to maximum M wave produces a measurement of motoneurone pool excitability. Although there is considerable variability in H/M ratios, this quotient for calf muscles is usually less than 0.7 (Delwaide, 1984).

The susceptibility of H reflexes to facilitation or inhibition varies with the amplitude of the reflex. This was investigated by Meinck (1980). He showed that the susceptibility of the human H reflexes to excitation or inhibition was strongly dependent on the size of the reflex. In his experiment the greatest facilitation was observed when the amplitude of control H reflex was below half-maximal.

Inhibition was seen over the wide range of control reflex amplitude. His findings could partly be described on the basis of different susceptibility of small and large motoneurones to excitatory or inhibitory influences. This was first described by Henneman et al. (1965b) in the decerebrate

cat, who noted that inhibition was most easily observed in larger motoneurones which show higher recruitment thresholds. Smaller motoneurones, exhibiting a lower recruitment threshold, were less susceptible to inhibition.

It is well known that the Jendrassik manoeuvre (Jendrassik, 1885) will increase the amplitude of a weak tendon reflex (Hugon, 1973; Delwaide and Toulouse, 1983). This manoeuvre consists of an effort to separate clenched interlocked hands during or just before tendon tap.

H reflexes are routinely recorded from soleus with the muscle at rest. However, during voluntary contraction of the calf muscle, the amplitude of the H reflex increases. This was first reported by Hoffmann (1918). It is known that brief voluntary contractions of many muscles potentiate H reflexes (Upton et al., 1971; Morin et al., 1982; Burke et al., 1989).

The effects of variations in the level of pre-existing or baseline EMG activity on the size of the flexor carpi radialis H reflex was studied on normal subjects (Verrier, 1985). The results established that with increases of the background EMG activity, the magnitude of H reflex was increased. The amplitude of the H reflex was increased up to 400% whilst the H/M ratio was less than 50%, i.e. at the lower range of stimulus intensities.

The Hoffman reflex following exercise of low and high intensity were studied by Bulbulian & Darabos (1986). The subjects participated in a control trial and two 20 minutes treadmill exercise at 40% and 75% of

VO_{2max}. They showed that after using low intensity exercise the ratios of H_{max}/M_{max} were significantly decreased to 12.8% while high intensity exercise reduced the H_{max}/M_{max} ratio by 21.5%. They suggested that these reductions provided objective evidence for the efficacy of high intensity exercise in stress reduction as measured by the Hoffmann reflex and provide indirect evidence for a possible thermal hypothesis for exercise induced stress reduction. They did not describe how long after the period of exercise the H reflex tests were made, and how extensive the fatigue was. Therefore is very difficult to differentiate between central and peripheral factors .

Clinical applications

The presence of H reflexes confirms the integrity of afferent, efferent pathways and functional segmental reflex pathways.

Angel and Hofmann (1963) measured motoneurone excitability by dividing of the largest obtainable H reflex by the largest M wave. The quotient has been named as ''the H/M ratio''. In hemiplegic patients, they found that this ratio was higher on the spastic than on the unaffected side.

The H reflexes latencies are related to age, leg or arm length, and height. The upper limit of normal latencies for calf H reflexes is 35 ms; and for flexor carpi radialis H reflexes 20 ms. Upper limits of normal for left to right latency differences are 1.5 ms for calf H reflexes and 1.0 ms for flexor carpi radialis (Fisher, 1992).

Andrews and Bruyninckx (1986) reported that a difference of more than 3 msec between the H reflex and the F wave response in soleus muscle could be an indicator of conduction delay along the S_1 motor fibres.

H reflexes can be a sensitive test for polyneuropathies, the H reflex latencies may be increased or the reflex may be absent in peripheral neuropathies and root compression. Calf H reflexes can be a sensitive indicator of S_1 radiculopathies (Deschuytere and Rosselle, 1973).

In older patients the reflex may appear in hypothenar muscle, though most commonly in subjects affected by central nervous system disorders (Hodes et al., 1962; Ioku, 1984).

French et al. (1961) elicited H reflexes in peroneal muscles from stimulation of the lateral peroneal nerve in children with phenylketonuria, but this reflex was absent in normal control children, as it is usually in adults.

1.7 Fatigue

The definition of fatigue

The term "fatigue" is complicated and has many meanings depending on the type of experiment. Generally, activation leads to decline of force production and speed, i. e. power output which is known as fatigue (Westerbland et al., 1991). The most appropriate definition of fatigue is "inability to maintain the desired or expected force" (Edwards, 1981; Enoka and Stuart, 1992).

Bigland-Ritchie and Woods (1984) used another definition for their purposes such as "any reduction in the force generating capacity which can be measured as the maximal voluntary contraction (MVC), regardless of the task performed". During prolonged periods of muscle activity a submaximal force can be sustained with increased effort. This is usually accompanied by an increased EMG/Force ratio and this is commonly regarded as an early indicator of fatigue. Indeed, by definition, an initially submaximal force can become maximal when it can no longer be maintained (Bigland-Ritchie, 1993). An increased EMG/Force ratio is the most relevant definition of fatigue and will be used in present thesis.

Two types of fatigue are commonly described. The reduction in force may be due to a loss of concentration or effort by the subject or may be due to failure of nerve transmission, excitation contraction coupling or force generation in the muscle fibre itself.

Central fatigue

An experimental volunteer needs considerable concentration and effort to sustain an isometric voluntary contraction in an experiment. Subjects often require visual feedback to maintain the given force. Without visual feedback and encouragement, force rapidly declines. However, force declines at maximal voluntary contraction even with visual feedback (Stephens and Taylor, 1972; Bigland-Ritchie, 1981).

A common experimental technique is to activate the peripheral motor nerves by applying electrical stimulation. Single or tetanic stimulation can identify whether a muscle is fully activated or additional force can be obtained by stimulation (Merton, 1954). Therefore, central fatigue can be recognised by the appearance of twitches after superimposing electrical stimulation during voluntary contractions (Bigland-Ritchie et al., 1986b). In their experiment the central and peripheral factors were investigated during fatigue of submaximal intermittent isometric contractions of the human adductor pollicis, quadriceps and soleus muscles. They used superimposed twitch both on target force of voluntary contraction and MVC. Their results showed that during fatigue of quadriceps and adductor pollicis, the central nervous system remains capable of full muscle activation. Thus, the reduction in force could result mainly or completely from failure of the muscle contractile apparatus.

In addition, the integrity of the chain of command linking higher centre, motoneurone, neuromuscular junction and muscle fibre could be checked by using electrical stimulation either on the scalp to activate the motor cortex or in the spinal cord to stimulate motoneurones. These

methods require special techniques such as high voltages or magnetic stimulation (Jones and Round, 1992).

Peripheral fatigue

Fatigue might be due to a failure of transmission at the neuromuscular junction, or of the muscle action potential or of the force generation capacity of the fibre (Westerbland et al., 1991).

Krnjevic and Miledi (1958) investigated the mechanism of neuromuscular failure during tetanic stimulation in rats, in vitro and in situ. Their results showed that muscle fibres cannot respond for more than a few minutes at frequencies higher than 50 Hz. However, the failure was very small with frequencies near 10 Hz.

In human subjects the propagation of action potential through neuromuscular junction can be easily assessed. This can be achieved by direct stimulation of the motor nerve and recording the action potential from the muscle, which is known as the M wave. The M wave is the summation of individual fibre action potentials of the muscle around the electrode. Neuromuscular junction failure was first investigated by Merton (1954). His results showed that in spite of progressive reduction of force during a sustained voluntary contraction, the M wave remained constant. This shows that the site of failure is not before the neuromuscular junction.

This conclusion was rejected by Stephens and Taylor (1972). In their experiments the mechanism of fatigue has been investigated in a sustained maximal voluntary contractions of the first dorsal interosseous muscle of the hand. Their results showed that during first minute the

force declined to 50% and EMG fell linearly with the same slope. However, in the second phase force reduced more than EMG. The size of the M wave evoked by ulnar nerve stimulation fell to 65% of initial value. Most of the reduction occurred in the first phase. They suggested that during the first stage, fatigue arose due to neuromuscular junction failure. Arterial occlusion did not affect this stage. In the second stage contractile element changes were the main cause of fatigue, particularly when the blood flow was occluded, probably, because muscle contraction stops circulation anyway.

Since then Bigland-Ritchie et al. (1982) have systematically attempted to resolve these differences. They fatigued adductor pollicis and first dorsal interosseous muscles by a maximal voluntary contractions lasting 60 seconds. Their results showed that despite 30-50% loss of force, the M wave amplitude did not change. It was suggested that neuromuscular block is not a cause of reduction in force.

There are two factors that could contribute to a reduction of membrane excitability during fatigue:

1- Accumulation of K^+ in the extracellular space and a smaller reduction in the intracellular K^+ concentration.

2- Metabolic change which could directly affect membrane characteristics and also influence the rate at which the membrane Na^+, K^+ transport mechanisms acts to redress the ionic imbalance.

Metabolite changes

During fatiguing activity, the concentration of muscle metabolites decline due to metabolic fluxes. Some of these changes associated with force production are:

The slowing of relaxation, which is a feature of fatigue state, is related to decreased adenosine triphosphate (ATP) and phosphoryl creatine (PC) levels and accumulation of lactate (Edwards et al., 1975). In his experiments, during prolonged tetanic stimulation at 20 Hz under anaerobic conditions PC fell rapidly after 15 seconds stimulation. In addition, ATP concentrations fell and lactate rose over the 60 seconds of stimulation. The ATP binds to myosin and the actomyosin complex is dissociated. In the absence of ATP and in presence of raised Ca^{2+}, the attached state will remain in cross bridge (rigor mortis).

A fall in intracellular pH following glycolysis and H^+ accumulation can lead to decrease in the maximum force generated. Fast muscle being more affected than slow (Donaldson and Hermansen, 1978; Fabiato and Fabiato, 1978).

The other possible cause of a reduction in force generation is a rise in inorganic phosphate in fatigued muscle (Kentish, 1986).

Electrical exercise

The type of muscle activity during an experiment is very important. This can be voluntary or electrical, isometric or isotonic. In order to avoid central fatigue effects during experiments, muscle can be fatigued by electrical stimulation.

The ankle dorsiflexor muscles were fatigued by intermittent stimulation of the common peroneal nerve at 15-20 Hz (Garland et al., 1988b). The voluntary EMG activity was subsequently reduced and they suggested that these reductions could not have been due either to failure at neuromuscular junctions since the M waves evoked by electrical stimulation of the common peroneal nerve were constant, or to central "cortical" fatigue because the fatigue was induced peripherally. It was concluded that the reduction in EMG activity was more likely to be a reflex phenomenon.

During electrical stimulation the time course of force reduction depends on the duration and the frequency. Fatigue can occur quickly following high frequency stimuli or more gradually by using low frequency. The muscle fibre membrane becomes depolarised during high frequency stimulation (Jones and Bigland-Ritchie, 1986), and a failure in excitation-contraction coupling occurs at low frequency fatigue (Edwards et al., 1977).

During electrical induced muscle activity the time course of reduction in force depends on the frequency of stimulation. At high frequencies (80-100 Hz in man) force declines rapidly within 30 seconds, during low frequency stimuli (20 Hz) the force can be maintained longer than 60 seconds (Edwards et al., 1977).

Slowing relaxation

The half relaxation time increases two or three fold after fatiguing voluntary contractions. This is the other characteristic of fatigued muscle. However, the mechanism of slowing relaxation is not clear but

there are two possibilities. Firstly a reduction of cross-bridge detachment and secondly a slowing of calcium reaccumulation by the sarcoplasmic reticulum. This is an ATP-dependent process which could be slowed in adverse metabolic circumstances (Edwards et al., 1977).

1.9   The effects of fatigue on EMG activity

The motoneurone firing rates may be regulated to match changes in muscle contraction. Therefore, the reduction in motoneurone firing rates is accompanied by a slowing of the relaxation time of fatigued muscle.

During a sustained voluntary contraction, rectified integrated electro myography (IEMG) has been shown to reduce roughly in parallel with the reduction in force (Bigland-Ritchie, 1981; Bigland-Ritchie et al., 1986b). The reduction could be due to failure in neuromuscular excitability. Alternatively, it might be possible due to exhaustion of descending motor pathway, or it could result from reflex inhibition of α motorneurones which comes via the afferent inputs from the exercising muscle.

In 1954 Merton reported no reduction in the size of M waves evoked by periodic single maximal intensity electrical stimuli to the ulnar nerve during sustained maximal voluntary contractions of the adductor pollicis muscle, despite a force decay almost to zero. He concluded that electrical propagation was unimpaired and that failure must be only due to the muscle contractile mechanism.

Bigland-Ritchie, Jones and Woods (1979) using the adductor pollicis, showed a decline in the voluntary EMG. However they found no similar reduction in the M waves. In the other experiment on the adductor pollicis muscle (Woods, Furbush & Bigland-Ritchie, 1987) showed the amplitude of the M wave evoked by ulnar nerve stimulation remained unchanged while the EMG activity decreased during the fatigue period, i.e. there was no evidence of neuromuscular junction failure. Even during 3 minutes of post fatigue ischaemic rest the M waves were constant.

To distinguish between these possibilities, Bigland-Ritchie et al. (1986a) investigated the effects of ischaemic exercise on motoneurone firing rates. They showed that during isometric contractions, the firing rates of brachial biceps motoneurones fell and remained low during subsequent ischaemic control periods. They returned to control 3 minutes after releasing arterial blood occlusion. It was suggested that the reflex inhibition of motoneurones was the main reason for the EMG reductions. In that experiment the authors did not reject the possibility of reductions due to neuromuscular failure or peripheral conduction fatigue.

Thomas et al. (1989) showed that the amplitude and area of M waves evoked by single shocks to the motor nerve usually remain constant or increase, despite up to 50% force decline. The M wave also remained constant during MVCs of anterior tibial muscles extending for up to 5 minutes, or during fatigue from intermittent submaximal contractions of

adductor pollicis and diaphragm continued for 30-50 minutes (Bellemare and Bigland-Ritchie, 1987).

The adaptation of the motoneurone discharge rates to constant excitatory drive was observed in anaesthetised cats by Kernell and Monster (1982a, b). In their experiments late adaptation occurred during the first 30 seconds of sustained stimulation.

On the other hand Enoka and Stuart (1992), suggested that there is no adaptation of the motoneurone during sustained maximal voluntary contractions. These are investigations of the intrinsic properties of motoneurones rather than reflex actions.

The mechanisms responsible for the loss of voluntary EMG activity was investigated by Garland et al. (1988). They found similar result which showed a reduction in EMG following electrical stimulation of the soleus muscle. The reduction in EMG cannot be due to depression of central effort. Because they employed different pathways i. e. peripheral during their experiments. It was also clear that EMG reduction could not be due to peripheral conduction changes because of relatively stable M waves. Thus, the decline in either voluntary or electrical EMG activity is more likely to be caused by a reflex phenomenon.

1.10 The effects and source of fatigue on the H reflexes excitability

Voluntary muscle relaxation was investigated in human soleus muscle by means of a H reflex technique (Enoka et al., 1980; Scheippati and Crenna, 1984; Scheippati, 1987). The amplitude of the soleus H reflex is clearly reduced during and following voluntary termination of contraction. The H wave showed a depression over a 50 seconds period following contraction (Enoka et al., 1980). It was suggested that, when an agonist muscle relaxed from a contraction, presynaptic inhibition of the Ia afferent fibres originating from the spindles of the relaxing muscle is the main mechanism responsible for the H reflex inhibition (Scheippati, 1987).

Garland et al. (1988b) also reported that under ischaemic conditions when ankle dorsiflexor muscles had been fatigued by intermittent stimulation of the common peroneal nerve at 15-20 Hz, there was a reduction in voluntary EMG activity. These reductions could not either have been due to failure in neuromuscular junction since the M waves evoked by electrical stimulation of the common peroneal nerve were constant, or to central fatigue because the fatigue stimulation was done peripherally. They suggested that the reduction in voluntary EMG activity was due to reflex inhibition of motoneurones which occurred from afferent inputs from fatigued muscle.

More recently the excitability of soleus motoneurones was tested during muscle fatigue using the H reflex (Garland and McComas, 1990). In their experiment soleus muscle was fatigued under ischaemic conditions by intermittent stimulation at 15 Hz. They showed that fatigue of soleus caused a depression of H reflex excitability of that muscle. They have attributed the H reflex inhibition to unidentified afferent inputs from activated muscle.

Macefield et al. (1991) investigated the discharge behaviour of single muscle spindle afferents, from the pretibial muscles, recorded during sustained isometric dorsiflexions. The contractions generally lasted for 1 minute and were kept below 30% of the maximal voluntary dorsiflexion force. Their results showed that the discharge rate of the spindle afferents had declined to two-thirds of its initial rate by 30 seconds and to half after 1 minute. The reduction in spindle discharge was statistically significant in the first 10 seconds.

The excitability of α motoneurones during contractions of ankle extensor muscle was investigated in the cat (Zytnicki et al., 1990). Their results showed that in α motoneurones, during a series of GM twitches at rate of 10/sec, contraction induced inhibitory potentials due to activation of homonymous Ib afferent fibres which originate from Golgi tendon organs (autogenetic inhibition). These rapidly subside before the end of the series. In contrast, excitatory potentials which are due to activity of primary afferent fibres during relaxation from contraction, persisted. They suggested that presynaptic inhibition of homonymous Ib

afferent fibres during muscle contractions is likely to be the main reason for declining of autogenetic inhibition.

Electrophysiological studies of group III and IV afferents from skeletal muscle show that they can be sensitive to the metabolic state of the muscle. Some group III receptors in the cat could be stimulated by noxious stimuli such as squeezing the muscle or injecting 6% NaCl (Paintal, 1960; Bessou and Laporte, 1961). The non-myelinated group IV fibres showed responses to contractions only if the muscle was activated under ischaemic conditions (Iggo, 1961). Kumasawa and Mizumura (1977) reported that the muscle group III and IV receptors in the dog were polymodal. They used heat, mechanical and chemical stimulation during their experiments.

Mense (1977) proved that algesic chemical stimuli are potent in producing an excitation of deep group III and IV receptors. Probably, most group IV receptors are activated by chemical stimulation as well as by muscle contraction (Kniffki et al., 1978; Mense and Stuhnke, 1983). These also belong to the polymodal nociceptive type.

The response of slowly conducting muscle afferent fibres (group III and IV) in cat during moderate force were investigated by Mense and Stahnke (1983). Their results showed that some of these fibres are activated in moderate contractions. They also found that some other populations of group III and IV receptors are activated in ischaemic activity.

Mense and Meyer (1985) suggested that there are different types of group III and IV receptors in skeletal muscle and tendon of the cat,

which might have different functions and respond to local pressure, muscle stretch, active contractions or temperature changes. Bigland-Ritchie et al. (1986a); Woods et al. (1987) and Bigland-Ritchie (1993) suggested that a peripheral reflex phenomenon from the fatigued muscle is the main reason for the EMG reduction. Receptors which are sensitive to the metabolic changes of the muscle might explain this.

There is no direct evidence on electrophysiological mechanisms of nociceptive muscle afferents in man. However, the role of small diameter afferent fibres in reflex inhibition were also investigated during human muscle fatigue by Garland (1991). In her experiments the sciatic nerve was compressed by placing a wooden bar distal to the ischial tuberosity to block the contribution of large myelinated afferent fibres before fatigue experiments. It was suggested that any reflex inhibition is mediated by smaller diameter afferents from the fatigued muscle. Garland also concluded that mechanical or metabolic changes could have mediated reflex inhibition, because the reductions in EMG remained while the cuff were inflated.

Recent similar studies (Duchateau and Hainaut, 1993) have also described more effectively the reduction of H reflex excitability.
In their experiments, the human abductor pollicis brevis and first dorsal interosseous were fatigued by either sustained maximal voluntary contractions or electrical stimulation at 30 Hz. The H reflex and long latency reflex were elicited during and after the fatigue experiments. Their results showed that the normalised H reflex amplitudes were

decreased significantly after 40 seconds contractions whilst the normalised long latency amplitudes showed no changes. It was suggested that the inhibitions are activated by metabolic or chemical changes in the fatigued muscle.

In conclusion, it is clear that firing rates of motor units slow during sustained contraction: In some types of fatigue also the EMG falls during sustained activity. This may be partly due to central fatigue phenomena or neuromuscular junction failures but part of it may be reflex in origin and related to group III and IV afferents sensitised during fatigue. This projects aims to extend human studies started by Garland and McComas (1990). It will study the anterior tibial muscles and investigate the central and peripheral factors in fatigue as well as examining how extensive the interactions with other muscles might be.

2. Methods

2.1 Subjects

Fifty neurologically normal subjects of both sexes participated in these studies. Their ages ranged from 17-42 years old. Every subject did not perform all combinations of experiments. Details of the subject's sex, age and height and which parts of the experiment they performed are given in tables 2 and 3. The experimental protocols were approved by the Western Infirmary Ethical Committee of the Greater Glasgow Health Board. In addition, the subjects gave their informed consent to their participation in the investigation.

2.2 Position of Subject

During experiments the subjects were seated in a relaxed semi-reclined position with one leg fixed to a supporting metal frame by straps. The head was fixed in a neutral position. The forearms were kept on arm rests to prevent any lateral deviation of the trunk, as is shown in figure 2. Subjects were advised to keep their body position stable and as relaxed as possible. In addition, surface EMG and force recordings were used to confirm the absence of significant muscle tone.

Details of Subjects Who Participated in Experiments Testing Soleus H Reflexes

Number	Age (years)	Height (cm)	Sex	Soleus H	Electrical Exercise	Voluntary Exercise
1	42	178	M	*	*	*
2	27	185	M	*	*	*
3	38	166	M	*	*	*
4	40	170	M	*	*	*
5	31	180	M	*	*	
6	26	164	M	*	*	
7	32	183	M	*	*	*
8	38	172	M	*		*
9	18	170	M	*		*
10	38	175	M	*		*
11	22	173	M	*		*
12	20	180	M	*		*
13	18	180	M	*		*
14	17	175	M	*		*
15	35	172	M	*		*
16	22	180	F	*		*
17	19	165	F	*		*
18	18	162	F	*		*
19	18	174	F	*		*
20	23	180	M	*		
21	22	179	M	*		
22	22	176	M	*		
23	28	174	M	*		
24	26	173	M	*		
25	24	167	M	*		
26	33	180	M	*		
27	39	171	M	*		
28	21	156	F	*		
29	21	165	F	*		

Total				29	7	17
Mean	26.8	173.3				
Range	17-42	156-185				

Table 2. This table shows details of subjects who took part in soleus H reflex experiments . For each subject it shows age, height, sex, electrical exercise and voluntary exercise. The mean of age was 26.8 ± 8.0 years (mean ± SD, range 17-42), the mean of height was 173.3 ± 6.9 cm (range 156-185), the total subjects who participated in soleus H reflex experiments were 29 (23 male and 6 female), in 7 of them anterior tibial muscles were fatigued electrically and in 17 of them anterior tibial or quadriceps muscle was fatigued voluntarily.

Details of Subjects Who Participated in Experiments Testing Anterior Tibial H Reflexes

Number	Age (years)	Height (cm)	Sex	Soleus H	Electrical Exercise	Voluntary Exercise
a	42	178	M	*	*	
b	27	185	M	*	*	
c	38	166	M	*	*	
d	40	170	M	*	*	
e	26	164	M	*	*	
f	31	180	M	*	*	
g	32	183	M	*	*	
h	36	157	F	*	*	
i	17	171	M	*		*
j	18	170	M	*		*
k	19	163	M	*		*
l	17	185	M	*		*
m	21	181	M	*		*
n	18	158	M	*		*
o	17	163	M	*		*
p	23	180	M	*		
q	26	173	M	*		
r	17	178	M	*		
s	17	170	M	*		
t	24	167	M	*		
u	19	165	F	*		

Total				21	8	7
Mean	25.0	171.8				
Range	17-42	157-185				

Table 3. This table shows details of subjects who took part in anterior tibial H reflex experiments . For each subject it shows age, height, sex, electrical exercise and voluntary exercise. The mean of age was 25 ± 8.4 years (mean $\pm$ SD, range 17-42), the mean of height was 171.8 ± 8.7 cm (range 157-185), the total subjects who participated in anterior tibial H reflex experiments were 21 (19 male and 2 female), in 8 of them anterior tibial muscles were fatigued electrically and in 7 of them voluntarily.
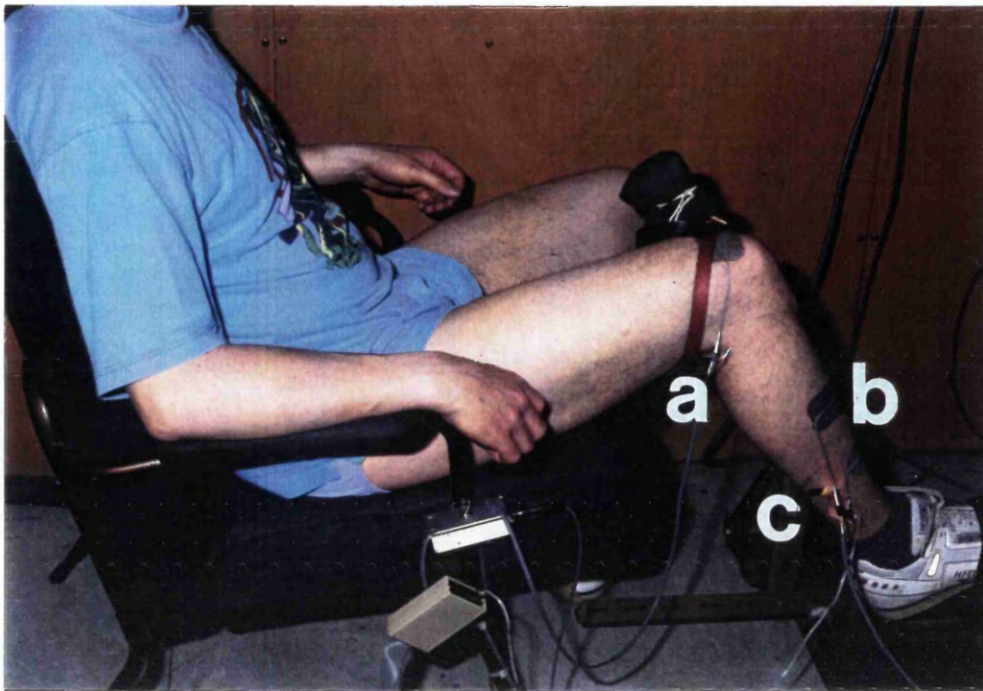
Figure 2. Photograph of trunk and upper limbs position. Forearms were kept on the arm rests. a. electrodes for stimulation of the tibial nerve, b. electrodes for direct stimulation of anterior tibial muscles and c. electrodes for soleus EMG recording. The cathode was placed on the popliteal fossa for stimulating tibial nerve and the anode was placed superior to the patella. The stimulating electrodes for electrical exercise of anterior tibial muscles were laid over those muscles. The recording electrode was placed 2 cm under the junction of lateral and medial head of gastrocnemius muscle, the reference electrode was placed to the skin 3 cm distal to the recording electrode on the soleus muscle and the ground electrode was attached to the skin approximately between the recording and reference electrodes. In this picture the security key for switching off the stimulator and underneath of that the amplifier of EMG which were fixed on the leg of chair are shown as well.

2.2.1 Position of the Lower Limb

The position of the knee and ankle joints can influence the excitability of the monosynaptic reflex of triceps surae (Desmedt, 1973). In experiments the knee was kept at 110° as recommended by (Hugon, 1973; Schieppati, 1989). In this position, gastrocnemius, which inserts on the femur is not stretched since this may depress the soleus H reflex excitability (Hugon, 1973). The angle of the ankle joint was fixed at about 90° (Hugon, 1973; Garland & McComas, 1990). This determines the extension of the soleus which inserts on the upper part of the tibia (Desmedt, 1973).

Figure 3 shows the lower limb position. The leg was fixed to a supporting metal bar with straps, which had been located in the medial side of the knee to prevent lateral or medial rotation. The foot was strapped to a metal plate which was mounted on a strain gauge transducer to allow measurement of plantarflexion and dorsiflexion torques.

In experiments using quadriceps an alternative supporting frame was used. The subjects were seated with their hip at 90° and the hips secured with a strap. The knee and ankle were kept at 90° which can be seen in figure 4. Subjects made isometric quadriceps contractions whilst knee extension torques were measured by attaching the leg just above the malleolus to a strain gauge transducer.

In all experiments the force signal was displayed in front of the subject on an oscilloscope. The temperature of the room was controlled between 22-25°C.
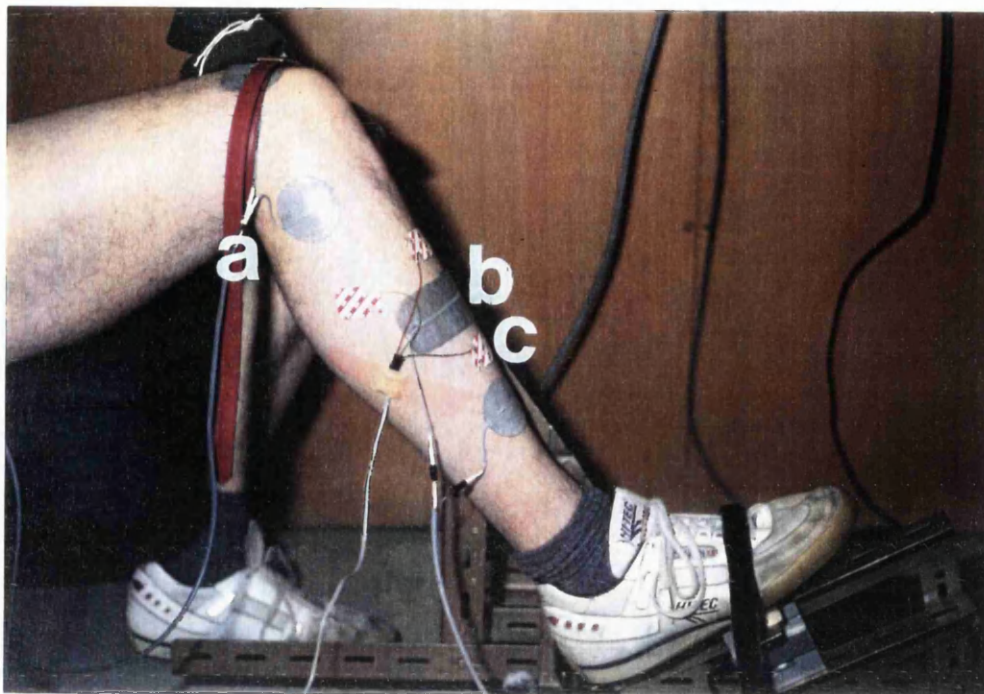
Figure 3. Photograph of limb position. The leg was fixed to a supporting metal frame. a. electrodes for stimulation of common peroneal nerve, b. electrodes for direct stimulation of anterior tibial muscles and c. electrodes for anterior tibial EMG recording. The cathode was placed over the head of fibula to stimulate common peroneal nerve and the anode was placed superior to the patella. The cathode of the stimulating electrodes for fatiguing activity of anterior tibial muscles was laid over those muscles between recording and reference electrodes while the anode was below the reference electrode and over that muscle. The recording electrode was placed over the upper third of the anterior tibial muscles, the reference electrode was placed to the skin between fatiguing electrodes on the same muscles and the ground electrode was attached to the skin of lateral side of the leg approximately behind the recording electrode.

Figure 4. This photograph shows the set up of quadriceps fatigue experiment. Whole the instruments which including of 1. PC, 2. Neurolog, 3. EMG, 4. Oscilloscope, 5. Stimulator, 6. Pulse Generator and Digitimer are illustrated in the right side. The position of subject is shown in left side of the picture. The electrode positions for stimulating of the tibial nerve to elicit soleus H reflex and the recording electrodes are shown on the leg. The cathode was placed on the popliteal fossa to stimulate tibial nerve and the anode was placed superior to the patella. The recording electrode was placed 2 cm under the junction of lateral and medial head of gastrocnemius muscle, the reference electrode was placed to the skin 3 cm distal to the recording electrode on the soleus muscle and the ground electrode was attached to the skin approximately between the recording and reference electrodes. In this picture the amplifier of EMG which was fixed near the leg of subject on the chair is shown as well. The leg just above the malleolus was securely strapped on to the strain gauge transducer.

2.3 Technique for eliciting H reflexes

Rather different techniques were used to elicit H reflexes in soleus and anterior tibial muscles. These are described in turn.

2.3.1 Soleus H reflexes

This muscle is located in the back and lower part of the leg about few centimetres below the gastrocnemius muscle. Therefore, subjects flexed their ankle to show the bulk of gastrocnemius muscle clearly. Then, the recording electrodes were positioned over the muscle belly.

H reflexes from soleus muscles were elicited in all subjects in relaxed muscles. In figure 5 a specimen of soleus H reflex is illustrated.

For obtaining soleus H reflex, the recording electrode was placed 2 cm under the junction of lateral and medial head of gastrocnemius muscle (Hugon, 1973), the reference electrode was placed to the skin 3 cm distal to the recording electrodes on soleus muscle.

The ground electrode was attached to the skin approximately between the recording and reference electrodes. The location of these electrodes are shown in figure 2.

The location of stimulation electrodes

After preparing the skin with alcohol, the self-adhering electrodes (Axelgaard Manufacturing Co., Ltd.) were positioned on the leg. The cathode was a 5 cm diameter disc placed on the popliteal fossa over the tibial nerve. The anode was larger size 5cm x 9 cm and was placed

superior to the patella. As Hugon (1973) has described, this arrangement is preferred to a longitudinal arrangement of electrodes along the nerve for three reasons:

1- The stimulus artefact is reduced.

2- Anodal block is less likely to develop on stimulation.

3- Selective stimulation of the nerve trunk is easier by means of a single active electrode.

Constant pressure of the electrode against the skin of subject was maintained by an elastic strap.

The duration and frequency of the stimuli

Single rectangular pulses were delivered every 5s, using timing pulses generated by a digital timing unit (Digitimer, Devices Ltd). The stimulus duration was between 0.1-0.5 msec.

The intensity of the stimuli

First, in each experiment the motor threshold (T) was measured by increasing stimulus intensity until the first signs of an M wave were seen on the oscilloscope. All subsequent stimulus intensities were expressed as multiples of motor threshold. A wide range of stimulus intensities, up to 15T were employed to identify maximal M and H waves. When looking for experimental changes in H reflex amplitude, it is necessary to adjust the stimulus intensity to obtain an H reflex about 50% of the maximal. This permits both increases and decreases of the response to be observed. Generally stimuli between 1.5T and 2.5T were used.

M and H Reflexes in Soleus
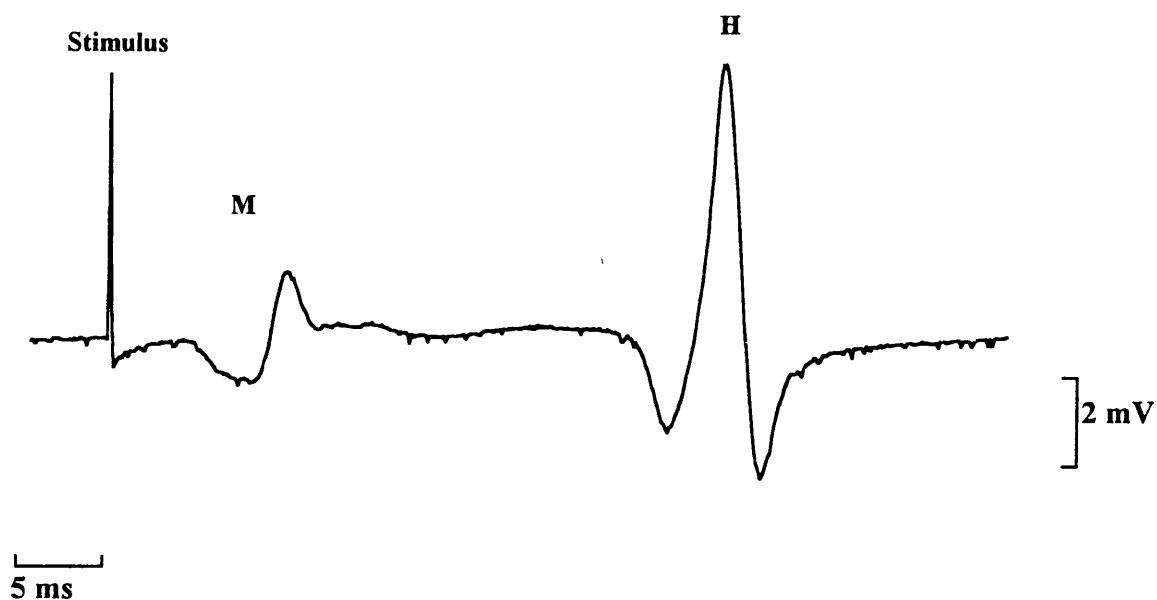
Figure 5. This figure shows a typical soleus M wave and H reflex. After 5 ms delay the stimulus artefact is seen, followed by the compound motor action potential about 5 ms. Later the H reflex which is three phases at about 34 ms.

2.3.2 Anterior tibial H reflexes

The anterior tibial is the first muscle located to the anterior border of the tibia 1cm to 2cm from the lateral side of the tibia. The bulk of muscle covers two-thirds of the lateral surface of the shaft of tibia. Subjects were asked to dorsiflex and invert their ankle to assist identification of the muscle. The EMG electrodes were placed over the upper third of muscle. The reference electrode was placed on the skin 3 cm distal to the recording electrodes.

The ground electrode was attached to the skin between the recording and reference electrodes. The location of these electrodes is illustrated in figure 3.

H reflexes can be difficult to obtain in relaxed anterior tibial muscles. However, if a low force voluntary dorsiflexion contraction is made, stable H reflexes can be obtained. During the experiments contractions of about 10% of maximal voluntary force were used. Figure 6 shows a specimen trace from such experiment. The subject was provided with visual feed back of the dorsiflexion force generated.

The location of stimulation electrodes

After preparing the skin with alcohol, the self-adhering electrodes (Axelgaard Manufacturing Co., Ltd.) were positioned on the leg. The cathode was a 5 cm diameter disc placed over the head of fibula to stimulate the common peroneal nerve. The anode was larger, 5cm x 9 cm, and was placed superior to the patella.

The duration and frequency of the stimuli

Single rectangular stimuli with pulse width between 0.1-0.5 msec were delivered every 5s, using timing pulses were generated by a digital timing unit (Digitimer, Devices Ltd)

The intensity of the stimuli

Similar procedures to those described earlier for eliciting soleus H reflexes were used to elicit H reflexes in anterior tibial muscles (ref 2.3.1). Half maximal H reflexes in anterior tibial muscles generally required stimulation below 1.5T.

M and H Reflexes in Anterior Tibial Muscle
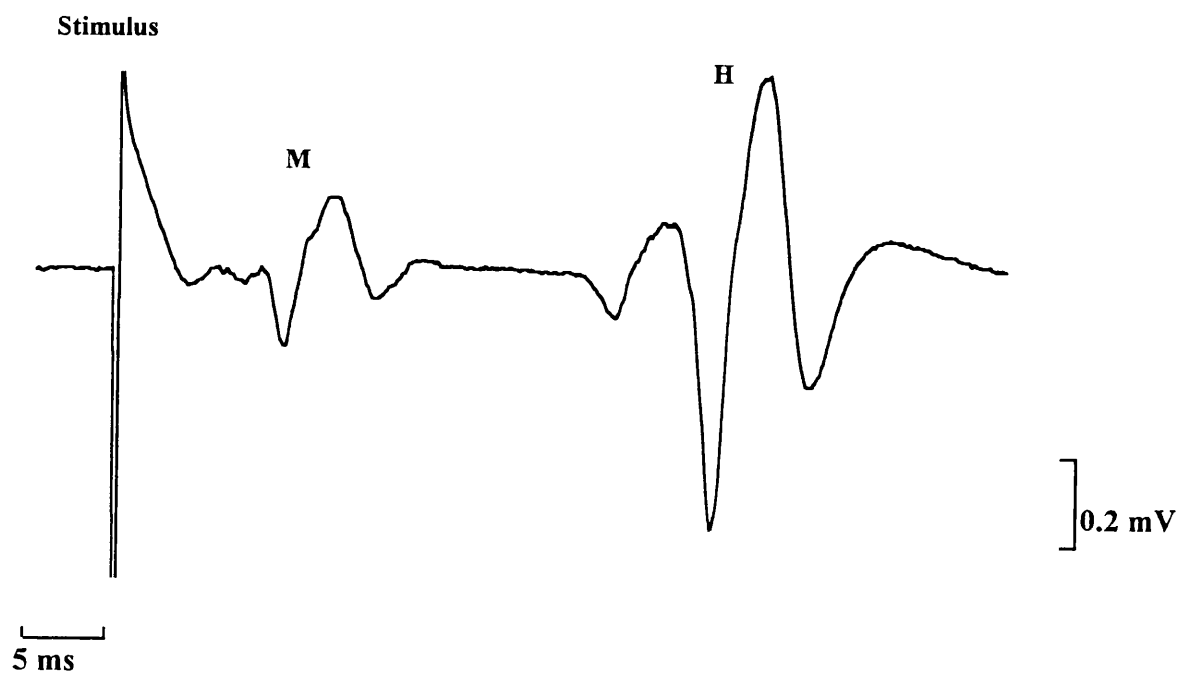
Figure 6. This figure shows an example of anterior tibial M wave and H reflex. After 5 ms delay the stimulus artefact is seen, followed by the compound motor action potential about 4 ms. Later the complex H reflex at about 30 ms.

2.4   EMG recording

The electromyogram (EMG) was recorded with surface metal foil electrodes. These were Littman Electrodes EKG made by 3M Ltd. They are disposable single-use adhesive electrodes (2x2cm) for diagnostic purposes. They were connected to a preamplifier positioned within a few mm of the skin surface by the bare end of thin wires.

The EMG signals were amplified (x1000) and band pass filtered between 10 Hz-5 kHz. A notch filter was employed to reduce mains noise. The filtered EMG was displayed on an oscilloscope and digitised by a PC26AT analogue input board (Amplicon Liveline. Ltd). The digitised signal was displayed and stored in a Viglen 386 PC running a commercial A/D software package (Microscope, Amplicon Liveline. Ltd). Data were saved for further analysis. The EMG was subjected to a 12 bit voltage conversion. As is shown in figure 5 the amplitude of EMG was typically about 10 mV. This was amplified so that the signal presented to the about 10 V. The input range of the card is ± 10 V, which is subjected to 12 bit conversion. Thus each voltage level is equivalent to approximately 5 mV or 5 μV at the muscle. Thus, the H wave will be digitised into about 2000 voltage levels and so the signal is faithfully represented.

A similar calculation can be used to establish the minimum time resolution. The EMG signals were digitised at 30 KHz, and the minimum time resolution was about 33 μsec. H reflex latency is typically about 30 msec and so these can be measured very accurately even after digitisation.

2.5   Stimulator calibration

A constant voltage stimulator was used during the experiments. Monophasic rectangular pulses lasting 0.1-0.5 msec were delivered from a Devices 3072 Isolated High Voltage stimulator. The stimulus was delivered through an isolation transformer to ensure safety for subjects. The output range of this stimulator is 0-400 V.

Calibration curves show this delivers a linear output into loads of 500Ω or 1000Ω. These curves are shown in figures 7, 8 and 9. These figures show the output of the stimulator is linear. Note, however, although nominal voltage is not achieved, linearity is more important due to the calculation of threshold as ratios.

Calibration of the Stimulator

Amplitude (V)

Set Voltage (volt)
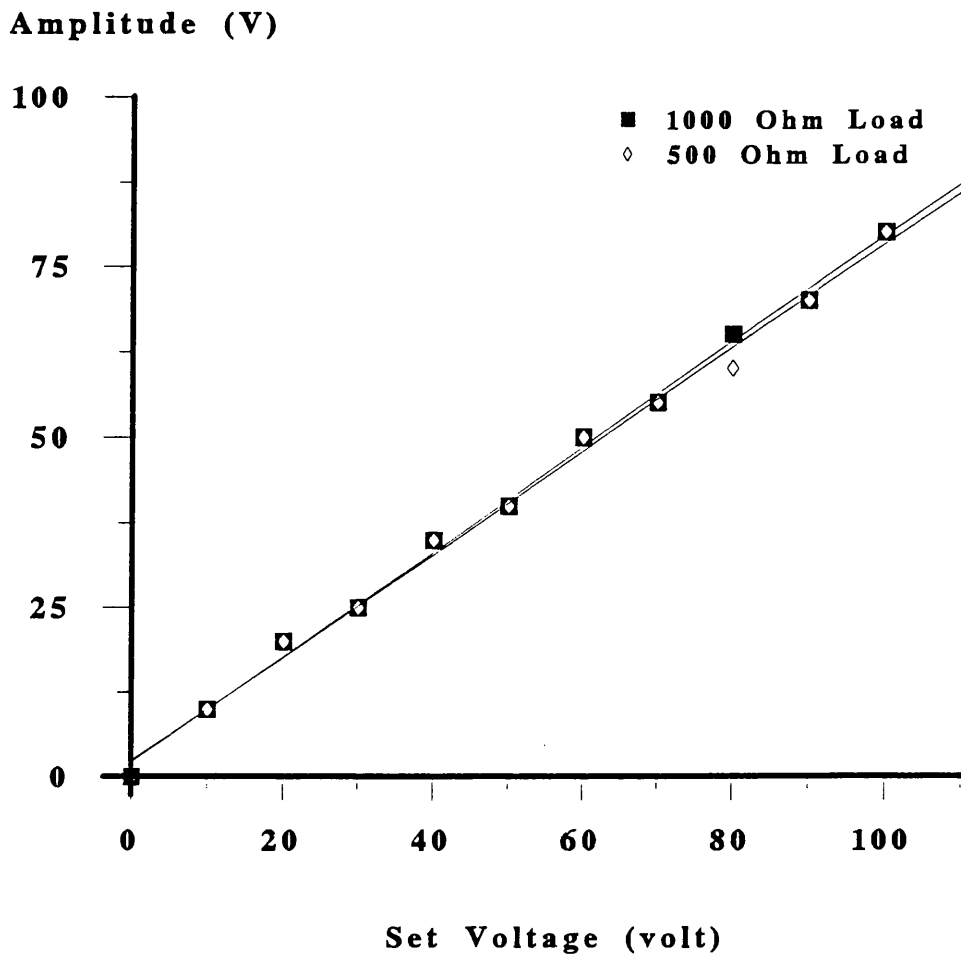
Figure 7. Calibration of the stimulator on the 0 to 100 volt range with 500 and 1000 Ω load resistances. The curvefit line was y = 2.50+0.76x, r^2 = 0.99 for 500 Ω resistance and y = 2.27+0.77x, r^2 = 1 for 1000 Ω resistance.

Calibration of the Stimulator
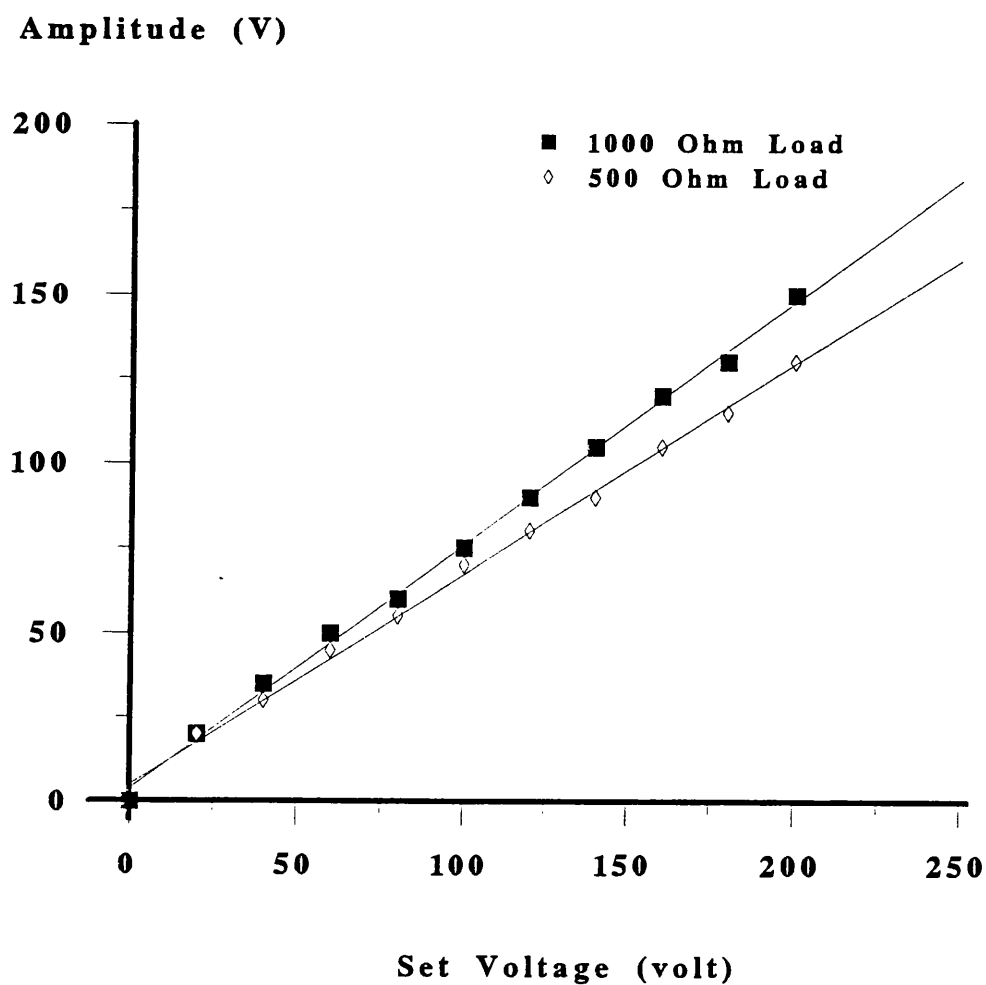
Figure 8. Calibration of the stimulator on the 0 to 200 volt range with 500 and 1000 Ω load resistances. The curvefit line was y = 5+0.62x, r^2 = 1 for 500 Ω resistance and y = 3.86+0.72x, r^2 = 1 for 1000 Ω resistance.

Calibration of the Stimulator

Amplitude (V)

Set Voltage (volt)
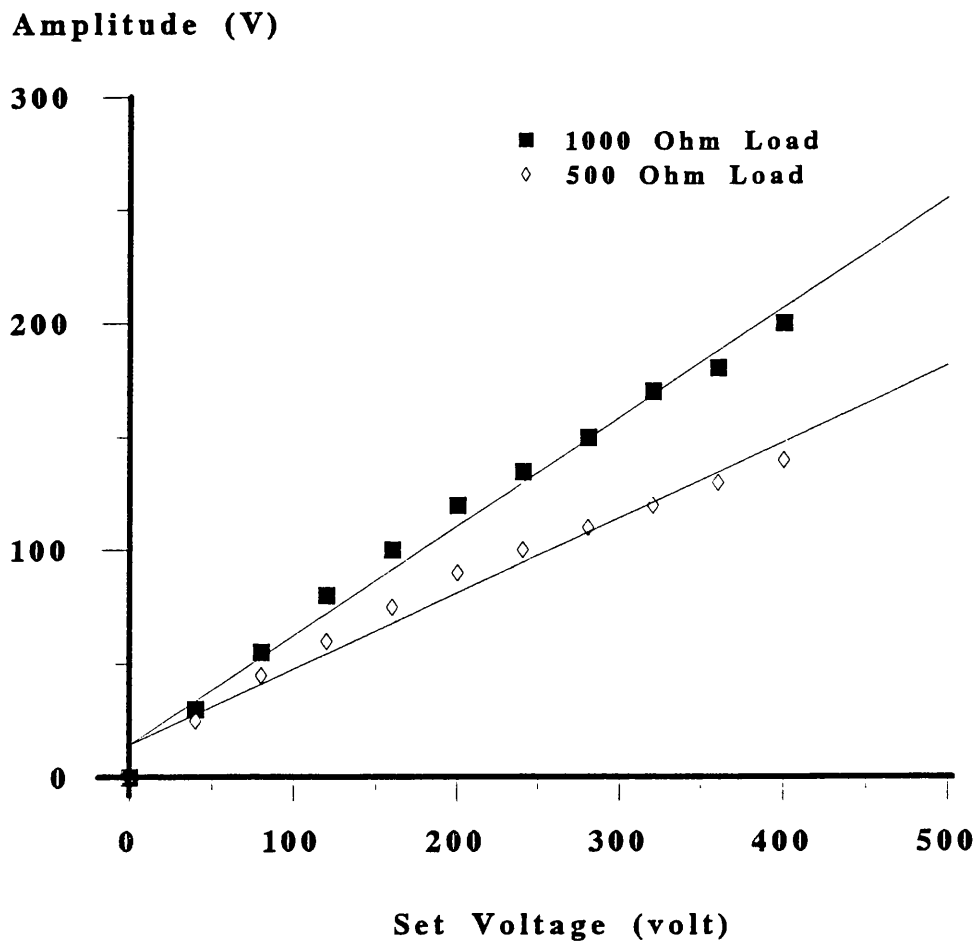
Figure 9. Calibration of the stimulator on the 0 to 400 volt range with 500 and 1000 Ω load resistances. The curvefit line was $y = 14.55+0.33x$, $r^2 = 0.97$ for 500 Ω resistance and $y = 14.55+0.48x$, $r^2 = 0.99$ for 1000 Ω resistance.

2.6   Calibration of strain gauge transducer

Two strain gauges were used during experiments:

A strain gauge with maximum rating of 20 kg, (RS, 632-742) was used to measure relatively low torques associated with dorsiflexion and plantarflexion of ankle joint. The foot was strapped on to a foot plate which mounted on the transducer. The strain gauge was calibrated to confirm its linearity. These data are shown in figures 10.

The larger knee torques, were measured with a strain gauge with a higher rating of 250 kg, (RS, 645-811). The leg just above malleolus was securely strapped on the transducer. This calibration curve is shown in figure 11.

Measurements of force and half relaxation time

Force were measured from the base line to the the maximal amplitude of the force before, after either voluntary or the electrical activity and after recovery. The half relaxation time were calculated from the peak force to half its value.

Calibration of Strain Gauge for Dorsiflexion & Plantarflextion
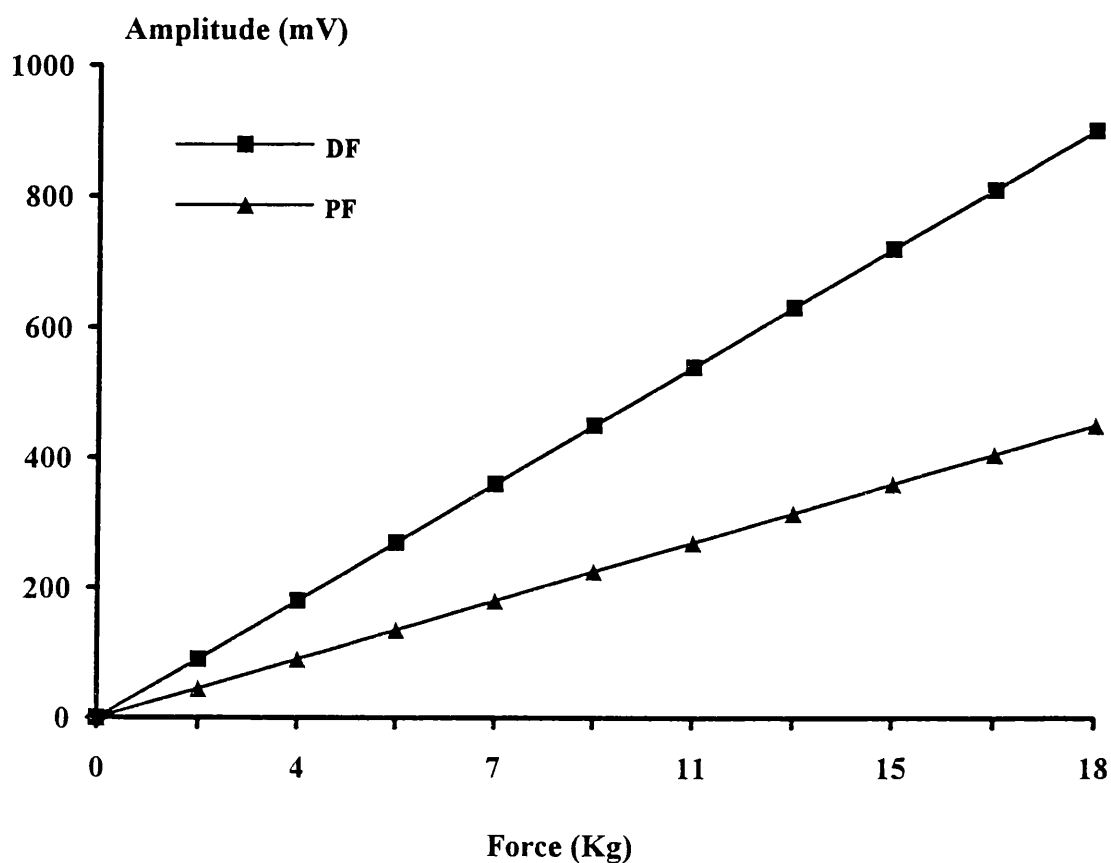
Figure 10. Calibration of the strain gauge for plantarflexion (PF, filled triangles) and dorsiflexion torques (DF, filled squares). The curvefit line was $y = -0.96 + 49.60X$, $r^2 = 1$ for dorsiflexion and $y = -0.48 + 24.80X$, $r^2 = 1$ for plantarflexion.

Calibration of Strain Gauge Transduder for Knee Extention
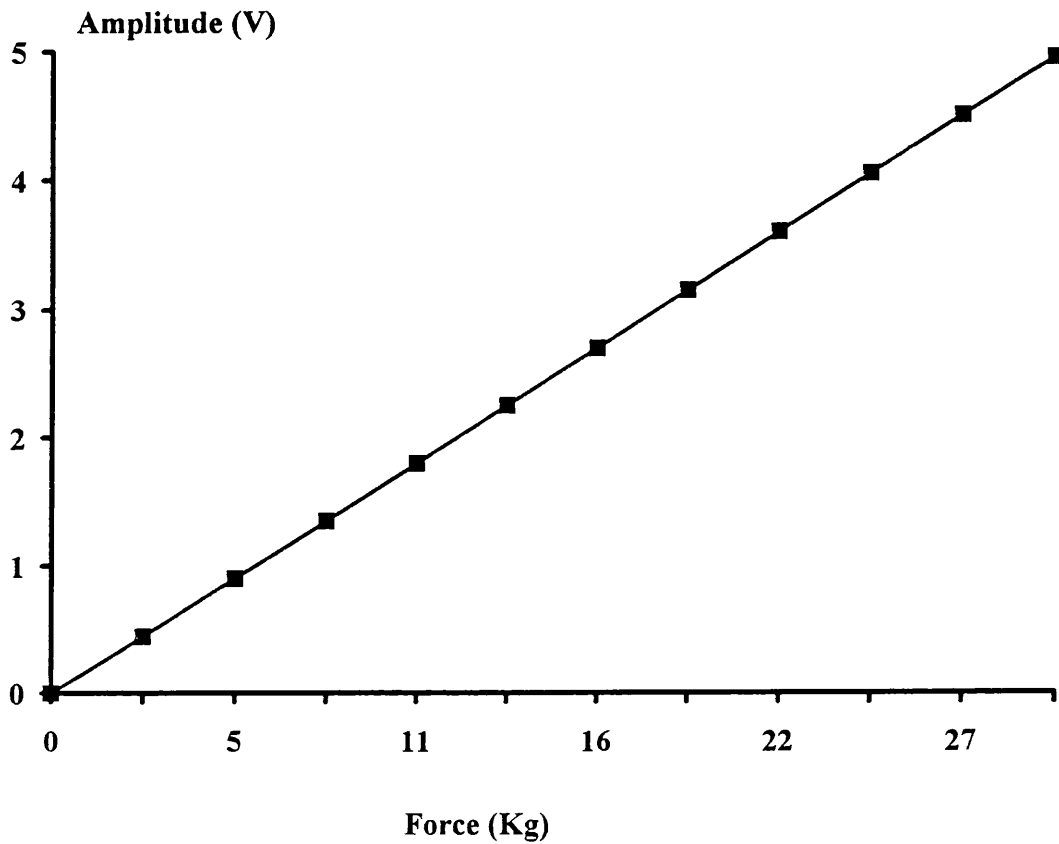
Figure 11. Calibration of the strain gauge for knee extension torque. The curvefit line was y = 0.03+0.16X, r^2 = 1.

2.7 Measurements of latency and amplitude

Latencies from the stimulation artefact to the first signs of the M or H waves were calculated. Peak to peak amplitudes of M and H waves were measured. Examples of this are shown in figures 12 and 13.

The anterior tibial H reflexes showed complex waves, as potentials were probably elicited from more than one muscle. But only the first response was measured.

2.8 Exercise in muscles

Exercise was performed voluntarily or by direct muscle stimulation.

Muscle were exercised to induce muscle fatigue. The extent of fatigue was assessed by comparing the magnitude of the maximal force developed after exercise with that from fresh muscle. In addition, the half relaxation times were also calculated.

Voluntary exercise

First, maximal voluntary contraction was measured at least two times by encouraging the subjects to make the best effort as they can. Then, the largest force was chosen. During the measurement, any trunk and arm movement was controlled to prevent the participation of the other muscles. Voluntary exercise to fatigue was performed by intermittent contractions at 30% of MVC. Each contraction lasted 7 sec followed by a 3 sec rest. Subjects were provided with "target" force profile on an

oscilloscope. The intensity and duration of each contraction were therefore carefully controlled.

This cyclical activity was sustained for up to 9 minutes. These periods of muscle activity in anterior tibial muscles were performed with and without an arterial occlusion cuff round the midthigh inflated to at least 150 mmHg to obstruct the blood flow during the experiment. Quadriceps experiments were performed only with normal blood flow. When blood pressure cuff was used, the contractions were only be sustained for 3 minutes. The timing of experimental procedures is illustrated in figure 14.

Electrical exercise

Activity in the anterior tibial muscle was induced by direct electrical stimulation. The pattern of contraction was similar to that already described above, 7 sec on 3 sec off. The stimuli were delivered through an isolation unit at a frequency of 20 Hz. Monophasic rectangular voltage pulses of 0.1 ms duration were used.

The intensity of stimulation was set at the highest intensity subjects found tolerable. This was usually 2-4 times motor threshold. The stimulating electrodes were two self-adhering electrodes; the cathode lay over the anterior tibial muscle between recording electrodes while the anode was below the recording electrodes.

The trains of stimuli were delivered for 3 to 9 minutes until the tetanic tension had fallen by more than half. The magnitude of forces typically was about 30% of maximal voluntary contractions. The volunteers would be able to stop the experiment, if they felt any discomfort or pain

during experiment. Figure 15 shows experimental details of timing electrical exercise experiment.

Blood pressure cuff

During the electrical or voluntary exercise the blood flow to the lower limbs could be obstructed. An arterial blood pressure broader cuff for use in thigh, 19 cm width was applied with its distal border about 10 centimetres above the knee around the thigh to obstruct the blood flow. The cuff was inflated to at least 150 mm. Hg.

2.9   Details of H reflex testing

Two types of H reflex tests were performed.

Submaximal H reflexes

These were done for both voluntary and electrical fatigue procedures. Submaximal H reflexes in anterior tibial and soleus muscles were tested by setting the intensity of stimulation to yield control H reflexes near 1/2 maximal. In view of the known variability of reflex responses an average of 10 to 20 successive responses were elicited at 5 sec intervals. Generally, half maximal H reflex in anterior tibial muscles required stimulus intensity below 1.5 times motor threshold, and in soleus stimulation between 1.5-2.5 times motor threshold was required. The half maximal H reflexes in control conditions before muscle fatigue were normalised to 100%.

A similar normalisation was performed on the submaximal M wave which preceded these H waves. The ratio of submaximal H to submaximal M wave was then 100% in control conditions. Each of these measurements were repeated after fatiguing exercise and after a recovery period. Thus values below 100% indicate a fall in amplitude or ratio and values above 100% indicate an increase.

Measurements for H/M ratios at the above stimulus intensity were compared before and after muscle activity and during recovery periods. At least 30 seconds elapsed after the end of the contraction before the first test was made. Subjects waited 10 minutes for recovery, and the same trials of H reflexes were averaged to compare with control values.

Recruitment curve

A type of H reflex test was done in experiments where anterior tibial and quadriceps femoris muscles were fatigued by voluntary activity. Single shocks at stimulus intensities from motor threshold up to 15 times motor threshold were delivered. Then, M waves and H reflexes were plotted against motor threshold (see figures 37 and 38 in section 3.12 of results). Maximal M waves, maximal H reflex amplitudes and H_{max}/M_{max} ratios was compared before and after periods of muscle activity. At least 30 seconds elapsed after the end of the contraction before the first test was made. Subjects waited 10 minutes for recovery, and the same stimuli were repeated. The latencies of M waves and H reflexes were measured before and after voluntary fatigue. The amplitudes of H_{max} and M_{max} in control conditions were normalised to 100%

Measurement of Soleus M & H Wave Latency & Amplitude
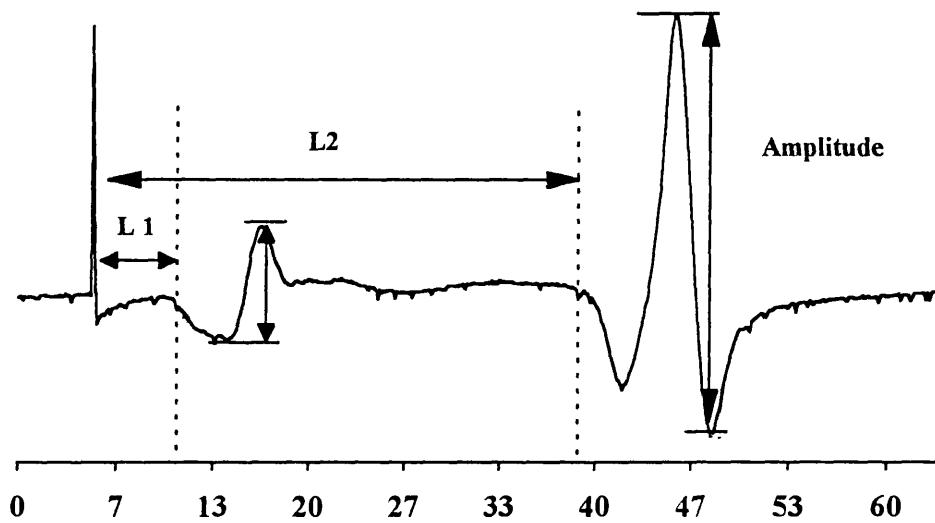
Figure 12. A specimen of soleus M and H waves recorded from one subject. As can be seen soleus M and H waves latency and amplitude were measured, which are summarised below:

Soleus M latency (L1) and amplitude= 5 ms, 2.5 mV.

Soleus H latency (L2) and amplitude= 34.5 ms, 8.47 mV

Measurement of anterior tibial M & H Wave Latency & Amplitude
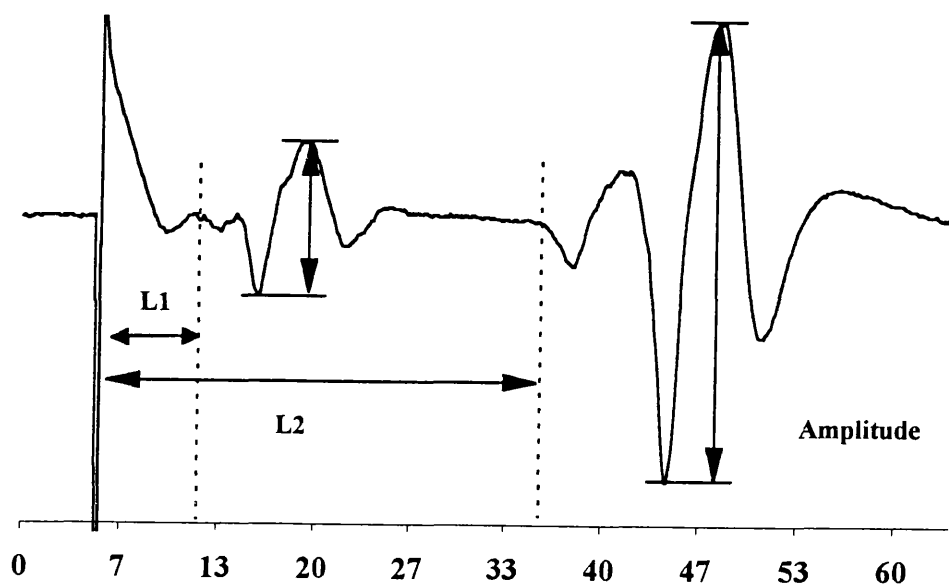
Figure 13. Anterior tibial M and H waves recorded from one subject. As can be seen M and H waves latency and amplitude were measured, which are summarised below:

Anterior tibial M latency (L1) and amplitude= 4.5 ms, 0.35 mV.

Anterior tibial H latency (L2) and amplitude= 30.4 ms, 1.16 mV
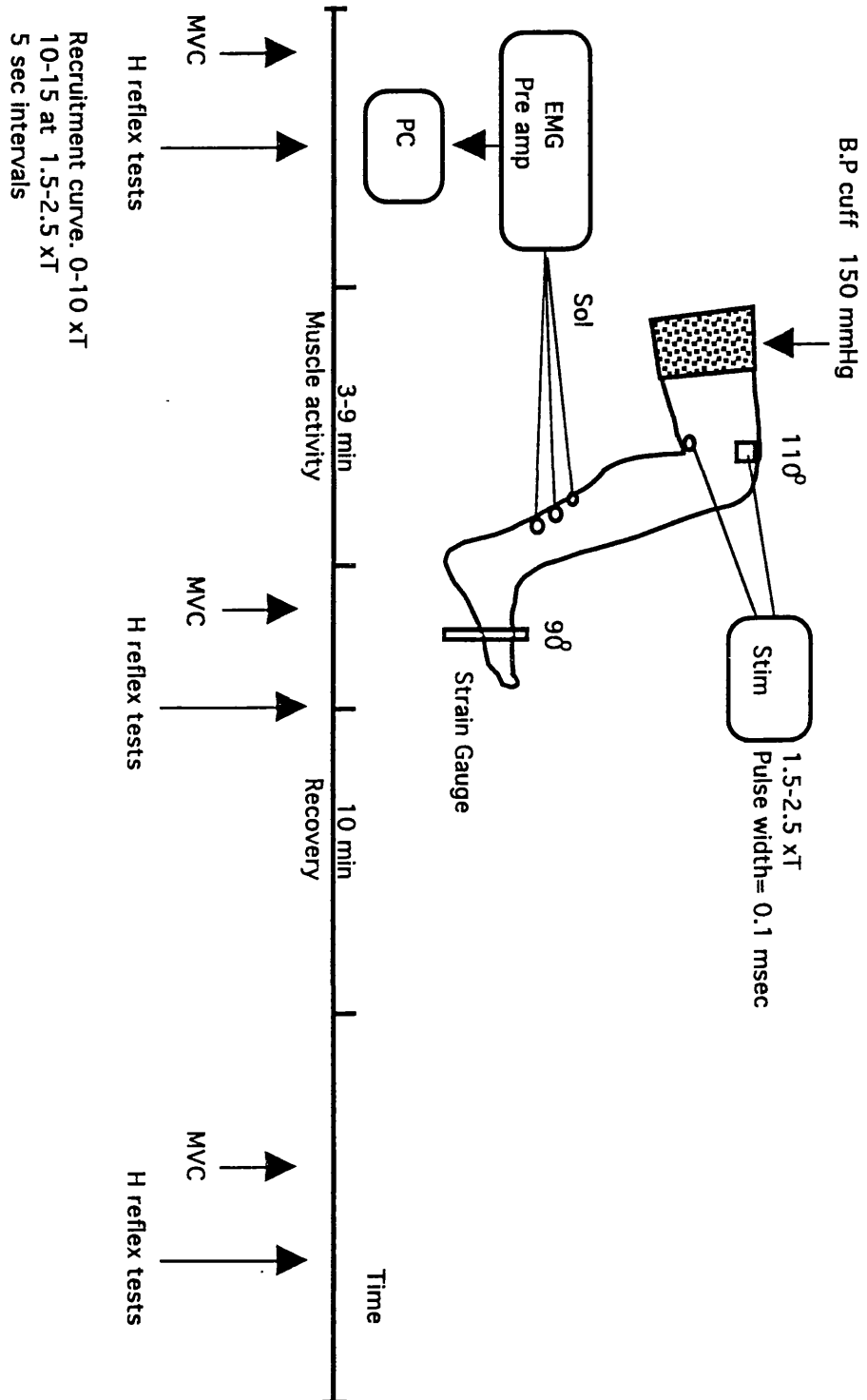
Figure 14. Experimental details of voluntary fatigue procedure. Alternatively, the electrode positions were changed to allow investigation of the anterior tibial muscles.

Electrical Fatigue Procedure
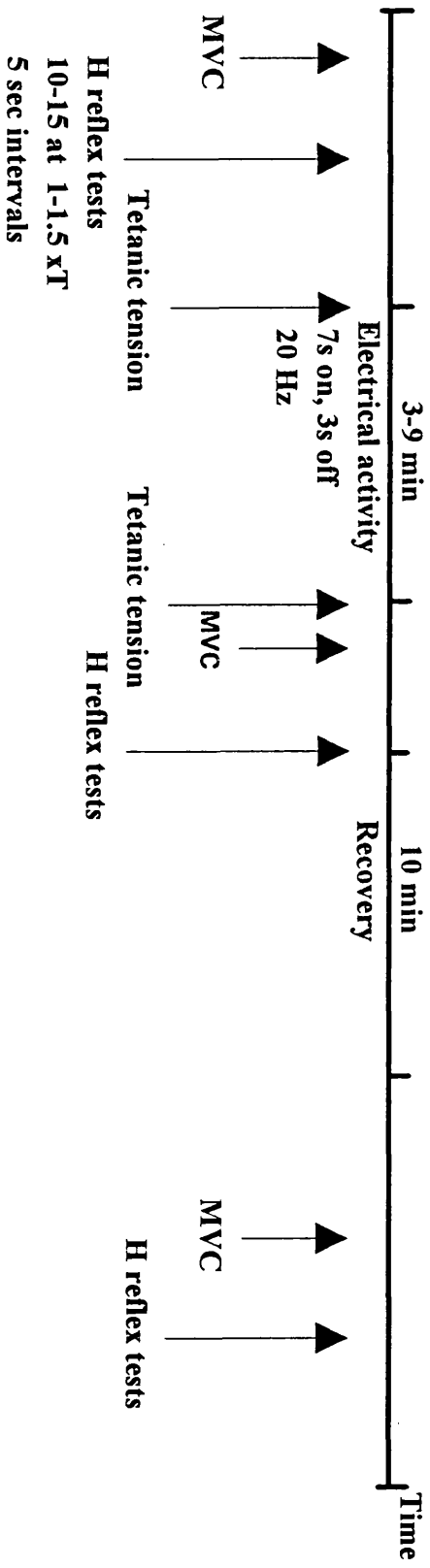
Figure 15. Experimental details of electrical fatigue procedure in anterior tibial muscles. Submaximal H reflexes in anterior tibial muscles were tested.

2.10 Statistical analysis

The aim of statistical analysis is to compare values of muscle force, H and M latencies, amplitudes, and H/M ratios in control periods with values immediately following exercise and after a period of recovery .

Maximal M and maximal H waves in control periods were normalised to 100%. Consequently, the ratio of H_{max}/M_{max} was also 100% in control conditions. The maximal voluntary contractions, tetanic force and half relaxation times in each subject were also normalised to 100%. All of these measurements were repeated after fatiguing activity and during recovery period and compared to control values using Student's paired t tests.

In other experiments submaximal responses were tested. In 10-20 trials, the mean M and H latencies, submaximal M waves and submaximal H reflex amplitudes, the ratio of submaximal H to submaximal M waves ratios were calculated. A similar normalisation was performed and each value was set to 100% in the control period. The mean values in control conditions were compared with the means of post activity and recovery periods. These data were analysed with Student's paired t tests

The α level of significance was set at $0.05 > P > 0.01$ with one star, $0.01 > P > 0.001$ with two stars and more than 0.001 with three stars.

Through out the text arithmetic mean with standard deviations are given.

3. Results

3.1 M wave and H reflex latencies

The latency of M waves and H reflexes in soleus and anterior tibial muscles were measured from onset of the stimulus artefact to the point where the EMG potentials (M wave and H reflex) leave the baseline. The results of subjects who participated in experiments testing soleus and anterior tibial M waves and H reflexes were presented in table 4 and 5.

The relationship between height and latency is illustrated in figure 16 and 17. These figure show M latencies are almost constant in all subjects. However, the H latencies appear dependent with height, and slightly increased in taller subjects.

Soleus and anterior tibial M wave and H reflex latencies were constant in each subject, and independent of the stimulus intensity. This is illustrated in the data for a typical subject shown in figure 18.

The mean latencies of soleus M waves and H reflexes latencies were calculated for 29 subjects. The mean latency for soleus M waves was 4.4 ± 0.5 ms (mean ± SD, range 3.6-5.5 ms) and the mean H reflexes latency was 30.9 ± 2.3 ms (range 26-36 ms). The results are shown in figure 19. The M waves latency were more consistent than H reflexes, and the increase in H reflexes latency did not effect on the M waves latency.

A similar analysis for the latency of anterior tibial M waves were used and the mean was 4.2 ± 0.6 ms (range 3.2-5.2 ms). The mean of anterior tibial H latency was 30.2 ± 1.5 ms (range 27.7-32.3 ms). Figure 20 shows the anterior tibial M and H latencies in different subjects.

The latencies of soleus M and H waves were compared to anterior tibial M and H waves, and no significant differences were found.

Results of Subjects Who Participated in Experiments Testing Soleus H Reflexes

Number	Height (cm)	Perceptual Threshold (Volts)	Motor Threshold (Volts)	M Wave Latency (msec)	H Reflex Latency (msec)
1	178	20	35	5.2	33.6
2	185	20	30	5	32.8
3	166	20	40	3.7	32
4	170	20	30	4.8	34.3
5	180	15	30	4.7	33.6
6	164	20	30	4.5	32
7	183	20	30	5	33
8	172	30	40	4.4	30.5
9	174	15	25	4.2	29
10	180	25	40	4	29
11	170	20	25	4	29.2
12	175	20	50	5.2	30.2
13	173	15	30	4	28.2
14	180	20	25	4.4	29.2
15	180	20	40	3.8	31.8
16	175	20	30	4.8	31
17	172	20	25	3.9	28.7
18	165	15	25	4	29
19	162	15	30	4.4	28
20	180	20	30	4	30
21	179	30	50	5	34
22	176	20	30	4.4	30
23	165	20	30	4.1	30
24	156	20	30	3.6	26
25	174	25	40	4.3	33
26	173	10	20	4.5	31
27	167	20	35	4	28.5
28	180	40	50	5.5	36
29	171	30	40	4.5	32

Mean	173.3	20.9	33.3	4.4	30.9
SD	6.9	5.8	7.9	0.5	2.3
Range	156-185	10-40	20-50	3.6-5.5	26-36

.

Table 4. This table shows results for subjects who took part in experiment on soleus H reflexes. For each subject it shows, height, perceptual threshold, motor threshold, M latency and H latency are shown. The height was 173.3 ± 6.9 cm (mean ± SD, range 156-185), the mean perceptual threshold was 20.9 ± 5.8 volts (range 10-40), the mean motor threshold was 33.3 ± 7.9 volts (range 20-50), the mean M latency was 4.4 ± 0.5 msec (range 3.6-5.5) and the mean H latency was 30.9 ± 2.3 volts (range 26-36).

Results of Subjects Who Participated in Experiments Testing Anterior Tibial H Reflexes

Number	Height (cm)	Perceptual Threshold (Volts)	Motor Threshod (Volts)	M Wave Latency (msec)	H Wave Latency (msec)
a	178	20	25	4.5	30.8
b	185	15	30	5.2	32
c	166	15	30	4.2	32
d	170	20	30	4.6	31
e	180	15	25	4.8	31.8
f	164	20	25	4	29
g	183	15	20	5.2	32
h	157	15	30	3.6	30
i	171	15	17.5	4.4	30.4
j	170	20	30	4	28
k	163	20	25	4.5	30
l	185	17.5	30	3.7	29.8
m	181	20	22.5	5.1	32.3
n	158	10	20	3.4	27.7
o	163	15	20	3.2	28.5
p	180	15	20	4.4	29
q	173	10	20	4	30
r	178	17.5	20	4.2	32
s	170	20	22.5	4.1	30
t	167	20	27.5	4.5	28
u	165	12.5	25	3.6	30

Mean	171.8	16.5	24.5	4.2	30.2
SD	8.7	3.3	4.3	0.6	1.5
Range	157-185	10-20	17.5-30	3.2-5.2	27.7-32.3

Table 5. This table shows results for subjects who took part in experiments on anterior tibial H reflexes. For each subject it shows, height, perceptual threshold, motor threshold, M latency and H latency. The mean height was 171.8 ± 8.7 cm (mean ± SD, range 157-185), the mean perceptual threshold was 16.5 ± 3.3 volts (range 10-20), the mean motor threshold was 24.5 ± 4.3 volts (range 17.5-30), the mean M latency was 4.2 ± 0.6 msec (range 3.2-5.2) and the mean H latency was 30.2 ± 1.5 volts (range 27.7-32.3).

The Relationship Between Height and soleus M, H Waves Latency

Latency (ms)
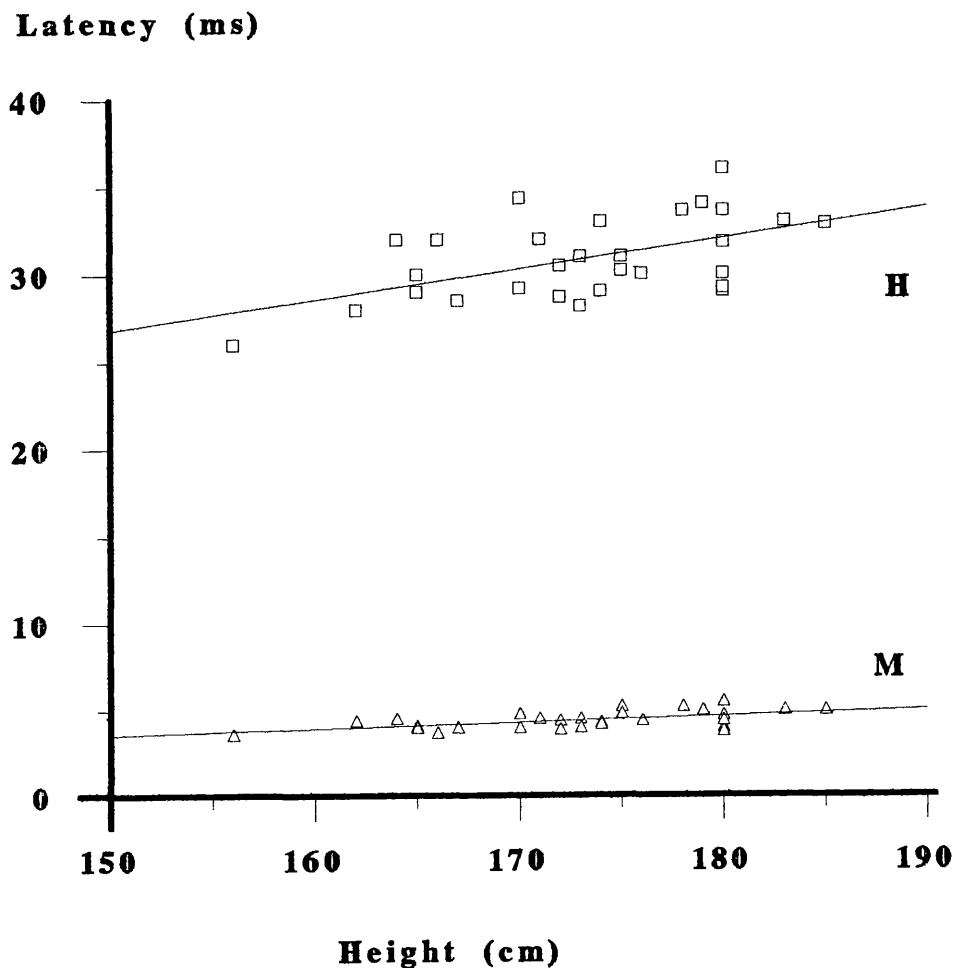
Height (cm)

Figure 16. This figure shows the relationship between height and soleus M and H waves latency. The M wave latencies almost were constant and the curvefit line was y = 0.04x -1.87, r^2 = 0.26. Whilst the H reflexes were slightly increased by increasing of the height, the curvefit line was y = 0.17x -1.02, r^2 = 0.27

The Relationship Between Height and Anterior Tibial M, H Waves Latency

Latency (ms)
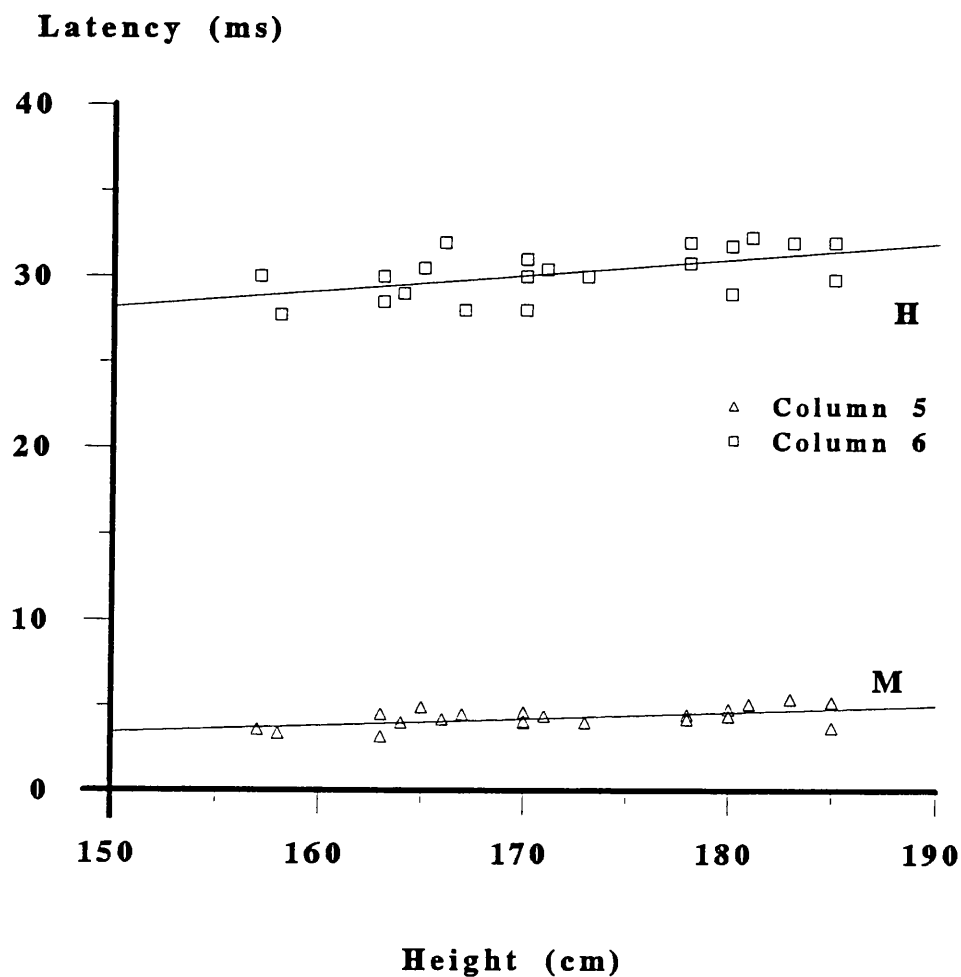
Height (cm)

Figure 17. This figure shows the relationship between height and anterior tibial M and H waves latency. The M waves latencies were almost constant and the curvefit line was y = 0.04x -2.28, r^2 = 0.33. Whilst the H reflexes were slightly increased by increasing of the height, the curvefit line was y = 0.09x -14.27, r^2 = 0.30

Soleus M and H Latencies at a Range of Stimulus Intensities
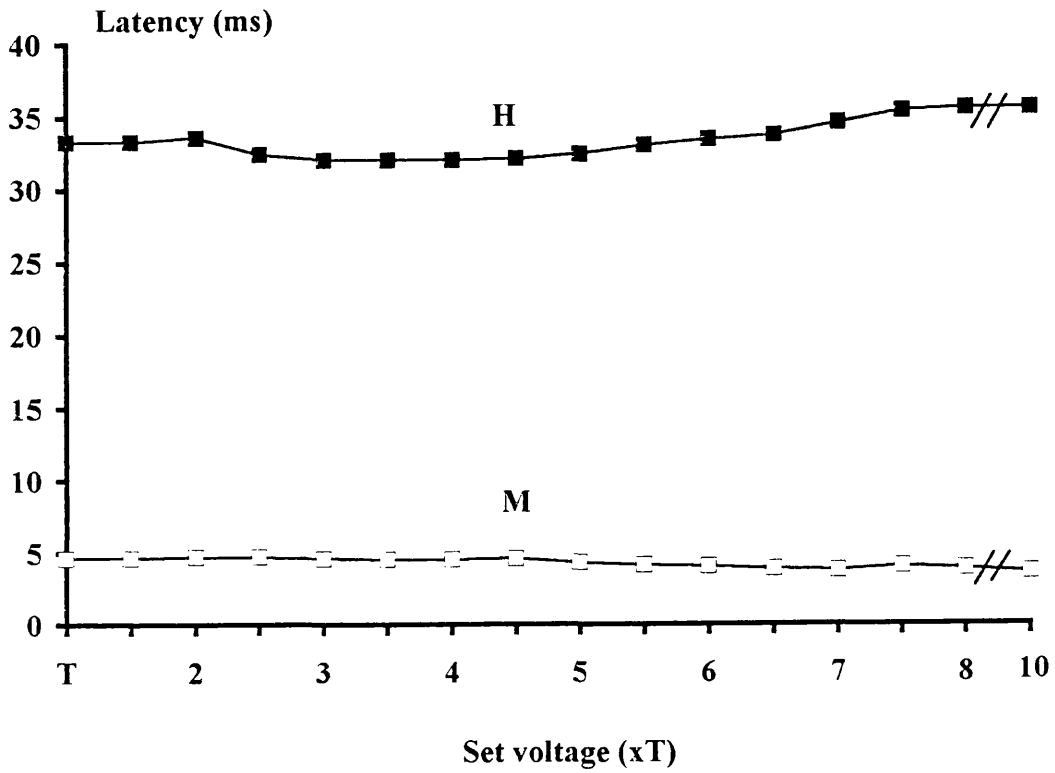
Figure 18. The soleus M wave and H reflex latencies at a range of stimulus intensities in one subject. The latencies are independent of stimulus amplitude.

Soleus M and H Waves Latencies in Different Subjects
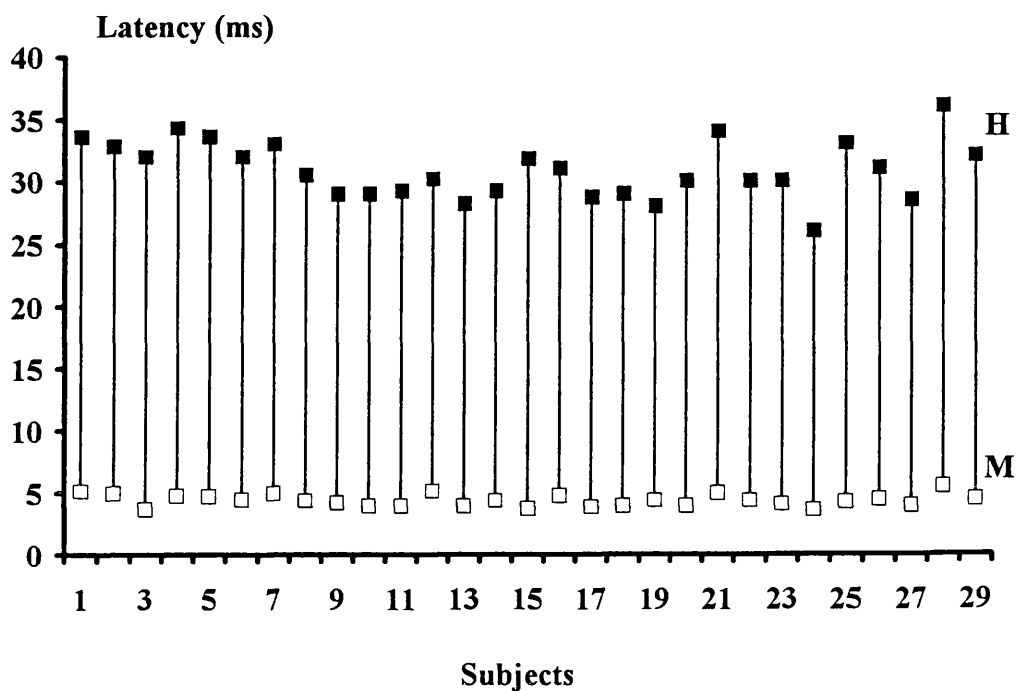
Figure 19. Soleus M wave and H reflex latencies at 1.5-2.5 times motor threshold for 29 subjects. Open squares show soleus M waves latency and filled squares show soleus H reflexes latency. The M latency is more consistent than the H latency. There is clear relationship between H and M latency in each subject.

Anterior tibial M and H Waves Latencies in Different Subjects
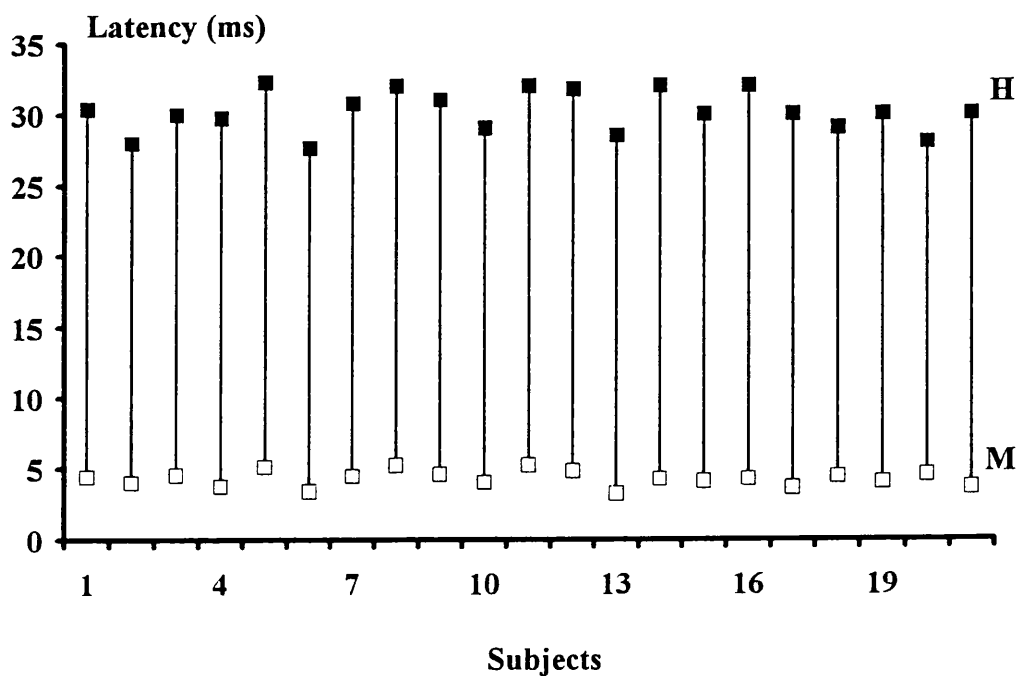
Figure 20. Anterior tibial M wave and H reflex latencies at 1-1.5 times motor threshold for 21 subjects. Open squares show anterior tibial M waves and filled squares show anterior tibial H reflexes latency. The M latency are more consistent than the H latency. There is clear relationship between M and H latency in each subject.

3.2 The effects of different positions on the H reflex excitability

During pilot experiments it was difficult to obtain stable H reflexes. The amplitude of H reflexes was observed to vary systematically with the latero-medial position of the knee. Data illustrating this from one subject is shown in figure 21. H reflexes were largest with the limb rotated to a medial position and smallest with the limb rotated laterally. The M wave amplitude was not affected by changes in position. The H/M ratios in the mid position were 0.65 which were closer to those reported in the literature for normal subjects, which is usually less than 0.7 (Delwaide, 1984). Therefore the right leg was fixed in mid position in all subjects, in all future experiments.

3.3 The effects of different intervals on the H reflex excitability

A single H reflex test affects the subsequent excitability of the motoneurone pool for up to 5 seconds (Hugon, 1973). This is a potential problem if repeated tests of H reflexes are to be made.

Experiments were performed to measure the amplitude of H reflexes with a range of intervals from 1-10 seconds between tests. These data are shown in figure 22. In all of traces the M waves were constant. In figure 22 A, B, C with intervals of 10, 7.5 and 5 sec, the H reflex amplitude remain relatively constant. In figure 22 D, with intervals of

2.5 seconds, there is a progressive reduction in amplitude. With repetitions at 1 second intervals, figure 22 E almost no H reflexes can be elicited.

Figure 23 shows the mean data from 3 subjects obtained during similar experiments. At intervals of more than 5 seconds the H reflex amplitudes are stable. At intervals shorter than 5 seconds the H reflex amplitudes falls to 72% ± 12% (mean ± SD) at 2.5 seconds and 34% ± 5% at 1 seconds, even though M wave remains constant. The stability of the M wave proves that the depression of H reflexes can not be attributed to changes in stimulus intensity.

Effect of Limb Position on Soleus M and H Waves
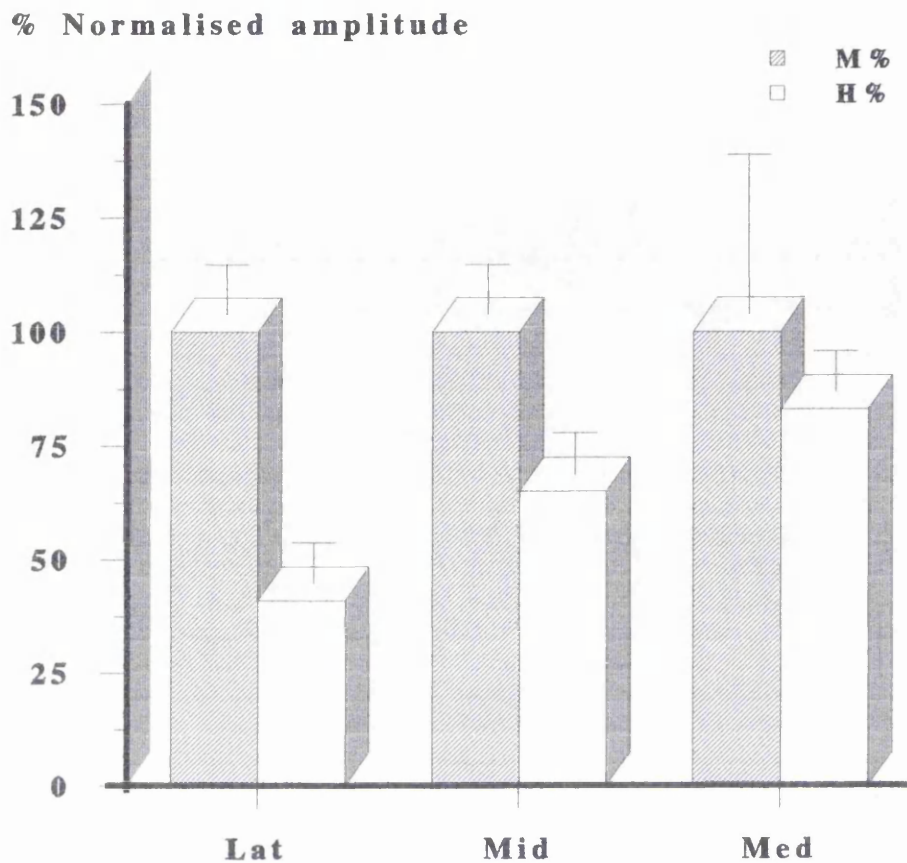
Figure 21. The effect of different positions of lower limb on soleus M and H reflex are illustrated in this figure. The stimulus intensity was adjusted to obtain an H reflex about 50% of maximal amplitudes, and each bar represents the average of 15 trials.

Soleus M & H Waves at Different Intervals

Figure 22. These traces show ten trials of soleus M and H waves elicited by a constant stimulus in one subject. Stimuli were delivered at 10 seconds (A), 7.5 seconds (B), 5 seconds (C), 2.5 seconds (D), and 1 seconds (E) intervals. In all of traces the M waves were constant. In A, B and C, the H reflex amplitude remains relatively constant. In D, with intervals of 2.5 seconds, there is a progressive reduction in amplitude. With repetitions at 1 second intervals (E) almost no H reflexes can be elicited.

Mean of Soleus M & H Waves Amplitudes at Different Test Intervals
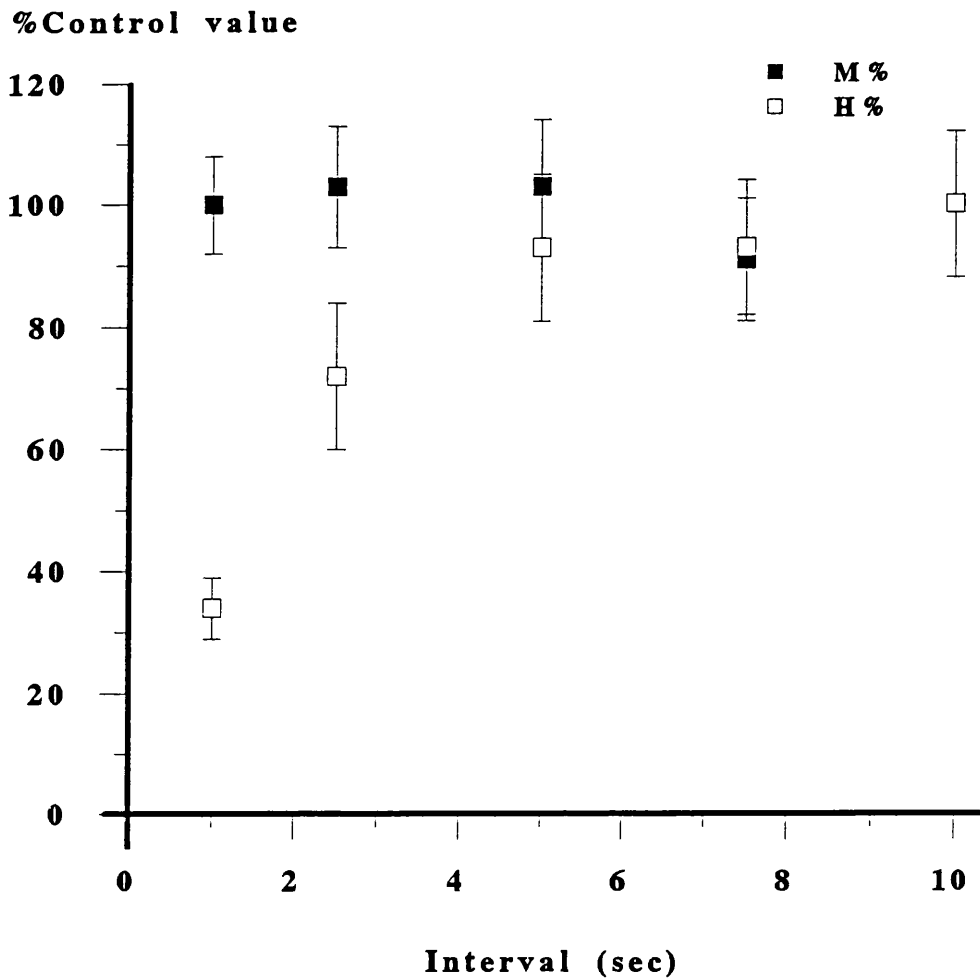
Figure 23. This figure shows the mean (± SD) M waves (filled squares) and H reflexes (open squares) amplitude in 3 subjects. Tests were maded at 1, 2.5, 5, 7.5 and 10 second intervals. The ordinate represents the percentage of control value and the abscissa represents the interval in seconds.

3.4   The effects of precontraction in dorsiflexion on anterior tibial H reflex excitability

H reflexes were difficult to elicit in anterior tibial when the muscle was fully relaxed. As shown in figure 26, H reflexes could not be elicited in 4 of 8 subjects when the muscle was relaxed. The H reflexes in the other 4 subjects were small with a mean amplitude 0.24 mV ± 0.07 mV. However, low force voluntary contraction of anterior tibial muscles increased H reflexes in all 8 subjects. Figures 24 and 25 show the effect of precontraction at 5 and 10% of MVC in anterior tibial muscle M and H reflexes. Precontraction had relatively little effect on M wave amplitudes in the range below 1.75. Between 1.75 and 2.5T, the M wave amplitude increases substantially with higher forces associated with larger M waves. The M_{max} amplitude was constant. The changes in M wave amplitude are probably due to small movements of the muscle nerve relative to the cathode.

The H reflex amplitude, shown in figure 25, is affected by contraction much more than the M waves. H reflexes increase substantially with increasing force between T-1.75T. The stability of the M waves over this range suggests the H increase is due to central facilitation rather than any peripheral effect. Further increases in force of contraction above 10% did not produce a further increase in H reflex amplitude. Figure 26 shows the summary data for sub maximal H reflexes in eight subjects. Precontraction to 10% MVC produces H reflexes in all subjects and the mean amplitude increases from 0.24 ± 0.07 to 0.61 ± 0.19. However, the variability of the H reflexes seems similar after

voluntary contraction. The variability of anterior tibial H reflexes were slightly less than soleus H reflexes which was 1± 0.4 mV (mean ± SD, range 0.56-1.63) at the same level of using precontraction. Both soleus and anterior tibial reflexes had similar amplitudes (50-75% max).

3.5   The effects of agonist and antagonist contractions on the soleus H reflex excitability

The H reflex is routinely recorded from soleus muscle at rest. However, voluntary contraction of the agonist muscle potentiates the amplitude of the H reflex (Hoffmann, 1918). During similar experiments on anterior tibial muscles contraction increased the amplitude of H reflexes (section 3.4). In addition, voluntary contraction of the pre-tibial muscles decreases the amplitude of the soleus H reflex (Hoffmann, 1918; Paillard, 1955).

The soleus H reflex excitability was investigated during voluntary plantarflexion contractions. The results of 8 subjects are shown in figure 27. All subjects had a soleus H reflex at rest. The soleus M waves were steady, while H reflexes increased significantly with increasing force, by 2.30 ± 0.22 mV at 5% (P<0.02), by 2.29 ± 0.31 mV at 10% (P<0.01) and by 2.55 ± 0.32 at 20% (P<0.03) of maximum voluntary contractions. Alternatively, the effects of dorsiflexion contraction on the soleus H reflex excitability were investigated with 10% and 20% of maximum voluntary contractions of anterior tibial muscles. The results of 6 subjects are shown in figure 28. During dorsiflexion, the soleus H

reflexes were progressively depressed in all subjects. These reductions were highly significant, P<0.0001 at both 10% and 20% of MVC.

The Effect of Precontraction of TA on TA M Wave Recruitment Curve
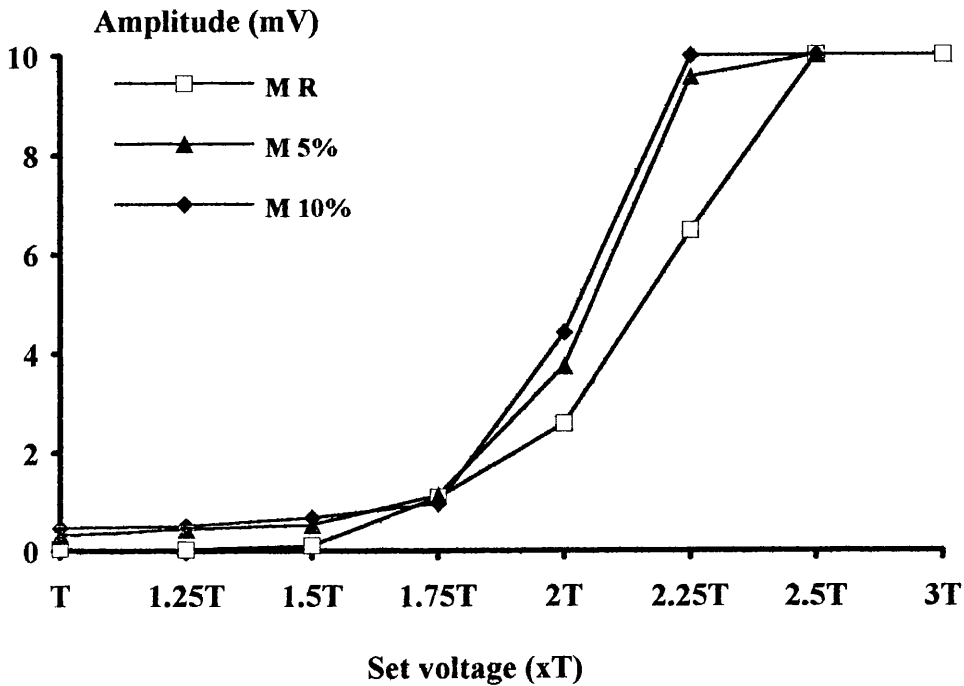
Figure 24. This figure shows the effect of 5 and 10% of background activity of anterior tibial muscles on its own M wave at different stimulus intensities in one subject. M wave recruitment curves show no change.

The Effect of Precontraction of TA on TA H reflex Recruitment Curve
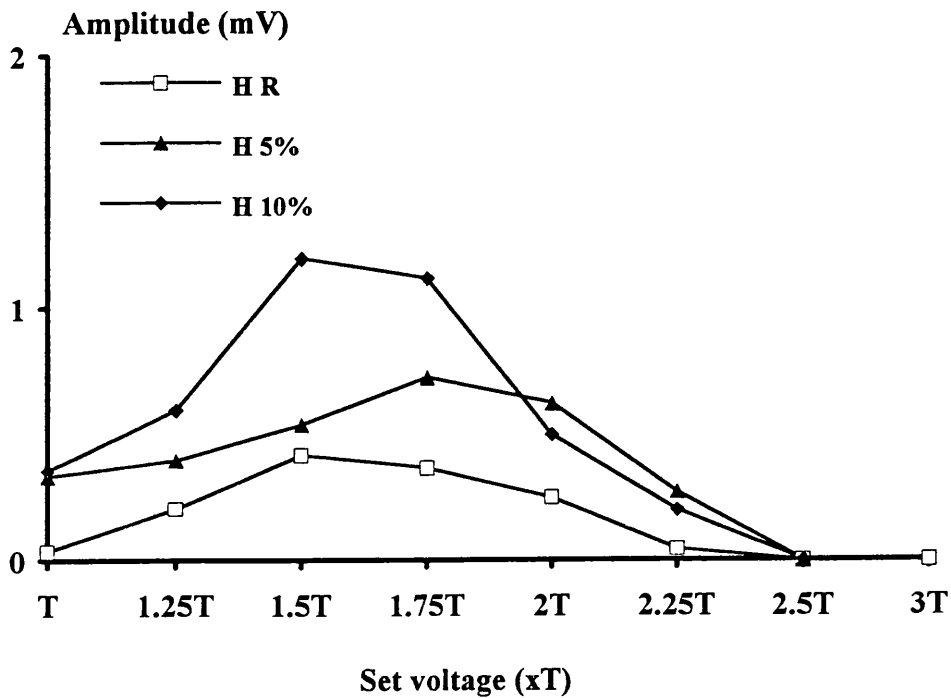
Figure 25. This figure shows the effect of 5 and 10% of background activity of anterior tibial muscles on its own H reflex at different stimulus intensities in one subject. As were shown the H reflex recruitment curves were progressively increased with increasing dorsiflexion torque, especially at 10% of MVC.

Effect of Background Activity in Dorsiflexion on TA H Reflex
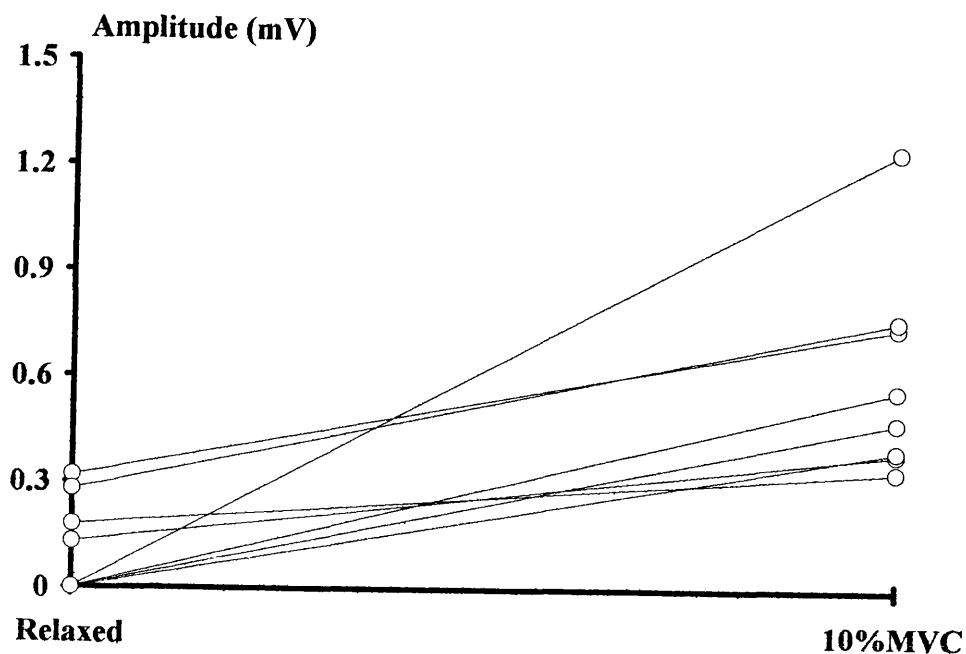
Figure 26. H reflex amplitudes in relaxed anterior tibial muscles and during weak dorsiflexion contraction. The contractions allowed H reflexes to be elicited in all subjects. The mean of anterior tibial H reflex amplitudes in relaxed muscles were 0.24 mV ± 0.07 and after 10% of MVC were 0.61 mV ± 0.19.

Effect of Agonist Contraction on Soleus H Reflex

Amplitude (mV)
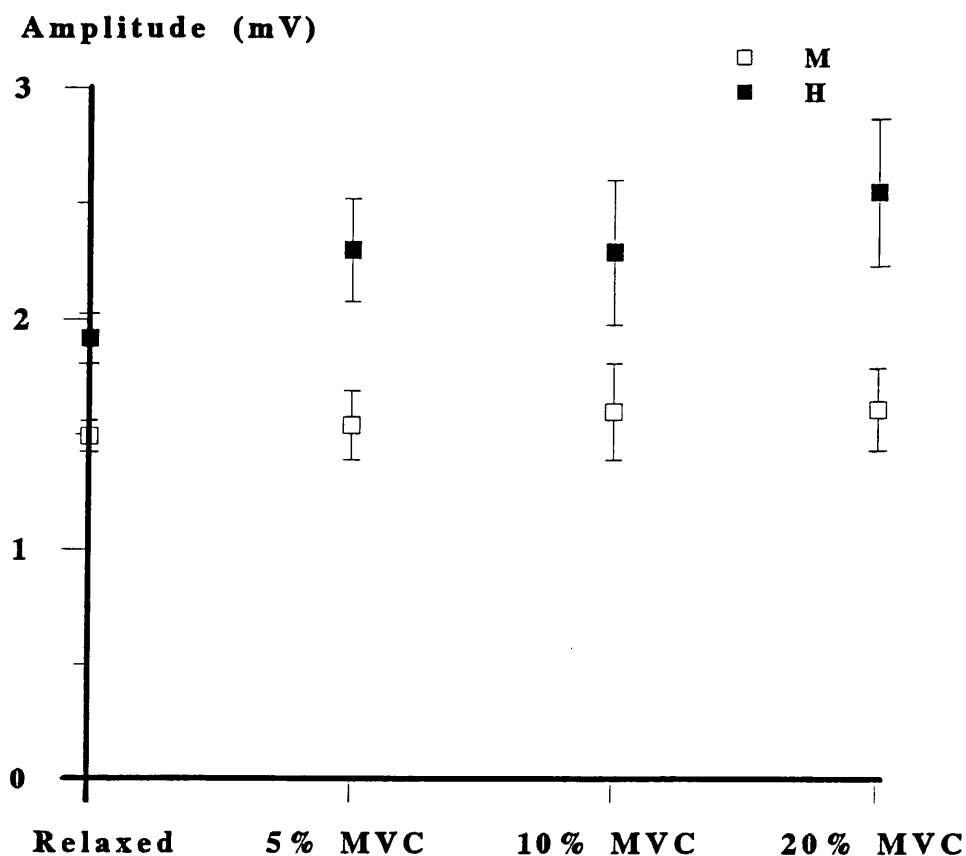
Figure 27. The excitation of soleus H reflex following applying 5, 10 and 20% of MVC in its muscle. The soleus H reflexes were significantly increased in 5% (P<0.02), 10% (P<0.01) and 20% (P<0.03) of background activity in those muscles.

Effect of Antagonist Contraction on Soleus H Reflex
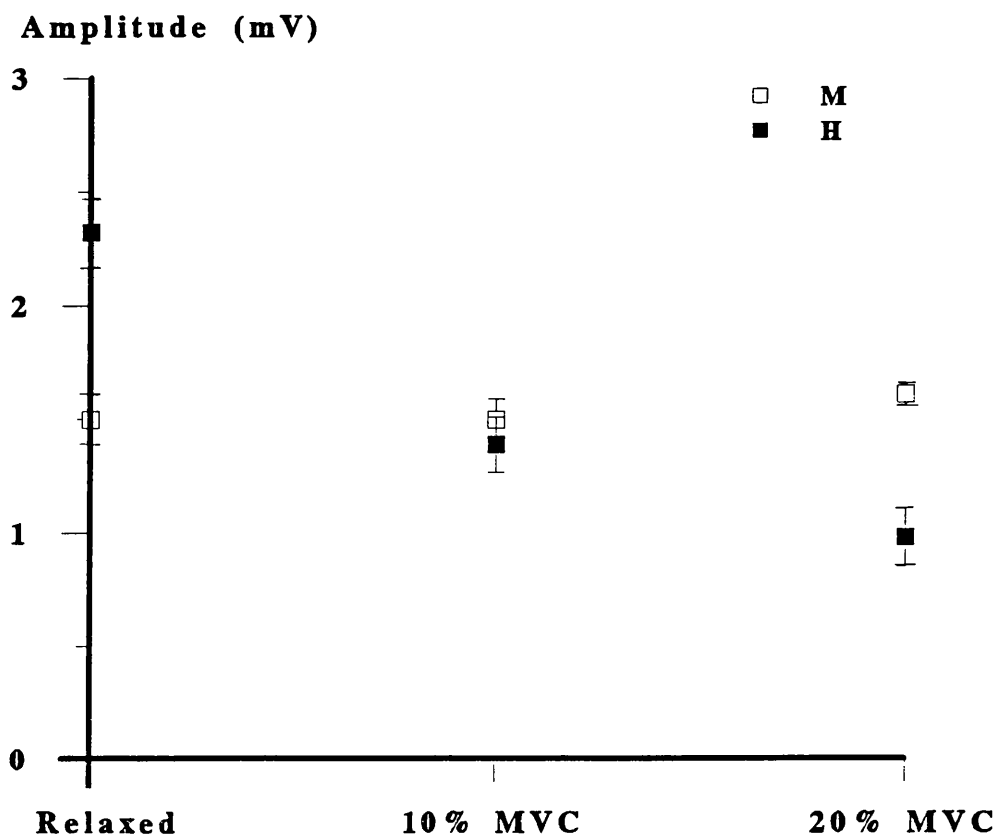
Figure 28. The inhibition of soleus H reflex succeeding 10% and 20% of MVC in anterior tibial muscles. The soleus H reflexes were significantly decreased in both 10% and 20% (P<0.0001) of background activity in its antagonist muscles.

3.6 The effects of fatiguing voluntary activity of the anterior tibial muscle on its own H reflex excitability

Voluntary exercise fatigued the anterior tibial muscles. Following 9 minutes voluntary intermittent contractions at 30% of MVC the fatigue was evident in a reduction in MVC of all subjects. The mean MVC for the 7 subjects was reduced to 86% ± 7% (mean ± SD). The results of all subjects are illustrated in table 6.

In experiments where submaximal stimulation was delivered to set up H reflexes of about half maximal amplitude, the amplitude of the M waves fell after fatiguing exercise in 5 of the 7 subjects. The M wave was constant for 1 subject and rose by 7% for another subject. The mean amplitude of the M waves in 7 subjects was 90% ± 11% (mean ± SD), which was not significantly different from control. The amplitude of H reflexes fell in 6 subjects but rose in 1 subject. For the 6 subjects with reduced H reflexes, the mean amplitude fell to 60% ± 28% (mean ± SD) after exercise. The H wave reduction was statistically significant (P<0.02, Student's t test). The mean amplitude of the H reflexes for all 7 subjects was 67% ± 32% (mean ± SD). Therefore, the H/M ratios were decreased to 68% ± 30% (mean ± SD). However, in one subject this ratio increased even though the MVC fell.

The average of ten submaximal H reflexes from subject 2 elicited during control period, at the end of voluntary activity and after the recovery period are shown in figure 29. In all three traces the M waves are similar. The H reflexes are complex, which might suggest they represent activity from adjacent muscles in the pre-tibial compartments. All

components of the H complex behave the same way, i.e., they were reduced after fatiguing activity. All these components recovered within ten minutes.

The Results of Anterior Tibial MVC, Submaximal M, H Waves and H/M Ratio in All Subjects

Number	MVC%	M%	H%	H/M%
1	88	79	63	83
2	85	93	47	51
3	71	76	10	13
4	88	107	82	78
5	84	83	74	92
6	93	100	86	88
7	91	92	109	119
Mean ± SD	86 ± 7	90 ± 11	67 ± 32	75 ± 34

Table 6. This table shows anterior tibial MVC, submaximal M, submaximal H waves and H/M ratios in each subject.

The problem with changes in M wave amplitudes after exercise were addressed by examining M_{max} and H_{max}. Stimuli at intensities up to 15T were applied . Recruitment curves for the M wave and H reflex were plotted against stimulus voltage in those 7 subjects. A typical recruitment curve is illustrated in figure 38. The results are summarised in table 7. The amplitude of the M_{max} waves rose up to 21% after fatiguing exercise in 3 of the 7 subjects. The M_{max} wave was constant for 2 subjects and fell for the other 2 subjects. The mean amplitude of the M_{max} waves in 7 subjects was 103% ± 11% (mean ± SD), which

was not significantly different from control. The amplitude of H_{max} reflexes fell in 6 subjects but rose in 1 subject. For the 6 subjects with reduced H_{max} reflexes, the mean amplitude fell to 61% ± 25% (mean ± SD) after exercise. The H_{max} wave reduction was statistically significant (P<0.01, Student's t test). The mean amplitude of the H_{max} reflexes for all 7 subjects was 68% ± 29% (mean ± SD). The ratio of H_{max}/M_{max} showed a statistically significant reduction after 9 minutes voluntary activity in all subjects except number 7 who, in the former experiment showed increasing in H/M ratio. The mean of H_{max}/M_{max} ratio fell to 58% ± 22% of preactivity values (mean ± SD, range 34%-85%, P<0.005).

The Results of Anterior Tibial MVC, M_{max}, H_{max} Waves and H_{max}/M_{max} Ratio in All Subjects

Number	MVC%	Hmax%	Mmax%	Hmax/Mmax%
1	88	35	100	34
2	85	42	111	38
3	71	49	107	45
4	88	57	91	63
5	84	97	121	80
6	93	85	100	85
7	91	110	89	124
Mean ± SD	86 ± 7	68 ± 29	103 ± 11	67 ± 32

Table 7. This table shows the normalised data of 7 subjects maximal anterior tibial M and H waves and H_{max}/M_{max} ratios (Mean ± SD) after fatiguing activity of anterior tibial muscles.

The H_{max} and M_{max} waves which were recorded from subject 2 during control, at the end of activity and after the recovery period are shown in figure 30. These traces show that the maximal M waves were constant during the experiment. The figure shows only the one component of a complex H_{max} reflex which decreased significantly following fatiguing activity and was restored to control values after 10 minutes recovery. The results of MVC, M waves, H reflexes, H/M and H_{max}/M_{max} ratios of 6 subjects at the end of voluntary activity and during recovery period were analysed in figure 31 and 32. The M waves were not significantly different, while the other characteristics were significantly reduced. MVCs, H waves, H/M and H_{max}/M_{max} ratios were restored to control values after 10 minutes recovery (figure 32). However, H/M ratios increased about 10% more than control value.

In two subjects the experiment was repeated after blood flow had been obstructed with a blood pressure cuff at midthigh. The contractions could be sustained for only 3 minutes. H reflexes of about half maximal amplitude were elicited by stimulation of the common peroneal nerve during control, during periods of cuff inflation, at the end of fatiguing activity and after 10 minutes recovery. Following 3 minutes ischaemic voluntary exercise of the anterior tibial muscles, the amount of reductions in MVC and H reflexes were relatively similar to the longer periods of activity with circulation.

The latencies of M wave and H reflex in the anterior tibial muscles were measured following intermittent voluntary contractions with and without normal blood flow. These data are shown in table 8.

The Results of Anterior Tibial M Waves and H Reflexes latency

No	Without Pressure Cuff				With Pressure Cuff			
	Mc	Mf	Hc	Hf	Mc	Mf	Hc	Hf
1	4.4	4.4	30.4	31.4	4.6	4.8	32	33.6
2	4	4	28	30.5	4.1	4.3	30.4	31.2
3	4.5	4.5	30	32	4.5	5	32.1	33.9
4	3.7	3.8	29.8	30.5				
5	5.1	5.1	32.3	34.5				
6	3.4	3.4	27.7	28.1				
Mean	4.2	4.2	29.7	31.2	4.4	4.7	31.5	32.9
SD	0.6	0.6	1.7	2.1	0.3	0.4	1	1.5

Table 8. The left side of table represents the mean anterior tibial M and H waves latencies of 6 subjects in control period and after 9 minutes voluntary activity of TA muscle with normal blood flow. The right side of table illustrates the same characteristics in the same sequences in 3 subjects after 3 minutes voluntary activity when blood flow was occluded.

The mean anterior tibial H reflexes latencies with normal blood flow before voluntary contractions were 29.7 ± 1.7 mV (mean $\pm$ SD), which were significantly increased to 31.2 ± 2.1 mV (mean $\pm$ SD, $P<0.01$) after 9 minutes voluntary contractions of anterior tibial muscles. The mean M

wave latencies before voluntary contractions were 4.2 ± 0.6 msec (mean ± SD), which were similar after voluntary fatigue 4.2 ± 0.6 msec.

The mean anterior tibial H reflexes latency when blood flow was occluded before voluntary contractions were 31.5 ± 1 msec (mean ± SD, range 30.4-32.1), which were increased significantly to 32.9 ± 1.5 msec (mean ± SD, P<0.04) after 3 minutes voluntary contractions of anterior tibial muscles. The mean M wave latencies before voluntary contractions were 4.4 ± 0.3 msec (mean ± SD), which was not significantly different after voluntary fatigue.

Effect of Voluntary Exercise of Anterior Tibial Muscles on Its Own Submaximal M and H Waves

A   **Control**

B   **End of Activity**

C   **After Recovery**

0.9 mV

5 ms
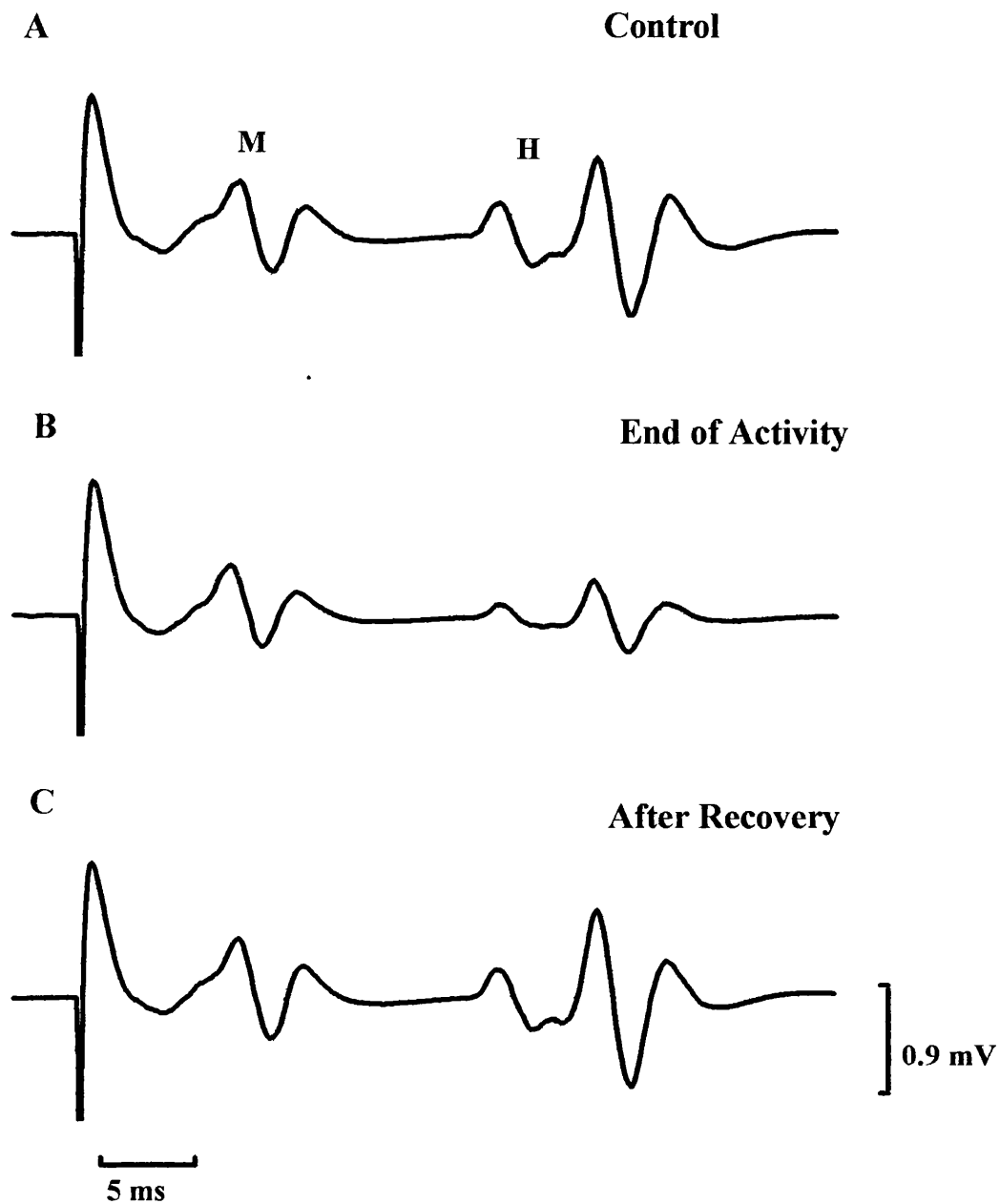
Figure 29. Average submaximal M waves and H reflexes in anterior tibial obtained in (A) control conditions, (B) after anterior tibial muscles activity and (C) in control conditions after recovery.

Anterior Tibial Mmax & Hmax Waves Following Voluntary Fatigue of Anterior Tibial Muscles

A   M max   H max   Control

B   End of Activity

C   After Recovery

2 mV

0.9 mV

5 ms
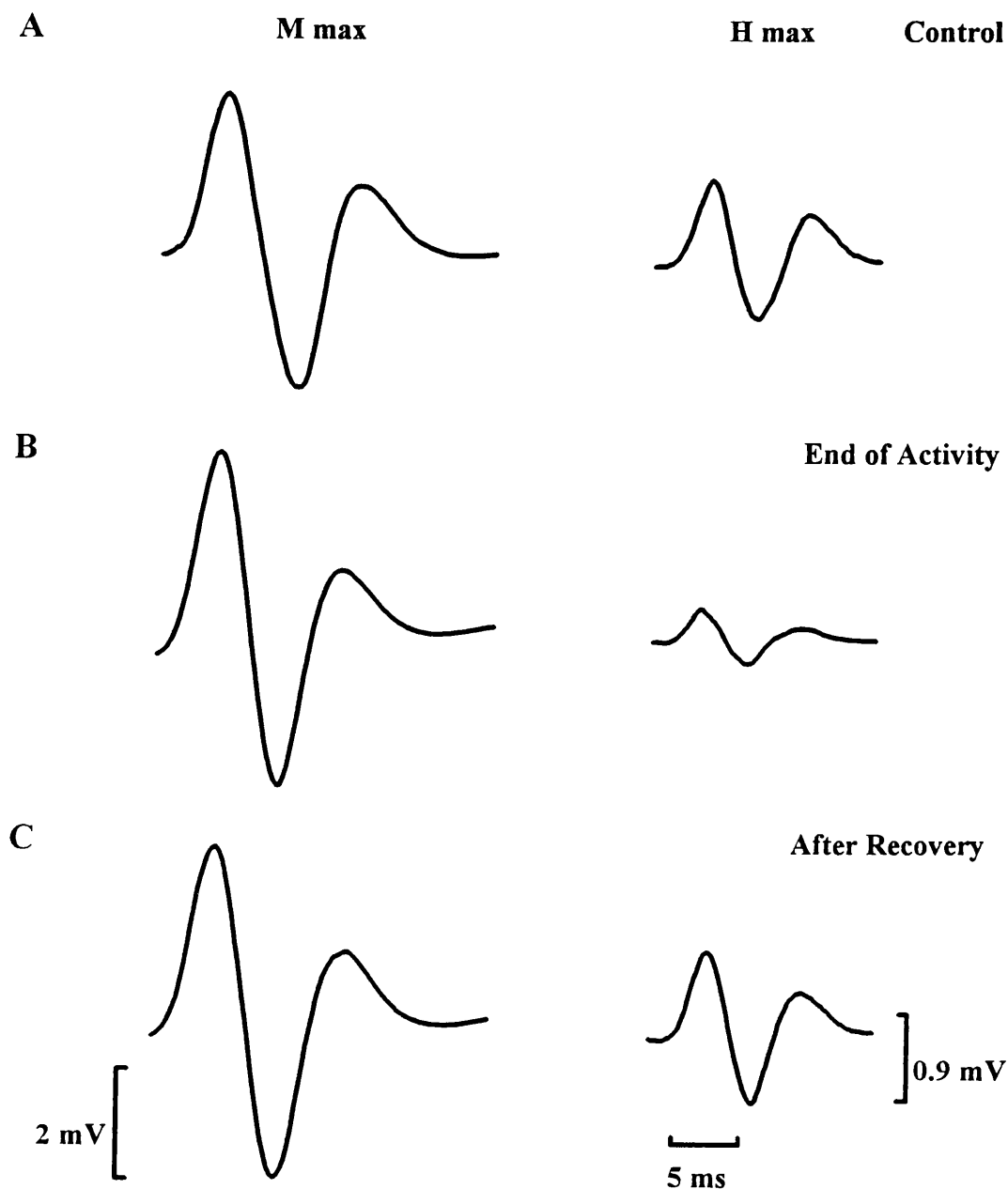
Figure 30. M and H max in control, at the end of activity and after recovery. The M waves were relatively constant in the subject, but the H waves were significantly reduced. Only the main component of the H is shown.

The Effects of Fatiguing Voluntary Activity of Anterior Tibial Muscles on Submaximal M and H Waves in TA.

% Control Value
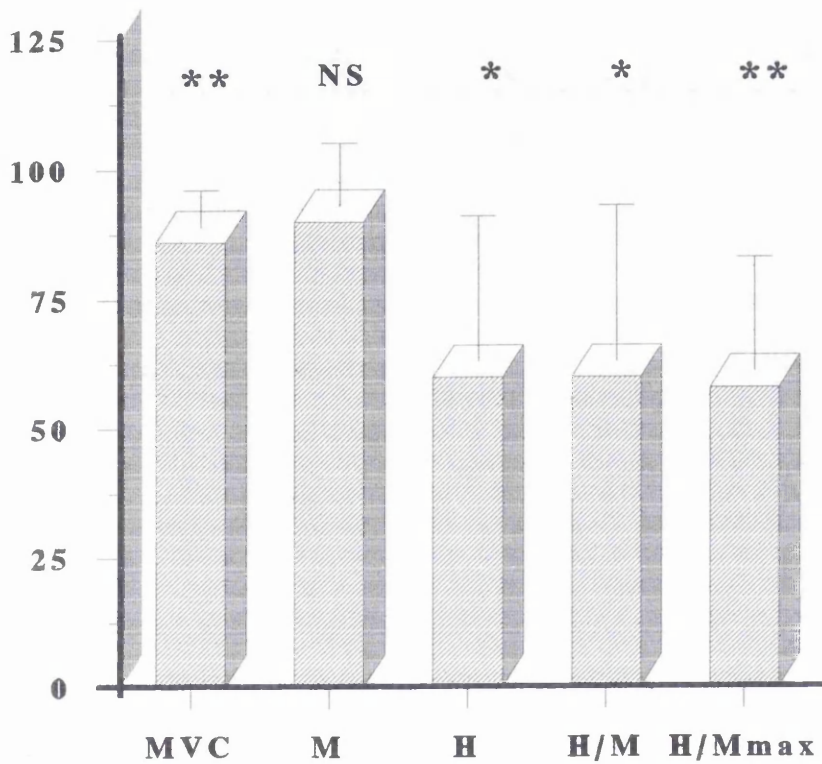
Figure 31. The results represent the mean of MVCs, anterior tibial submaximal M waves, submaximal H reflexes, submaximal H/M and H_{max}/M_{max} ratios of 6 subjects in the minutes following fatiguing activity in anterior tibial muscles.

TA M, H Waves and H/M, Hmax/Mmax Ratios After Recovery

% Control Value
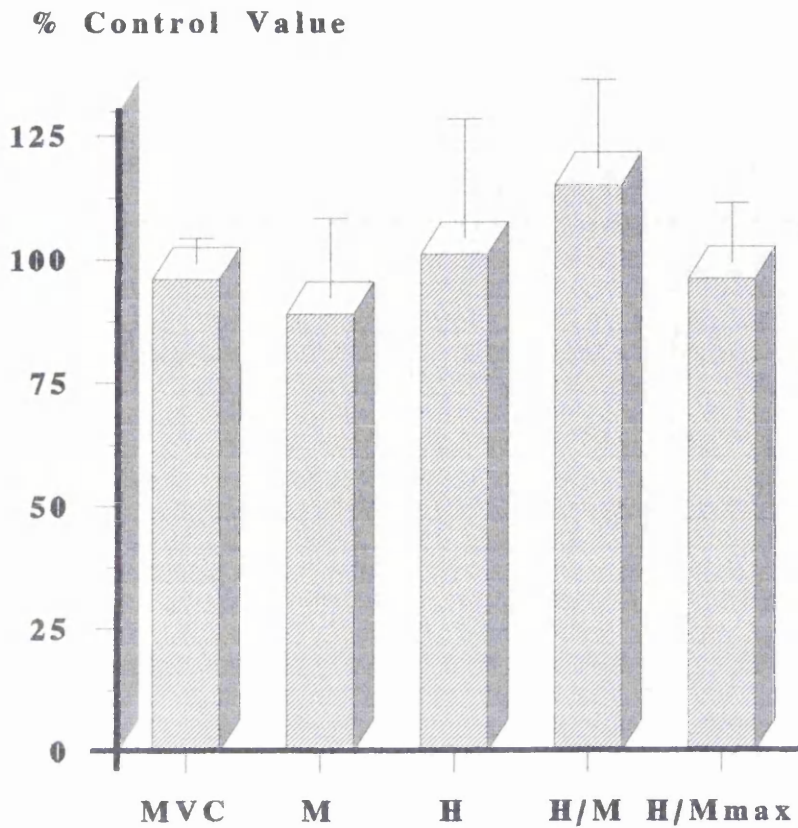
Figure 32. All the characteristics which are shown in figure 31 were restored after recovery period with no significant differences from control period

3.7 The effects of fatiguing voluntary activity of the anterior tibial muscle on soleus H reflex excitability

A series of experiments on 8 subjects were performed to investigate the effects of fatiguing exercise of anterior tibial muscles on the H reflex excitability of soleus. In these experiments the difficulties associated with changing M wave amplitudes seen in section 3.6 can be avoided. The fatiguing exercise protocol described earlier in section 3.6 was repeated but this had no significant effect on soleus H reflexes. Data for the 8 subjects is shown in table 9.

The Results of MVC and Submaximal M, H Waves and H/M Ratio in Soleus Muscle

Number	MVC%	M%	H%	H/M%
1	90	94	99	107
2	95	101	94	93
3	88	98	104	106
4	91	89	95	107
5	91	97	100	103
6	100	99	101	102
7	88	97	89	91
8	100	117	97	83
Mean ± SD	93 ± 5	99 ± 8	97 ± 5	99 ± 9

Table 9. This table shows MVC, submaximal M waves, submaximal H waves and H/M ratios in soleus muscle in each subject.

Additional experiments were performed with the anterior tibial muscles exercise repeated after the muscle blood flow had been occluded with a

pressure cuff at a midthigh position. Intermittent voluntary contractions could be sustained for only 3 minutes at 30% MVC. This produced a significantly greater reduction in MVC 79% ± 5 versus 93% ± 5 (mean ± SD, P<0.001). The results of 8 subjects are illustrated in table 10.

The Results of MVC and Submaximal M, H Waves and H/M Ratio in Soleus (Blood Flow Was Occluded)

Number	MVC%	M%	H%	H/M%
1	83	119	97	81
2	88	100	115	103
3	75	104	94	90
4	80	92	40	43
5	82	95	69	72
6	72	104	98	93
7	75	105	72	70
8	76	96	137	141
Mean ± SD	79 ± 5	102 ± 8	90 ± 30	87 ± 29

Table 10. This table shows MVC, submaximal M waves, submaximal H waves and H/M ratios in soleus muscle in each subject with anterior tibial exercise after blood flow were occluded.

In experiments where submaximal stimulation was delivered to set up H reflexes of about half maximal amplitude, the amplitude of the M waves was constant after fatiguing exercise for 8 subjects. The M waves were relatively constant. The mean amplitude of the M waves in all subjects was 102% ± 8% (mean ± SD), which was not significantly different from control values. The H reflex amplitudes of were decreased in 4

subjects but rose by up to 37% in 2 subjects and were constant in 2 subjects. The mean amplitude of H reflexes for the 8 subjects was 90% ± 30% after exercise. The H wave reduction was not statistically significant. However, the H/M ratios were decreased in 6 subjects but rose in 1 subject and was constant in 1 subject. For the 6 subjects with reduced H/M ratios, the mean amplitude fell to 75% ± 18% after exercise. The H/M ratio reduction was statistically significant different with P<0.02.

The average of ten submaximal H reflexes from subject 5 elicited during control period, at the end of voluntary activity and after the recovery period are shown in figure 33 A. In all three traces the M waves are similar. The H reflexes are reduced after fatiguing activity and recovered within ten minutes.

The experiments were repeated with a wider range of stimulus intensities to examine M_{max} and H_{max}. Single stimuli at intensities up to 15T were applied . Recruitment curves for the M wave and H reflex were plotted against stimulus voltage in those 8 subjects. A typical recruitment curve is illustrated in figure 37. The results are summarised in table 11.

The amplitude of the M_{max} waves were relatively constant after fatiguing exercise in all of the subjects. The mean amplitude of the M_{max} waves was 101% ± 3% (mean ± SD), which was not significantly different from control. The mean amplitude of H_{max} waves in all subjects except one was decreased to 64% ± 20% after exercise. The H_{max} wave reduction was statistically significant (P<0.006, Student's t

test). The ratio of H_{max}/M_{max} also was significantly decreased after 3 minutes voluntary activity in those 7 subjects (P<0.004). The mean of H_{max}/M_{max} ratio reduction fell to 64% ± 19% of preactivity values.

The Results of MVC and Soleus M_{max}, H_{max} Waves and H_{max}/M_{max} Ratio (Blood Flow was Occluded)

Number	MVC%	Mmax%	Hmax%	Hmax/Mmax%
1	83	106	97	92
2	88	101	60	60
3	75	100	71	71
4	80	100	95	95
5	82	100	61	61
6	72	106	48	45
7	75	96	51	53
8	76	102	122	120
Mean ± SD	79 ± 5	101 ± 3	76 ± 26	75 ± 25

Table 11. This table shows the normalised data of 8 subjects maximal soleus M and H waves and H_{max}/M_{max} ratios after fatiguing activity of anterior tibial muscles.

The H_{max} and M_{max} waves recorded from subject 5 during control, at the end of activity and after the recovery period are shown in figure 33 B, C. These traces show that the maximal M waves were constant during the experiment. The figure shows H_{max} reflex to be decreased significantly following fatiguing activity and to be restored to control values after 10 minutes recovery. The results of MVC, M waves, H reflexes, H/M and H_{max}/M_{max} ratios of all subjects at the end of

voluntary activity and during recovery period were analysed in figure 34, and 35. The M waves were not significantly different, while the other characteristics were significantly reduced. MVCs, H waves, H/M and H_{max}/M_{max} ratios were restored to control values after 10 minutes recovery. This is illustrated in figure 35.

Inflation of the pressure cuff caused changes in M_{max} or H_{max} amplitudes compared on their control values. Figure 36 shows the data from 8 subjects. The mean amplitude of the M_{max} waves was 103 ± 7 (mean ± 7) after cuff inflated, which was relatively constant. The mean amplitude of the H_{max} waves was 96% ± 13% (mean ± SD), which was not significantly different from control period.

However, to avoid even these small changes the amplitude of M and H waves were renormalised to 100% after cuff inflation.

The Effects of Voluntary Fatigue of TA on Soleus M, Mmax, H and Hmax Reflexes
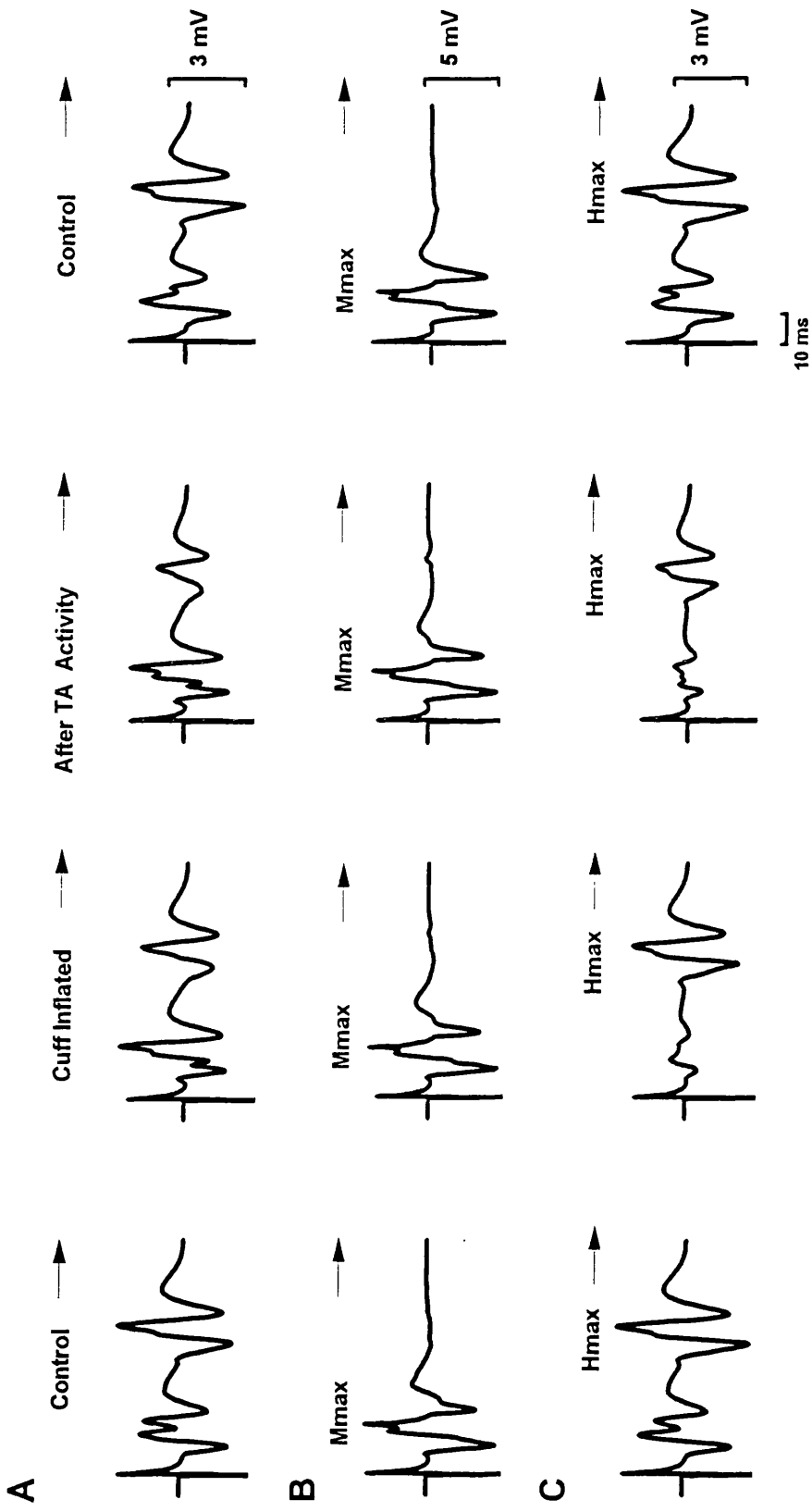
Figure 33. M_{max} waves and H_{max} reflexes in soleus in control conditions with normal blood flow, cuff inflated, after 3 minutes activity in anterior tibial (with blood flow occluded), and after 10 minutes recovery period. Sequence A- averaged submax soleus H reflexes obtained in control conditions, after inflation of BP cuff, after anterior tibial activity and in control conditions. Sequence B- in the same subject, maximal M waves in the same sequence. Sequence C- maximal H waves.

Effects of Anterior Tibial Activity on the Soleus M, H Waves and H/M, Hmax/Mmax Ratios at the End of Activity.

% Control Value
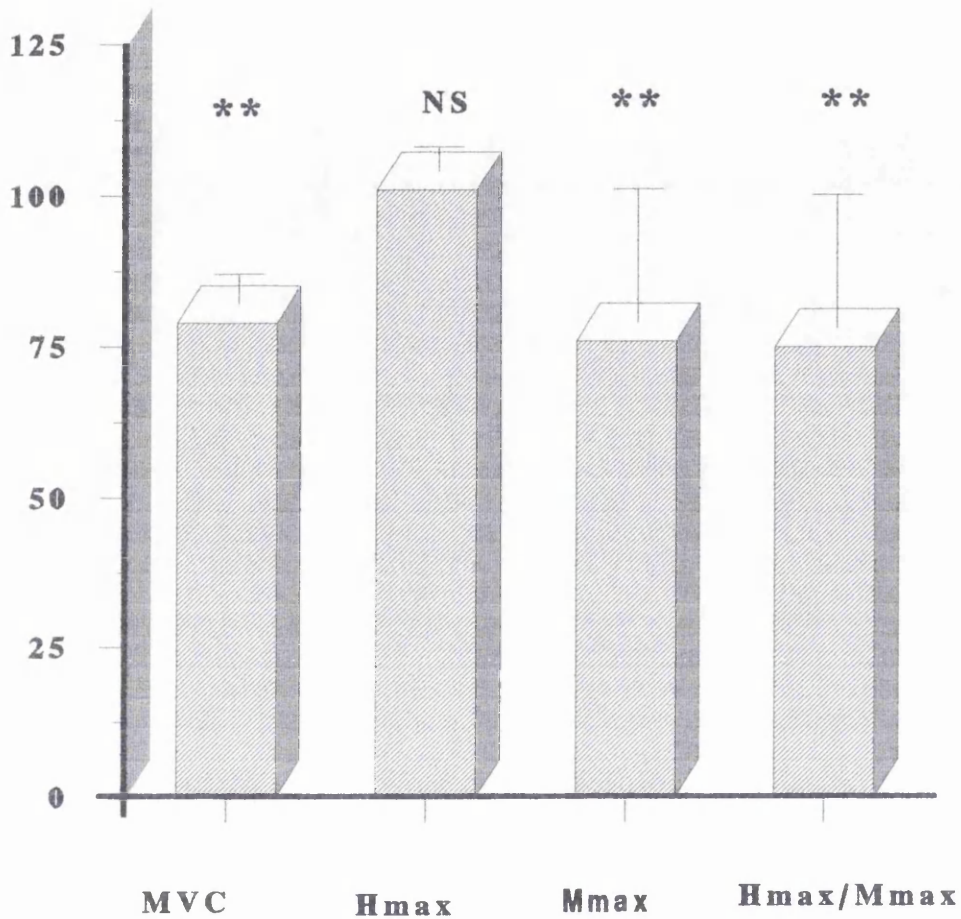
Figure 34. This figure shows MVCs, soleus M_{max} waves, soleus H_{max} reflexes and H_{max}/M_{max} ratios in the minutes following fatiguing activity in anterior tibial muscles. MVCs in anterior tibial muscles were reduced to 79% ± 5% (mean ± SD, range 72-88%) after 3 minutes exercise. Soleus M_{max} waves were stable with no changes. Soleus H_{max} reflexes and H_{max}/M_{max} ratios were reduced significantly to 64% ± 19% of control values.

Soleus Mmax, Hmax Waves and Hmax/Mmax Ratios After Recovery.
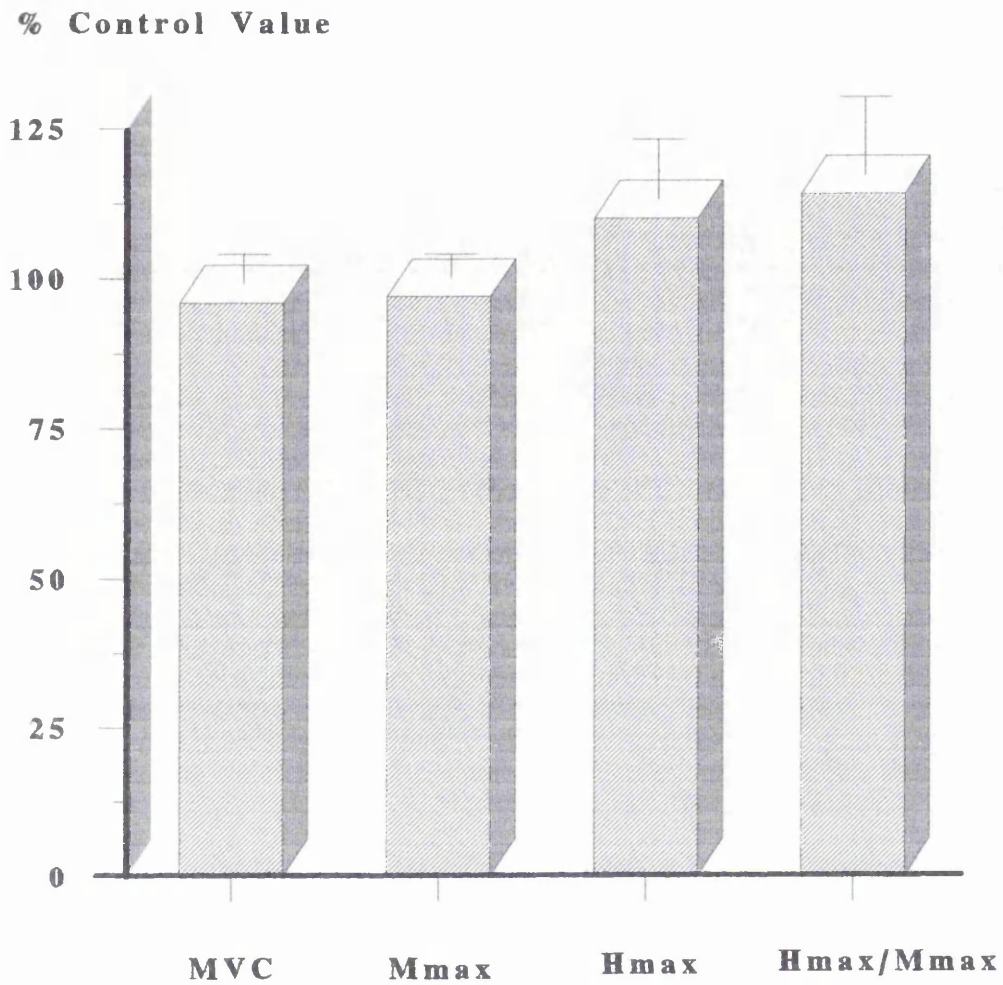
% Control Value

Figure 35. This figure shows MVCs, soleus H_{max} reflexes and H_{max}/M_{max} ratios which were restored to control values after 10 minutes recovery.

Effects of Ischaemia on Soleus Mmax, Hmax Waves and Hmax/Mmax Ratios.
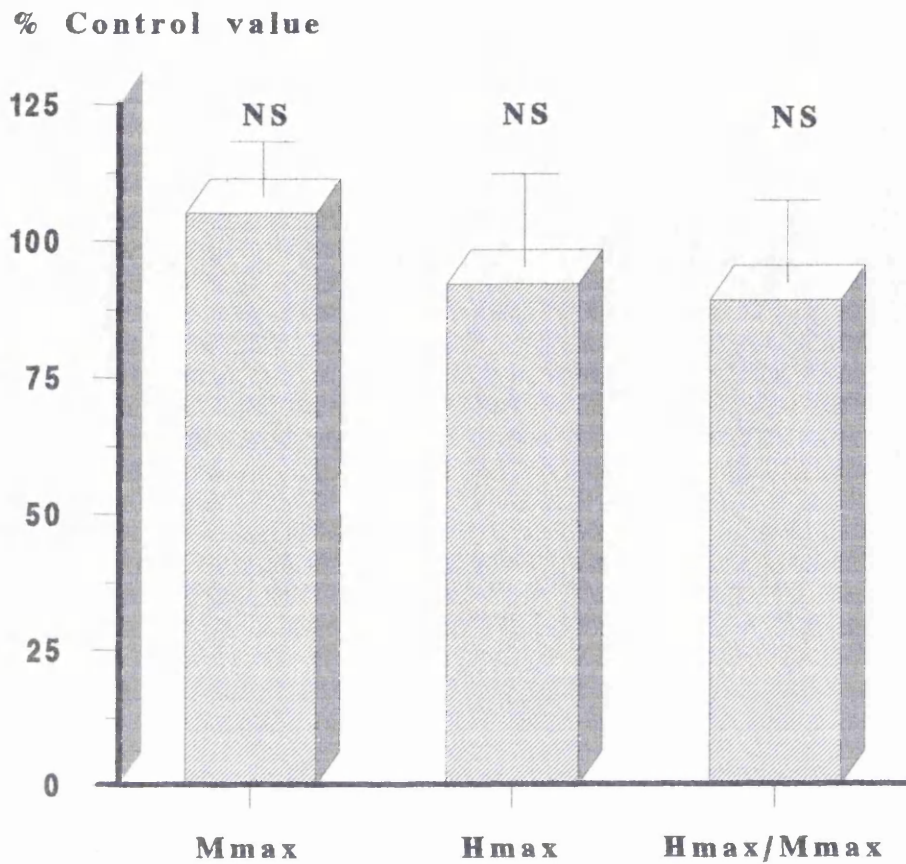
Figure 36. The results represent the mean of 8 subjects soleus M_{max} waves, H_{max} reflexes and H_{max}/M_{max} ratios after occlusion of blood flow. There was no significant difference between control and after cuff inflation.

3.8 Comparison between soleus and anterior tibial muscles M wave and H reflex recruitment curves before and after fatigue

The recruitment curves for soleus and anterior tibial H reflexes were briefly described in section 3.6, 3.7 and used to identify M_{max} and H_{max} values.

Figure 37, shows data for soleus stimulation in one subject before and after exercise of anterior tibial. The position of the M curve is almost unchanged, showing that stimulation conditions remain constant. The clear reduction in H wave amplitude cannot be attributed to any change in stimulus efficiency or at the neuromuscular junction.

Figure 38, shows data for another subject for anterior tibial stimulation before and after anterior tibial exercise. The same stimulus intensities were delivered during the experiment. The small M waves fall at low stimulus intensities, whilst maximal M waves rise at higher stimuli. This suggests that no block occurred at neuromuscular junction. However, both small H and H_{max} reduced significantly after exercise.

Recruitment Curves of Soleus Before & After Voluntary Activity of Anterior Tibial Muscles
Sol
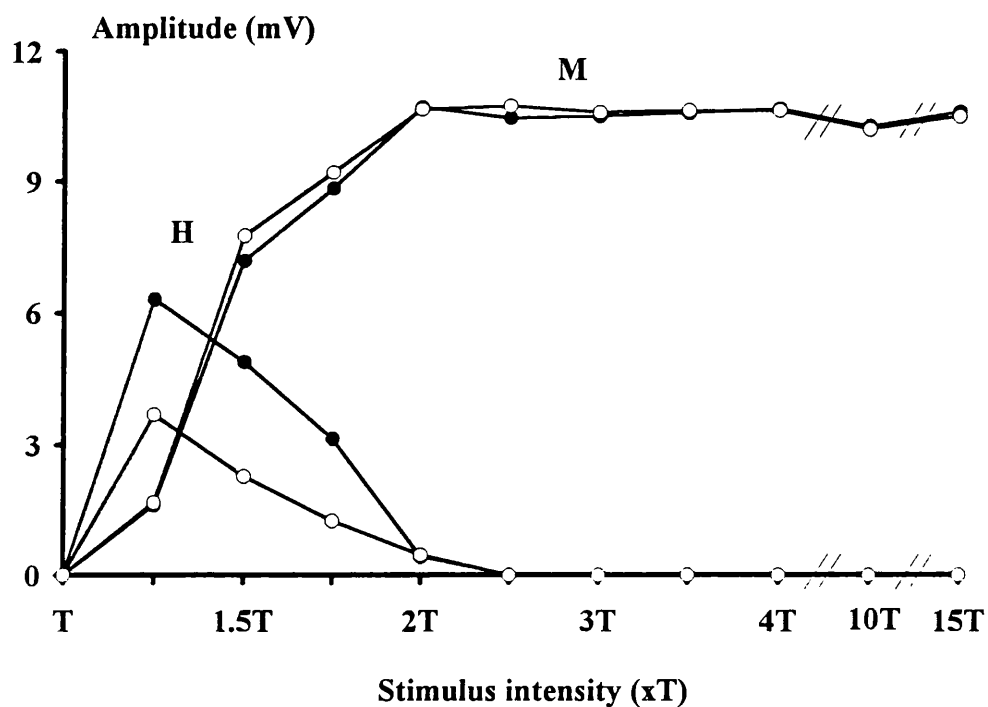
Figure 37. A specimen of soleus M wave and H reflex recruitment curves from one subject. Filled circles show data obtained before activity in anterior tibial muscle and open circles in the minute following activity.

Recruitment Curves of Anterior Tibial M, H Waves Before & After Voluntary Activity of Anterior tibial
TA
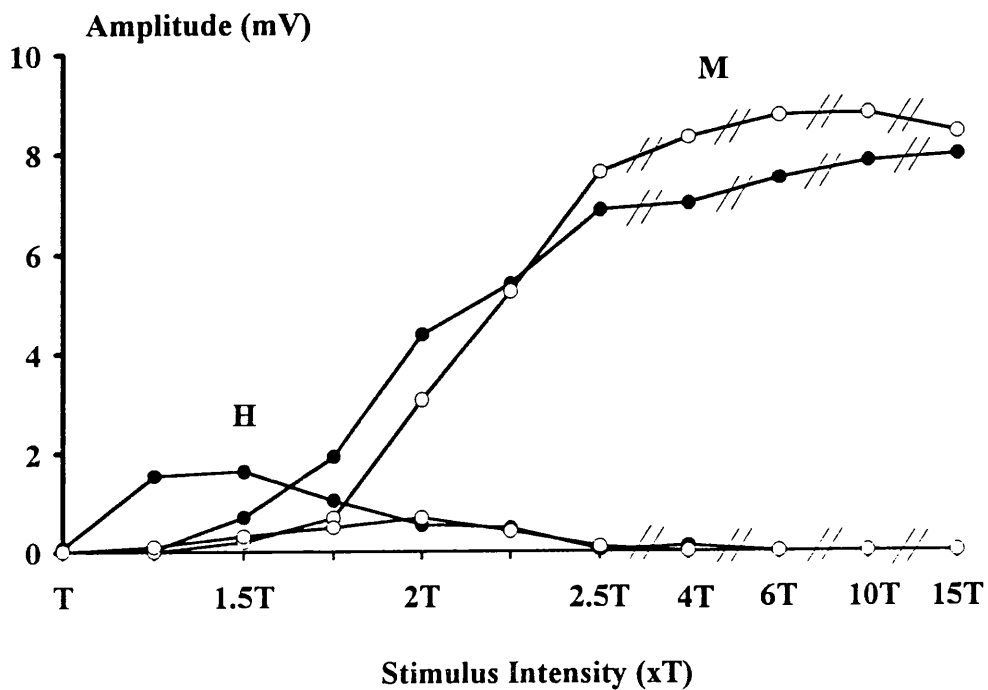
Figure 38. An example of anterior tibial M waves and H reflexes recruitment curves from one subject. filled circles show data obtained before activity in anterior tibial muscle and open circles in the minute following activity.

3.9 The effects of fatiguing voluntary activity of the quadriceps muscle on the soleus H reflex excitability

Further experiments were performed to examine the effects of fatiguing exercise of quadriceps on the excitability of soleus H reflexes. An essentially similar experimental protocol to that described earlier (3.6, 3.7) was used. The quadriceps muscle group was fatigued by intermittent voluntary contractions, 7 sec on, 3 sec off, at 30% of maximal voluntary contraction, sustained for up to 9 minutes.

The fatigue was evident by a reduction in MVC of all subjects. The mean MVC for the 6 subjects was reduced to 74% ± 6% (mean ± SD). The results of all subjects are illustrated in table 12.

The Results of MVC and Submaximal M, H Waves and H/M Ratio in Soleus in All Subjects

Number	MVC%	M%	H%	H/M%
1	81	93	66	71
2	70	99	43	45
3	77	96	71	73
4	79	121	50	43
5	70	94	72	77
6	65	86	80	88
Mean ± SD	74 ± 6	98 ± 12	64 ± 14	66 ± 18

Table 12. This table shows quadriceps MVC and submaximal M waves, submaximal H reflexes, H/M ratios in soleus muscle in each subject.

In experiments where submaximal stimulation was delivered to set up H reflexes of about half maximal amplitude, the M waves were relatively constant in 5 subjects and rose by 21% for one subject. The mean amplitude of the M waves in all subjects was 98% ± 12% (mean ± SD), which was not significantly different from control period. The amplitude of H reflexes fell in all subjects. The mean amplitude of the H reflexes for all subjects was 64% ± 14% (mean ± SD) which was statistically significant (P<0.002, Student's t test). Therefore, the H/M ratios were decreased significantly to 66% ± 18% (P<0.006).

The average of ten submaximal H reflexes from subject 3 elicited during control period, at the end of voluntary activity and after the recovery period are shown in figure 39. In all three traces the M waves are similar. The H reflexes were reduced significantly after fatiguing activity and recovered after ten minutes.

In the next part of experiment single stimuli at intensities up to 15T were applied. Recruitment curves for the M wave and H reflex were plotted against stimulus voltage in those 6 subjects. The mean amplitude of the M_{max} waves in all subjects was 101% ± 4% (mean ± SD), which was stable. The mean amplitude of the H_{max} reflexes was 104% ± 8% after exercise, and the mean ratio of H_{max}/M_{max} was 103% ± 9%. Neither was significantly different from control value. The results are shown in table 13.

The Results of Anterior Tibial MVC, M_{max}, H_{max} Waves and H_{max}/M_{max} Ratio in All Subjects

Number	Mmax%	Hmax%	Hmax/Mmax%
1	100	90	90
2	93	109	118
3	100	100	99
4	102	112	106
5	106	111	105
6	102	103	101
Mean ± SD	101 ± 4	104 ± 8	103 ± 9

Table 13. This table shows the normalised data of 6 subjects maximal soleus M and H waves and H_{max}/M_{max} ratios (Mean ± SD) after fatiguing activity of quadriceps muscle group.

The results of MVC, M waves, H reflexes, H/M ratios of 6 subjects at the end of voluntary activity and during recovery period were analysed in figures 40, and 41. The M waves were not significantly different, while the other characteristics were significantly reduced. MVCs, H waves and H/M ratios were restored to control values after 10 minutes recovery (figure 41).

The latencies of M wave and H reflex in the soleus muscle were measured following intermittent voluntary contractions. These data are shown in table 14.

Soleus M Waves and H Reflexes Latency

No	Latency (msec)				
	Control	Fatiguing exercise			Recovery
		3 min	6 min	9 min	
1	32.6	33.5	34.2	34.5	33.6
2	28.2	28.5	28.7	29	28.6
3	32.8	33.1	34	34.1	33.4
4	34.3	34.9	35.1	35.2	34.8
5	30.1	30.2	30.5	30.7	30.3
6	31.6	32.1	32.3	32.6	31.7
Mean	31.6	32.1	32.5	32.7	32.1
SD	2.2	2.3	2.5	2.7	2.3

Table 14. This table represents the mean of soleus H reflexes latency recorded from 6 subjects in control, after 3, 6, 9 minutes voluntary fatiguing activity and after 10 minutes recovery.

The mean soleus H reflexes latency after 9 minutes voluntary contractions in quadriceps muscles were 32.7 ± 2.7 (mean $\pm$ SD), which was significantly increased after 9 minutes exercise ($P<0.002$).

**Effect of Voluntary Activity of Quadriceps on Submaximal
H Reflexes in Soleus Muscle**
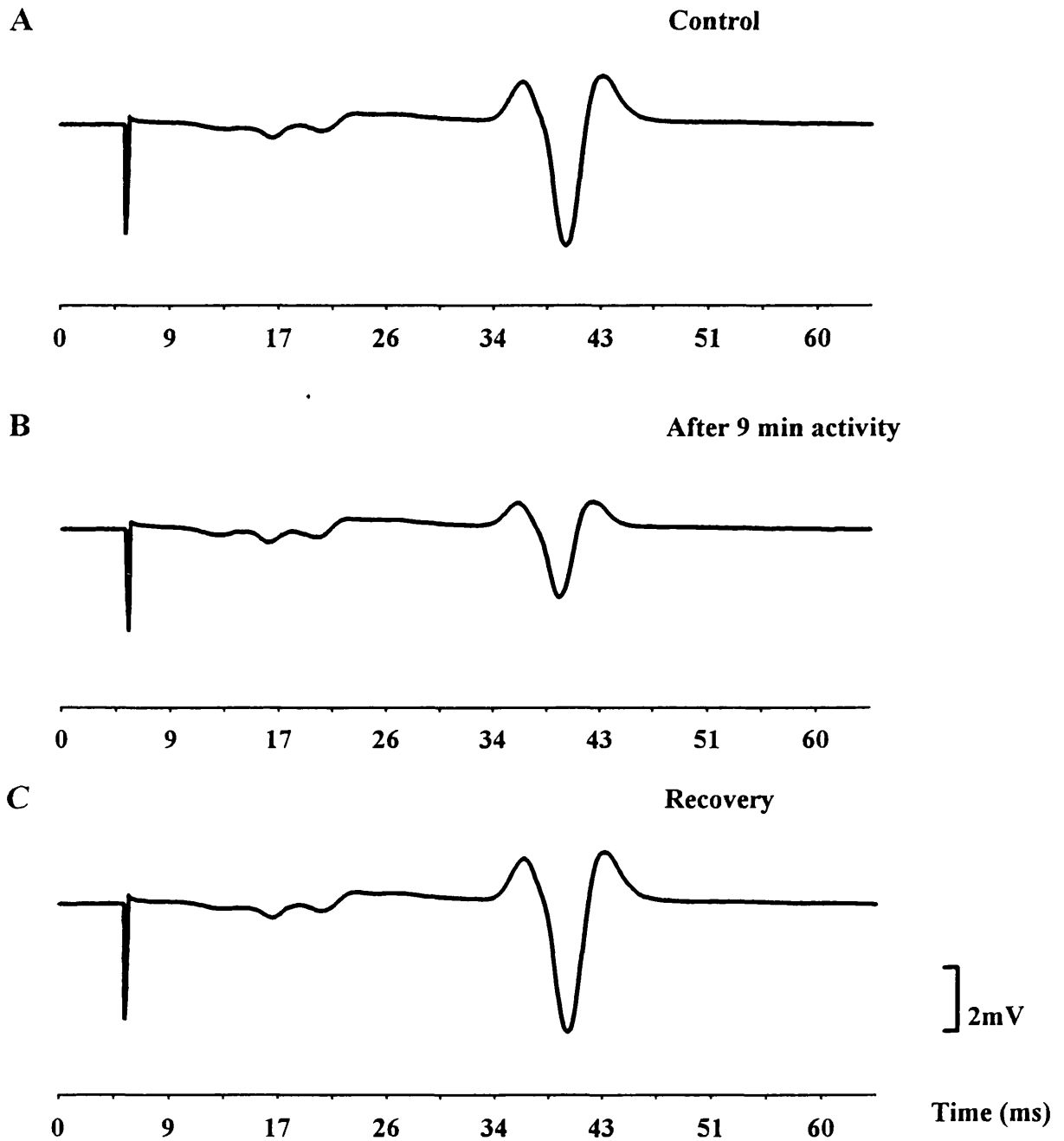
Figure 39. Effect of voluntary contraction of quadriceps muscle on soleus H reflex. These traces shows the average of half maximal soleus H reflexes in control, after 9 minutes activity and during recovery in one subject. The M waves were constant in whole part of experiments, whilst H reflexes showed about 50% reduction.

Effects of Quadriceps Activity on Submaximal
M, H Waves and H/M Ratios in Soleus Muscle.

% Control Value
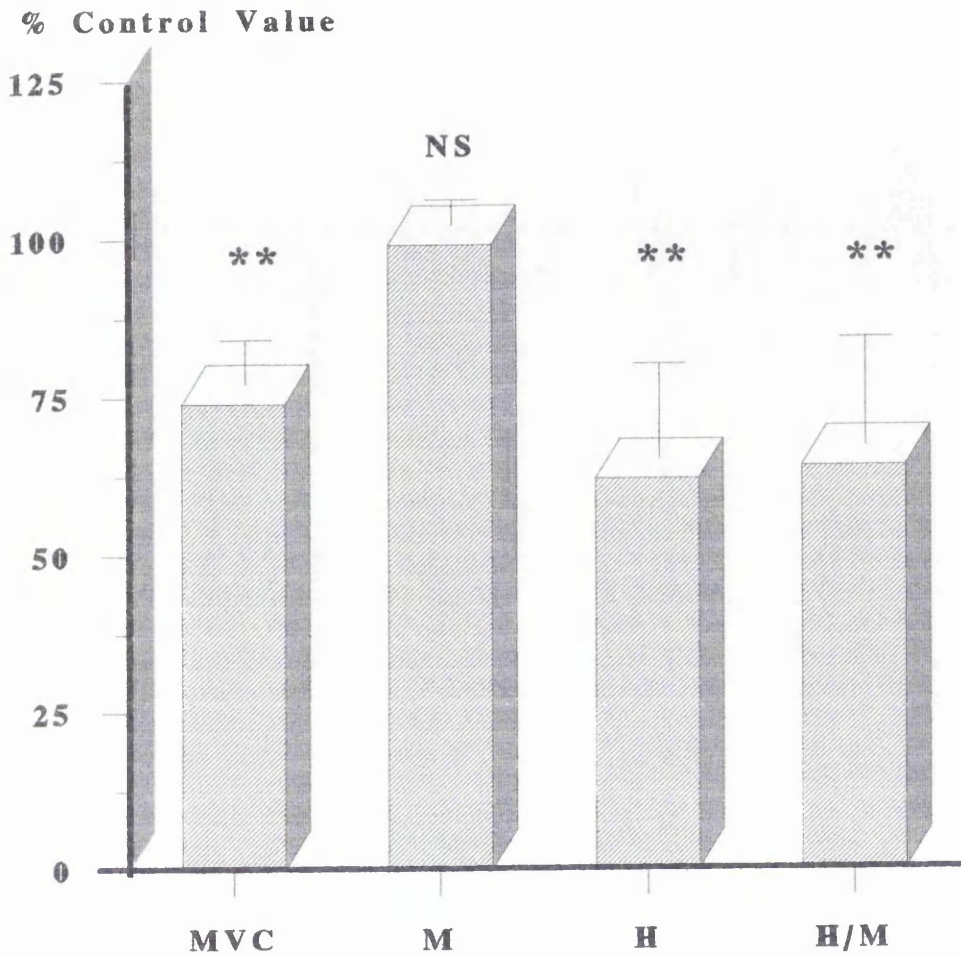
Figure 40. The results represent the mean of 6 subjects MVCs, submaximal M waves, submaximal H reflexes and H/M ratios in soleus muscle in the minutes following fatiguing activity in quadriceps muscles. MVCs in quadriceps were reduced to 74% ± 6% (mean ± SD, range 70-81%) after 9 minutes exercise. Soleus M waves were stable with no changes. The mean soleus H reflexes and H/M ratios were reduced to 64% ± 14% (P<0.002) and 66% ± 18% (P<0.006) of control values.

Submaximal M, H Waves and H/M Ratios in Soleus Muscle After Recovery
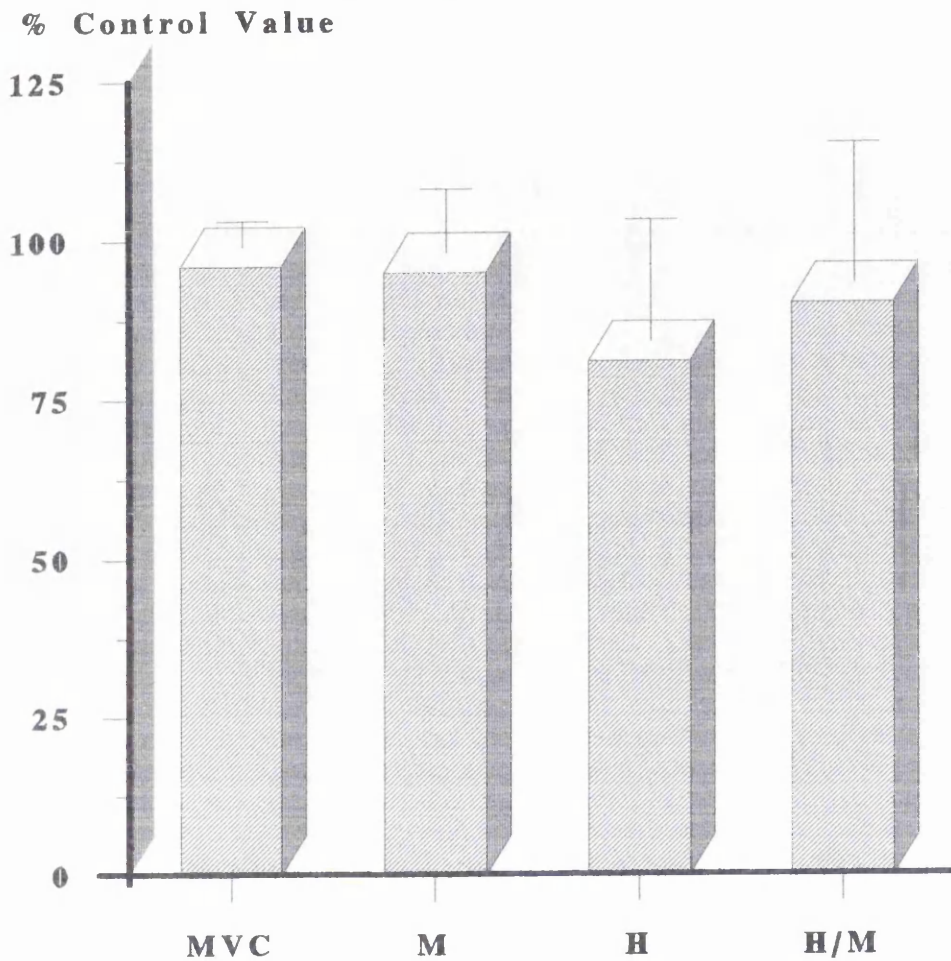
% Control Value

Figure 41. The data shows MVCs and submaximal M, H reflexes and H/M ratios in soleus muscle after 10 minutes recovery. All values were restored to control values .

3.10 Time course of force and H reflex changes during intermittent isometric voluntary contraction

The MVC and H reflexes changes during fatigue induced by intermittent submaximal voluntary contractions of quadriceps muscles were tested in the soleus H reflexes in 6 subjects by testing their values after 3, 6 and 9 minutes voluntary contraction.

The maximal force dropped progressively during 9 minutes voluntary contractions. The results are shown in figure 42. After 3 minutes the mean force had fallen significantly from its initial value to 89% ± 8% (mean ± SD, range 73%-96%, P<0.02). By 6 minutes there was a further fall in force to 81% ± 9% (range 68%-92%, P<0.004) and ultimately after 9 minutes the force was reduced to 74% ± 6% (range 65%-81%, P<0.0001).

After fatigue tests of identical duration, the M waves showed no significant change in peak amplitude, which were constant. However, after 3 minutes the mean H reflexes had fallen significantly from its control value to 80% ± 6% (mean ± SD, range 69%-85%, P<0.001). By 6 minutes there was a further fall in H reflexes to 60% ± 23% (range 26%-82%, P<0.008), and ultimately after 9 minutes the force was reduced to 52% ± 19% (mean ± SD, range 23%-77%, P<0.002).

The results are illustrated in figure 43.

Time Course of Force Changes During Quadriceps Activity
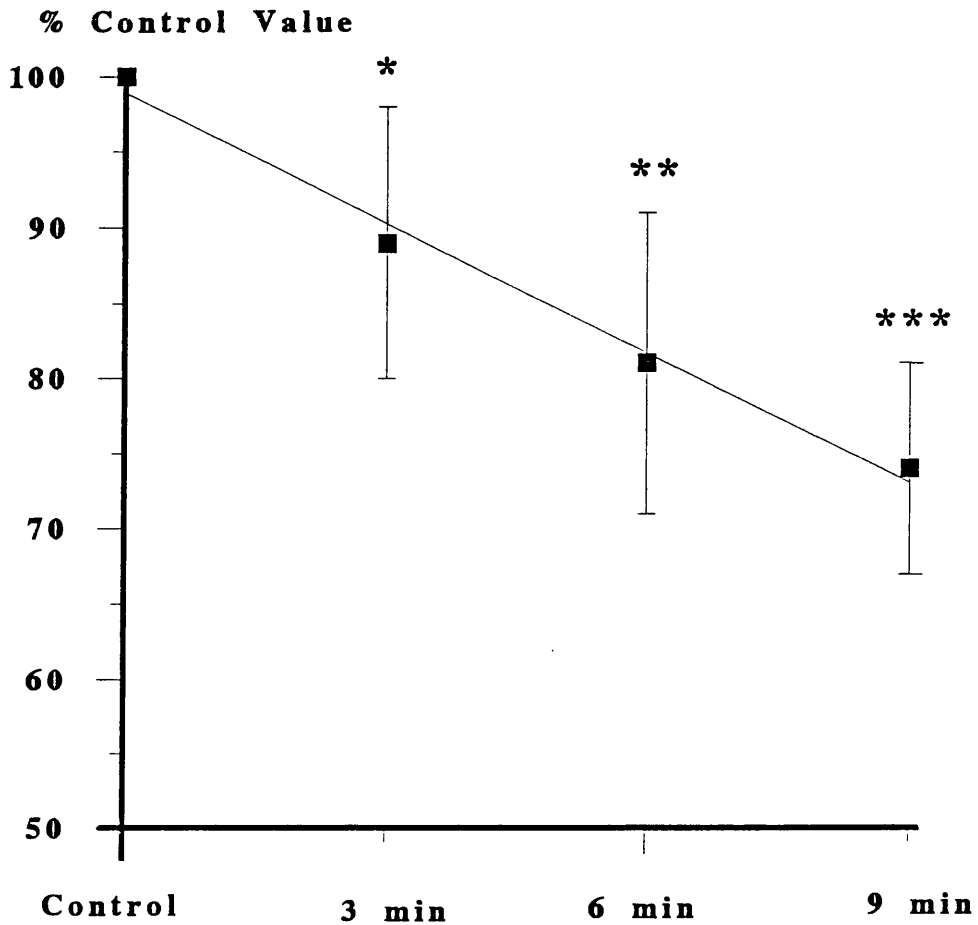
Figure 42. This figure shows the mean of MVC in 6 subjects after 3, 6 and 9 minutes voluntary activity of quadriceps muscle. The maximal force dropped progressively during fatigue to mean values which were significantly different from control values. The curve fit line was
$y = 107.5 - 8.6x$, $r^2 = 0.99$.

Time Course of Submaximal H Reflex Changes in Soleus Muscle During Quadriceps Activity
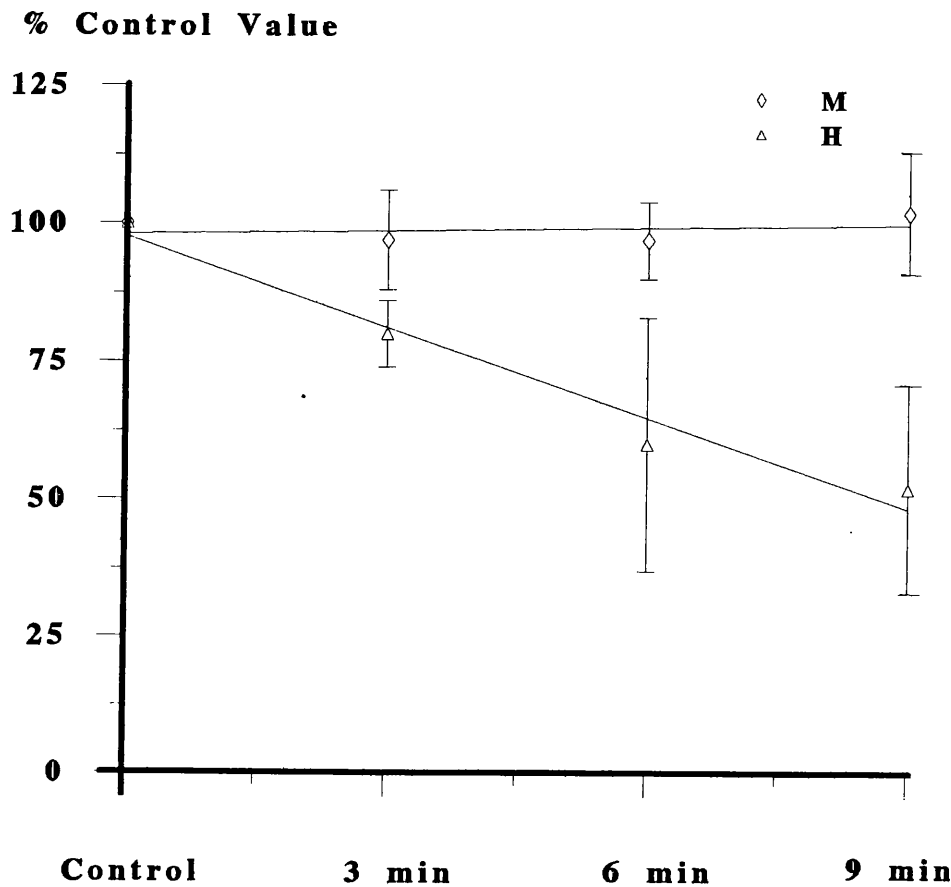
Figure 43. This data shows the mean of submaximal M wave and H reflex amplitudes in soleus muscle in 6 subjects after 3, 6 and 9 minutes voluntary activity of quadriceps muscle. After fatigue tests, the H reflex amplitudes decreased progressively, whilst the M waves were stable. The curve fit line for M wave was $y = 97.5+0.6x$, $r^2 = 0.1$, and for H reflex was $y = 114-16.4x$, $r^2 = 0.97$.

3.11 The effects of fatiguing electrical activity of the anterior tibial muscle on its own H reflex excitability

The aim of these experiments was to compare the effects of voluntary fatiguing contractions with a similar activity pattern produced by direct stimulation of the muscle belly. The intention here is to eliminate any possible psychological effects associated with voluntary effort as well as reflex inputs from other muscles (Garland and McComas, 1990) and to try and distinguish between central and peripheral fatigue mechanisms. Electrically induced exercise should produce less central fatigue than voluntary exercise. Anterior tibial H reflex testing procedures have already been described in section 3.6.

Following intermittent electrical stimulation of the right anterior tibial muscles at 20 Hz, repeated every 10 seconds (7 sec on, 3 sec off) and sustained for up to 9 minutes, the fatigue was evident in a reduction in MVC of all subjects. The mean MVC for the 8 subjects was reduced significantly to 83% ± 9% (mean ± SD, P<0.001) and there was no significant difference between this value versus the former value of MVC in voluntary fatigue (see table 6, section 3.6). The tetanic force produced during stimulation reduced by up to 66% ± 9% which was significantly different from control value (P<0.0008). The mean half relaxation times are significantly increased to 163% ± 25% with P<0.0002. The mean of 8 subjects half relaxation time in control was 201 ± 58 msec which was increased to 325 ± 96 msec after fatiguing electrical activity. The results of forces, MVC and half relaxation times in 8 subjects are shown in table 15.

The Results of Anterior Tibial MVC, Submaximal M, H Waves and H/M Ratio in All Subjects

Number	MVC%	Tetanic Force%	1/2 R.T%	Amplitude M%	Amplitude H%	H/M%
1	67	43	182	98	70	71
2	93	72	157	76	69	91
3	89	75	160	97	74	76
4	75	68	188	54	32	59
5	81	69	197	97	9	9
6	81	51	154	102	30	29
7 *	89	63	132	72	92	128
8 *	91	85	131	92	105	114
Mean ± SD	81 ± 9	63 ± 13	173 ± 18	87 ± 19	47 ± 27	56 ± 31

Table 15. This table shows anterior tibial MVC, force, 1/2 relaxation time, M waves, H reflexes and H/M ratios in each subject. Number 7 and 8 were excluded. The M and H waves are submaximal.

However, in subjects 7 and 8 the H/M ratio increased even though the MVC were slightly decreased, the tetanic force fell and the half relaxation times were slightly increased. There was no significant difference between these results obtained with electrical induced fatigue versus the former values of M, H waves and H/M ratios which were achieved in voluntary fatigue (refer to these results, table 6 page 93).

In experiments where submaximal stimulation was delivered to set up H reflexes of about half maximal amplitude, the amplitude of the M waves was constant in 5 subjects and fell after fatiguing exercise in 3 other subjects. The mean amplitude of the M waves in 8 subjects was 86%±

17% (mean ± SD), which was not significantly different from control value. However, the amplitude of H reflexes fell in 6 subjects but was not changed in 2 subjects. For the 6 subjects with reduced H reflexes, the mean amplitude fell to 47% ± 27% after exercise. The H wave reduction was statistically significant (P<0.005, Student's t test). The mean amplitude of the H reflexes for all 8 subjects was 60% ± 33%. Therefore, the H/M ratios were decreased significantly to 56% ± 31% (P<0.02).

The average of ten submaximal H reflexes from subject 5 elicited during control period, at the end of voluntary activity and after the recovery period are shown in figure 44 and 45. In all traces the M waves are similar. The H reflexes are complex , probably because they represent activity from adjacent muscles. All components of the H complex behave the same way, and they were reduced after fatiguing activity. All these components recovered within ten minutes.

The results of M waves, H reflexes, H/M ratios of 6 subjects in control, at the end of electrical activity and during recovery period are shown in figure 46. The M waves were not significantly different, while the other characteristics were significantly reduced. The H reflexes, H/M ratios were restored to control values after 10 minutes recovery.

Submaximal M Waves and H Reflexes in TA
Amplitude Against Time

A   **Pre test**

B   **After 3 min fatigue**

C   **Recovery**

M

H

1 mV

5 ms
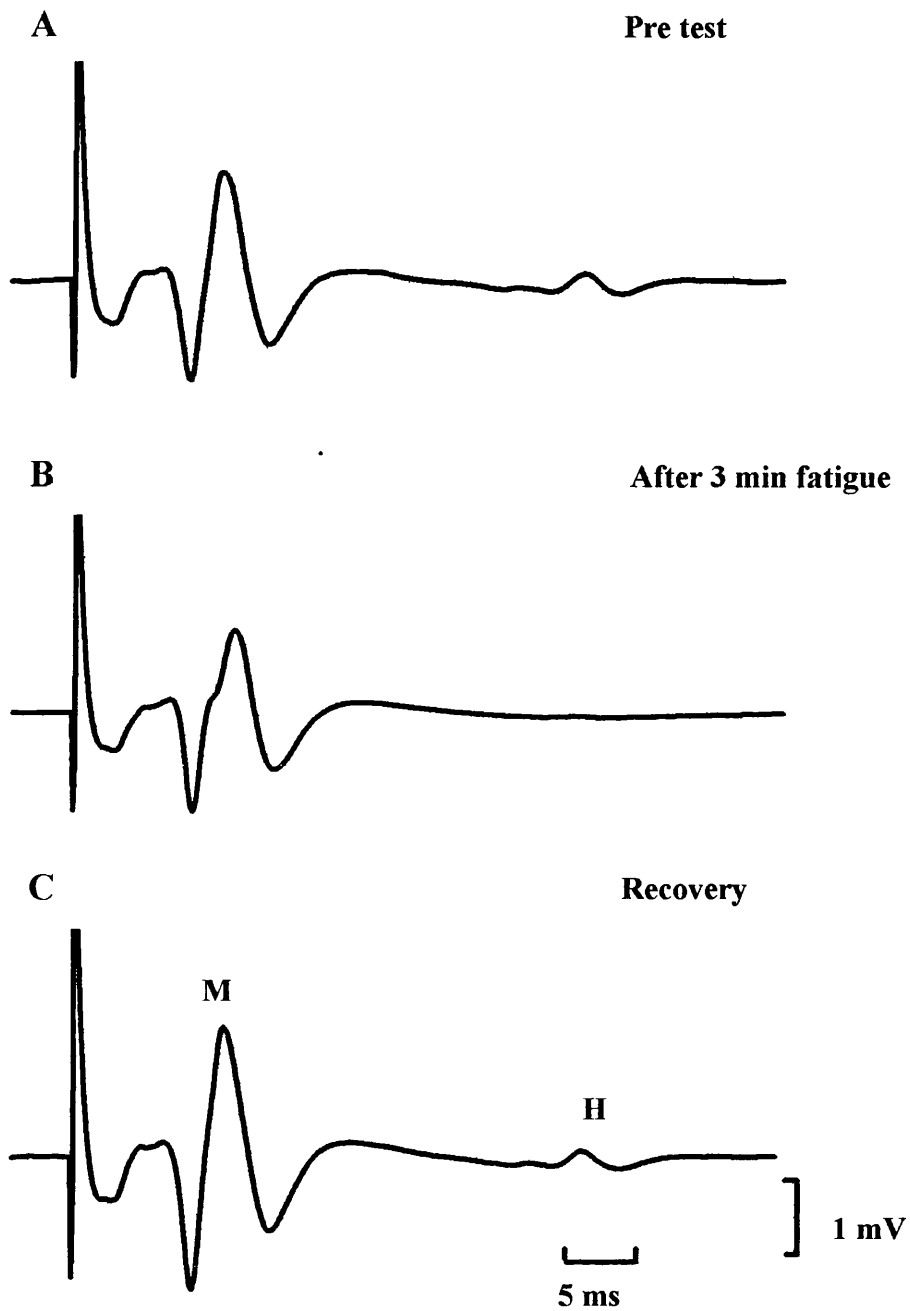
Figure 44. Comparison between anterior tibial M waves and H reflexes after electrical activity shows that the M wave is constant but the H reflex nearly disappeared. The M and H waves are submaximal.

Submaximal M Waves and H Reflexes in TA
Amplitude Against Time

A   Pre test

B   After 3 min fatigue

C   Recovery

0.3 mV

5 ms
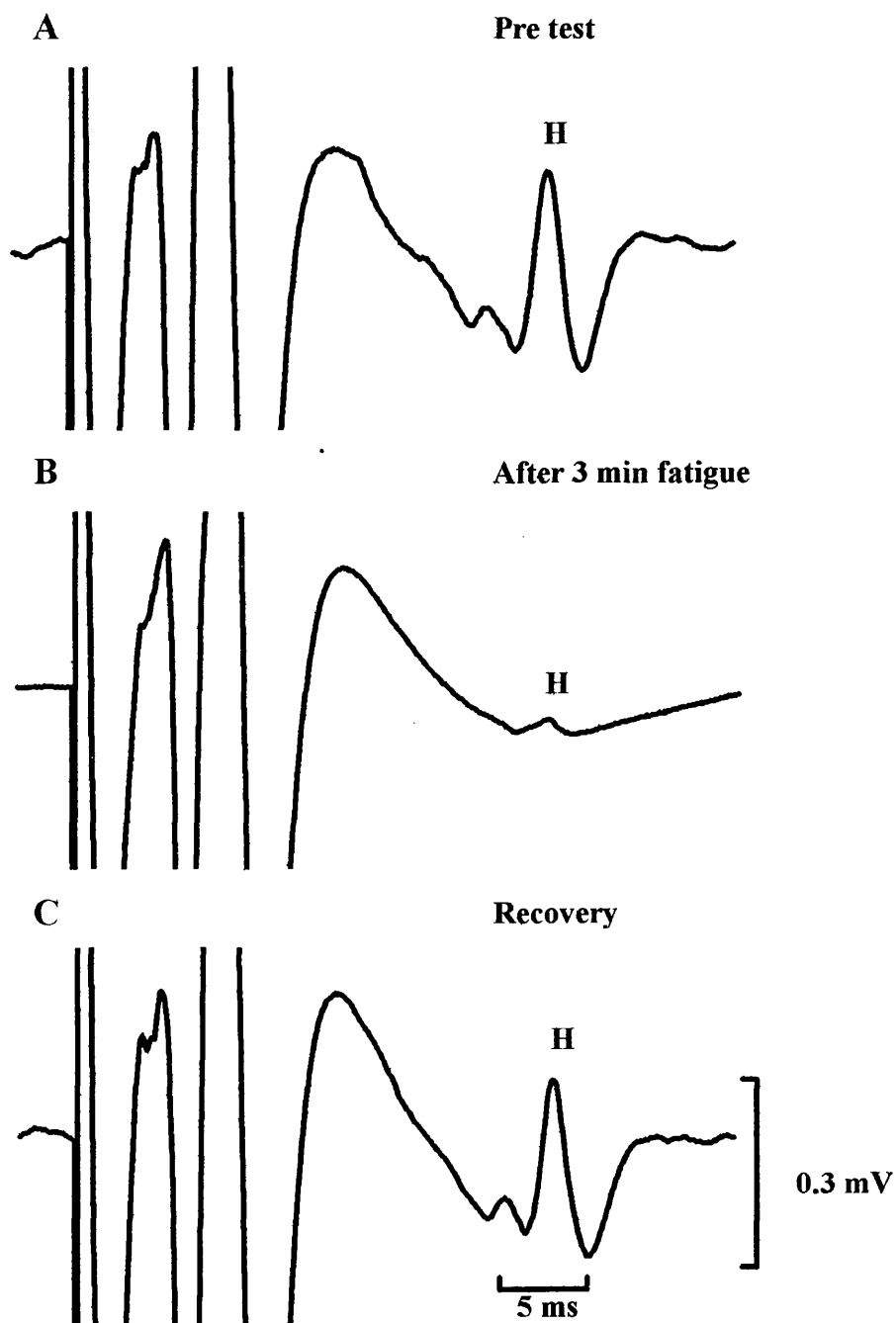
Figure 45. As figure 44 but at higher gain to show small residual submaximal H reflexes.

Effects of TA Activity on Submaximal M, H Waves and H/M Ratios in TA
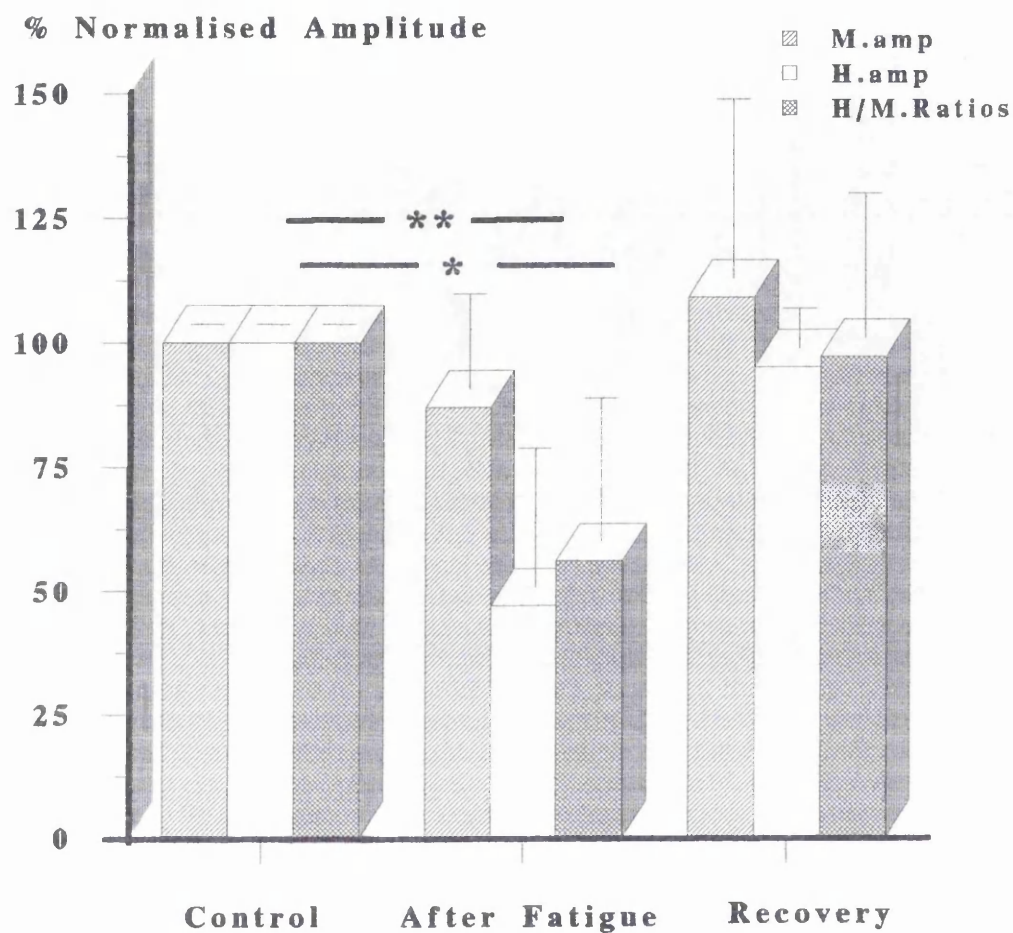
Figure 46. The results of 6 subjects submaximal M waves, submaximal H reflexes and H/M ratios in anterior tibial muscles before, immediately at the end of fatiguing activity and after 10 minutes recovery.

3.12 The effects of fatiguing electrical activity of the anterior tibial muscle on soleus H reflex excitability

A series of experiments on 7 subjects was performed to investigate the effects of fatiguing exercise of anterior tibial muscles on the H reflex excitability of soleus. In these experiments any problem associated with changing M wave amplitudes seen in section 3.11 can be avoided. The other aim of these experiments is compare the effects of voluntary fatiguing contractions with a similar activity pattern produced by direct stimulation of the muscle belly. The fatiguing exercise protocol described earlier in section 3.11. Data for the 7 subjects is shown in table 16.

The Results of Anterior Tibial MVC, Submaximal M, H Waves and H/M Ratio in Soleus Muscle in All Subjects

Number	MVC%	Tetanic Force%	1/2 R.T%	Amplitude M%	Amplitude H%	H/M%
1	67	43	182	106	98	92
2	93	72	157	83	79	95
3	89	75	160	93	90	97
4	75	68	188	83	85	102
5	81	69	197	124	79	63
6	81	51	154	99	78	79
7	85	64	175	110	84	76
Mean ± SD	82 ± 9	63 ± 12	173 ± 17	100 ± 16	85 ± 5	86 ± 15

Table 16. This table shows anterior tibial MVC, force, 1/2 relaxation time, soleus submaximal M and H waves and H/M ratios in each subject.

Following intermittent electrical stimulation of the anterior tibial muscles at 20 Hz, repeated every 10 seconds (7 sec on, 3 sec off) and sustained for up to 9 minutes, the fatigue was evident as a reduction in MVC of all subjects. The mean MVC for the 7 subjects was reduced significantly to 82% ± 9% (mean ± SD, P<0.001). This is a significantly greater force reduction than was seen with voluntary exercise of similar duration (see table 9, section 3.7) where mean MVC was reduced to 93%. The tetanic force produced during stimulation was reduced to a mean of 63% ± 12%. This was significantly different from control value (P<0.0002). The mean half relaxation time are significantly increased to 173% ± 17% with P<0.00002. The mean of 7 subjects half relaxation time in control conditions was 209 ± 59 msec which was increased to 344 ± 91 msec after fatiguing electrical activity.

In experiments where submaximal stimulation was delivered to set up H reflexes of about half maximal amplitude, the amplitude of the M waves were relatively constant in all subjects. The mean amplitude of the M waves in 7 subjects was 100% ± 16% (mean ± SD) which was not significantly different from control value. The mean amplitude of H reflexes fell in 6 subjects but was not changed in 1 subject. The mean amplitude of H reflexes in all subjects fell significantly to 85% ± 5% after exercise (P<0.005, Student's t test). Therefore, the H/M ratios were decreased significantly to 86% ± 15% (P<0.04).

The average of ten submaximal H reflexes from subject 6 elicited during control period, at the end of voluntary activity and after the recovery period are shown in figure 47. In all three traces the M waves are

similar. The H reflexes were reduced significantly after fatiguing activity and recovered after ten minutes.

There was a significant difference between the reductions of H reflexes after electrical exercise where compared to reductions in H reflexes after voluntary fatigue $P<0.003$ (see table 9, section 3.7). However, there was no significant difference between M waves in those experiments.

The results of M waves, H reflexes, H/M ratios of 7 subjects in control, at the end of electrical activity and during recovery period are shown in figure 48. The M waves were not significantly different, while the other characteristics were significantly reduced. The H reflexes, H/M ratios were restored to control values after 10 minutes recovery.

The Effects of Electrically Fatigue of Anterior Tibial Muscles on Submaximal M and H Reflex Amplitudes in Soleus Muscle

A   Pre exercise

B   After fatigue
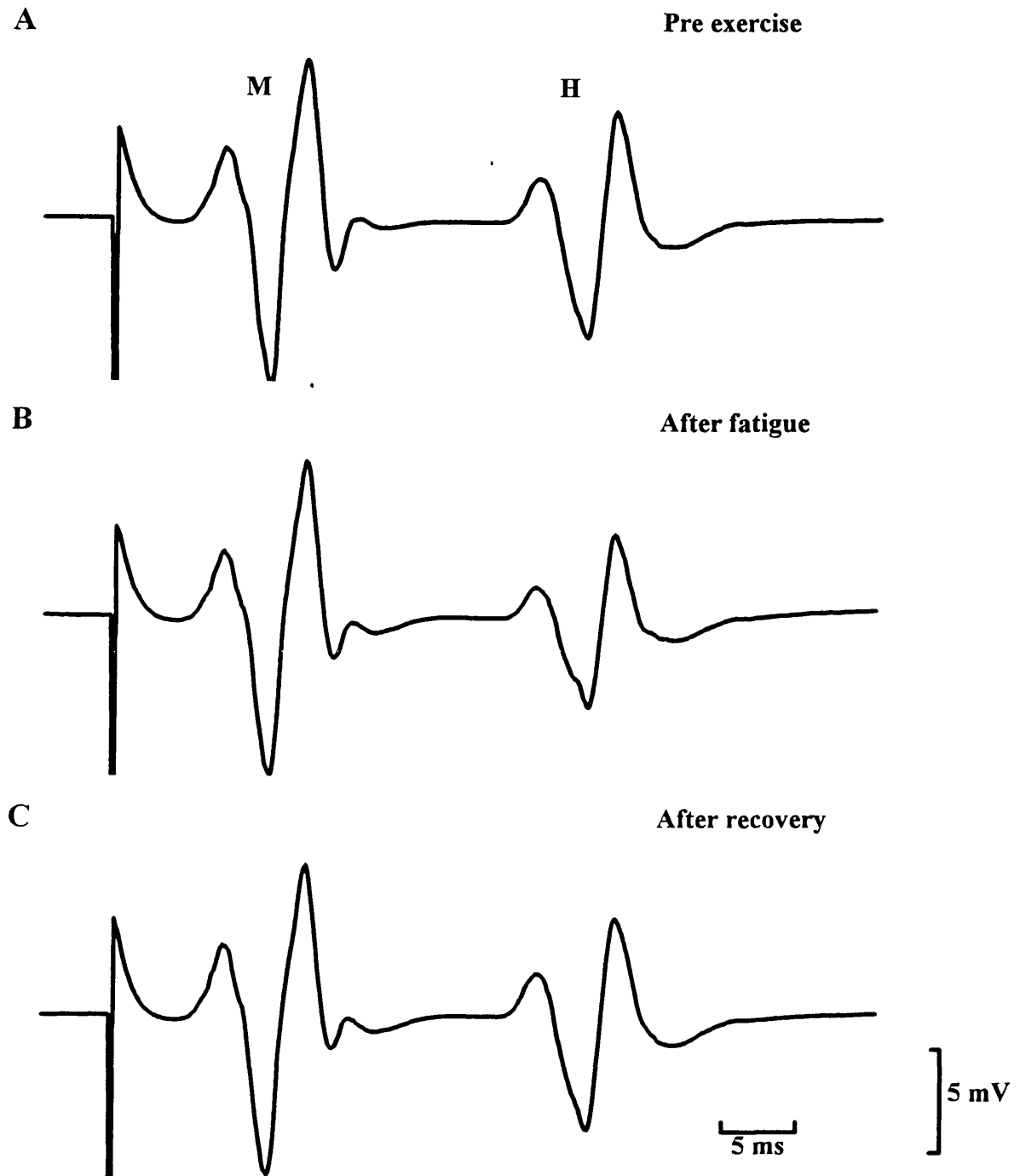
C   After recovery

Figure 47. Average of 15 trials of submaximal soleus H reflexes obtained in control conditions, end of TA activity and after recovery. In this case the submaximal M waves show no change, while the amplitude of H reflexes were reduced by more than 20%.
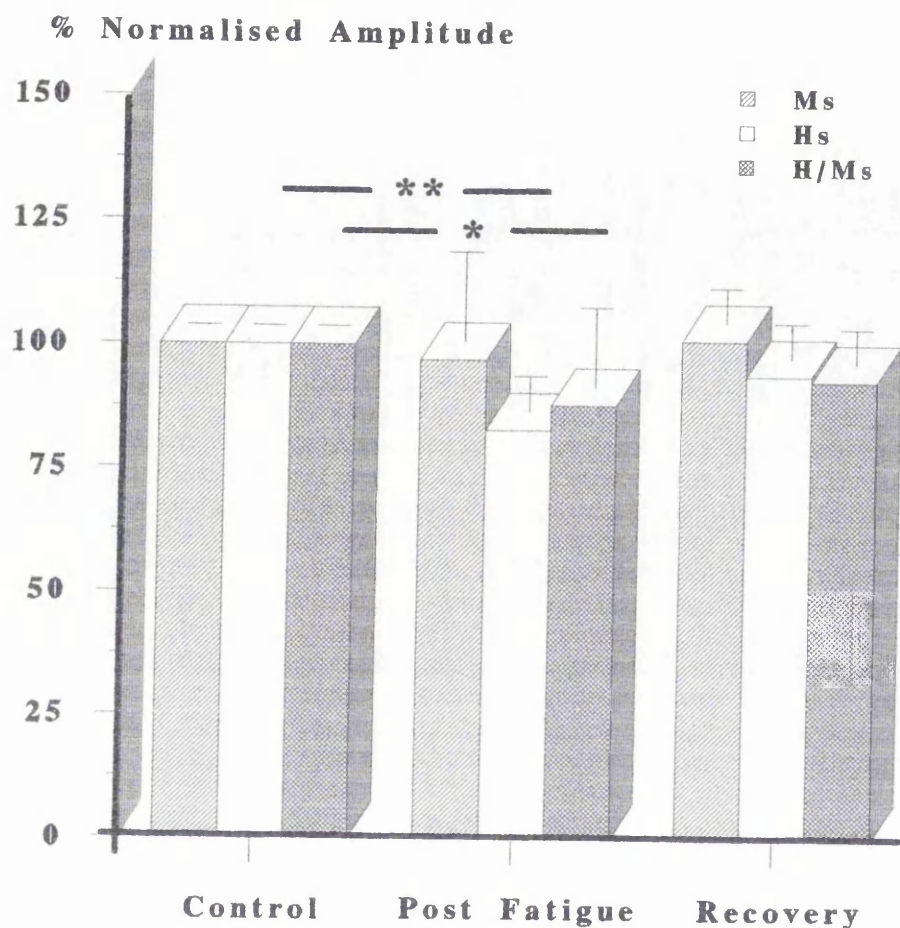
Figure 48. The results represent the mean of submaximal M waves, submaximal H reflexes, H/M ratios in soleus muscle in 7 subjects following fatiguing activity in anterior tibial muscles. The mean M waves was $100\% \pm 16\%$, but the amplitude of soleus H reflexes were declined to $85\% \pm 5\%$ (mean $\pm$ SD, P<0.005). The mean of H/M ratios were reduced to $86\% \pm 15\%$.

4. Discussion

4.1 Summary of the results

The main aim of this research was to determine the effects of fatiguing activity on the excitability of anterior tibial and soleus H reflexes.

In addition, the differences between voluntary fatiguing activity and involuntary exercise by direct muscle stimulation were investigated. H reflexes were reduced after a few minutes fatiguing activity of the muscle itself or of its antagonist. This result does not depend on the nature of exercise but the extent of the depression of H reflexes increases as the fatigue increases. All the changes in H reflexes and forces were restored to control values after a 10 minute recovery period.

H reflexes in anterior tibial muscles were depressed by fatiguing activity of anterior tibial muscles. Soleus H reflexes depressed by fatiguing activity of anterior tibial and quadriceps muscles. The sizes of changes in H reflex amplitudes are summarised in table 17.

The fatigue developed during experiments was relatively severe, particularly when the blood flow was occluded. In experiments using direct muscle stimulation, the mean force was reduced by approximately 40% and the half relaxation time increased by more than 70%.

A.

	Soleus Reflex After Activity % (Mean ± SD)			
	H	Significant	Hmax	Significant
Anterior Tibial	90 ± 30	no	64 ± 20	yes (P<0.006)
Quadriceps Group	64 ± 14	yes (P<0.002)	104 ± 8	no

B.

	Soleus & Anterior Tibial H Reflex After Activity % (Mean ± SD)			
	Sol	Significance	TA	Significance
Anterior Tibial	85 ± 5	P<0.005	47 ± 27	P<0.005

Table 17. These table summarise the changes in soleus H and H_{max} reflexes following voluntary activity in anterior tibial and quadriceps group muscles. Experiments using voluntary exercise are shown in part A. Experiments using electrical exercise are shown in part B.

4.2 Experimental techniques

H reflex testing

The posture of the subject and the techniques for stimulation and recording techniques are all closely modelled on the technique described by Hugon (1973). These are standard techniques which worked well and yielded stable H reflexes.

The only significant problem with experiment was that of obtaining secure H reflexes in anterior tibial muscles. This was solved by asking subjects to make low force voluntary contractions to enhance H reflex excitability. This is also a well established modification of the Hugon method and has been well described by other authors (Upon et al., 1971; Pierrot-Deseilligny and Bussel, 1973; Tanaka, 1980, Burke et al., 1989). The reflex response in anterior tibial muscles can be securely identified as a true H reflex on the following grounds:

1. The latency of the response was very short, with a mean latency of 30.2 msec. This is directly comparable with 30.9 msec in soleus where there can be no doubt about the nature of the reflex. A typical distance from stimulus site to the spinal cord (L_5-S_1 segment) was about 75 cm, Andrews et al. (1986) measured motor conduction velocity in tibial and common peroneal nerves which were about 50 and 49 metres/sec. Therefore, the conduction time of efferent and afferent fibres can be simply calculated by dividing by distance to half H latency minus two. This is assumes an estimated delay of 1 msec for the central synapse,

and 1 msec for the neuromuscular junction. The conduction velocity is estimated to be approximately 53 m/sec.

Macefield, Gandevia and Burke in 1989 also reported that the mean conduction velocities of the fastest fibres in the tibial nerve was 52.8 ± 3.2 m/sec.

2. Secondly, the reflex response observed was associated with single excitations of the lowest threshold afferents in the peroneal or tibial nerves. The threshold for these fibres was close to that of the largest motor fibres. In many cases the reflex was elicited with stimulation intensities below motor threshold.

However, H reflexes normally appear as relatively simple, near synchronous single discharges of motor units. This is just how the H reflex recorded in soleus appears in figure 39. The response in anterior tibial muscles are smaller and more complex with a series of waves extending over more than 5 msec (refer to figure 29). These are probably the result of slightly asynchronous H reflexes in several adjacent muscles, e.g. anterior tibial, extensor hallucis longus and extensor digitorum longus. They are close functional synergists and they are all innervated via branches of the common peroneal nerve. During the voluntary dorsiflexion they are probably all active, their Ia afferents will be synchronously excited and their motor units may participate in the H response with a slight time dispersion due to different conduction delays. Thus, the complex wave form is most likely a consequence of a dispersed series of simple H reflexes rather than a more complex reflex

confined to anterior tibial. It is interesting to note that each of the components behaves in the same way during recruitment and fatigue as it was shown in figure 29. In all three traces the M waves are similar. The H reflexes are complex , which might suggest they represent activity from adjacent muscles. All components of the H complex behave the same way, and they were reduced after fatiguing activity. All these components recovered within ten minutes.

Thomas et al. (1989) showed that the amplitude and area of M waves evoked by single shocks to the motor nerve usually remain constant or increase, despite up to 50% force decline, even in MVCs of TA extended for up to 5 minutes. They suggested that well-maintained amplitudes of anterior tibial potentials resulted from cross-contamination from other unfatigued synergistic muscles due to activity of all dorsiflexors of the foot simultaneously. The discrepancy between the same behaviour of muscles after fatigue reported here and those from Thomas et al. (1989) probably depends largely on the using of different methods for inducing muscle fatigue.

F reflexes

The F wave (Magladery and McDougal, 1950) is a late muscle potential response which is obtained by a supramaximal stimulus intensity (Kimura, 1983), from antidromic stimulation of anterior horn cells and therefore is always preceded by an M response. The amplitude of the F wave is usually the only about 1% that of the M response (Andrews and Bruyninckx., 1986). However, the H reflexes described in this thesis were generally elicited between 1-2.5 xT, and the maximal M waves

were obtained more than 4 xT in the present results. Thus F waves are seen at substantially higher stimulus intensities than those used here.

In addition, the F wave has a variable latency and is inconsistent in its appearance. This is due to activation of different groups of motoneurons. Upper limits of normal for minimal F latencies are 36 and 61 ms when recording from calf, and foot muscles, respectively (Fisher, 1992). Similar results on human normal subjects were reported by Kimura (1983). The mean F wave latency was 42.7 ± 4 msec for common peroneal nerve and 52.3 ± 4.3 msec for tibial nerve. However, the mean H reflexes in the present results was 30.9 ± 2.3 msec for soleus muscle and 30.2 ± 1.5 msec for anterior tibial muscles.

Fatigue

Generally, activation leads to decline of force production and speed, i.e. power output which is known as fatigue (Westerbland et al.,1991), or failure to maintain the required or expected force (Edwards, 1981; Enoka and Stuart, 1992). The causes of fatigue can be central or peripheral.

1. Central fatigue: this type of fatigue is achieved by voluntary activity. An experimental volunteer needs increased concentration and effort to sustain a contraction. This is associated with increasing EMG amplitude. During such experiments subjects often require visual feedback to maintain the given force and without visual feedback and encouragement, force rapidly declines.

During voluntary contractions, the behaviour of the central nervous system is modified during the whole period of activity to generate the increased effort necessary to counteract the reduced muscle performance. Central fatigue can be recognised by superimposing electrical stimulation during maximal voluntary contractions (Bigland-Ritchie, 1986b). Single or tetanic stimulation can identify whether a muscle is fully activated or if additional force can be obtained by stimulation (Merton, 1954).

The function of the ascending and descending pathways can be checked by using electrical stimulation either on the scalp to activate the motor cortex or in the spinal cord to stimulate motoneurones. These methods require special techniques such as high voltages or magnetic stimulation.

2. Peripheral fatigue: this type of fatigue generally occurs during activity. Often the concentrations of muscle metabolites change due to metabolic activity. The mechanism of such fatigue has been investigated during sustained maximal voluntary contractions of the first dorsal interosseous muscle of the hand by Stephens and Taylor (1972). Their results showed that during the first minute the force declined to 50% and the EMG fell with the same slope. However, in the later second phase force reduced more than EMG. They suggested that during the first stage fatigue was due to neuromuscular junction failure. Arterial occlusion did not affect this stage. During the second stage contractile element failure was the main cause of fatigue. Occlusion of the blood flow did affect this stage. There are two factors that could contribute to a reduction of membrane potential during fatigue. Firstly, the accumulation of K^+ in

the extracellular space and a smaller reduction in the intracellular K^+ with lower resting membrane potential. Secondly, the metabolic changes could directly affect membrane characteristics and also influence the rate at which the membrane Na^+, K^+ transport mechanisms act to redress the ionic imbalance.

Electrical exercise: During a long term of electrical activity the time course of force reduction depends on the frequency of stimulation. Fatigue occurs quickly during high frequency stimuli and more gradually by using low frequency. The muscle fibre membrane becomes depolarised during high frequency stimulation (Jones and Bigland-Ritchie, 1986), and a failure in excitation-contraction coupling occurs during low frequency fatigue (Edwards et al., 1977).

The half relaxation time increases up to about two fold after fatiguing contractions. This is the other characteristic of fatigued muscle. However, the mechanism of slowing relaxation is not clear but there are two possibilities. It may be due to a reduction of cross-bridge detachment rate. A possible second mechanism concerns slowing of calcium reaccumulation by the sarcoplasmic reticulum. This is an ATP-dependent process which could be slowed in adverse metabolic circumstances (Edwards et al., 1977).

Garland and McComas (1990) investigated the changes of motoneurone excitability by employing fatiguing electrical activity of soleus muscle. Their results showed the reduction of soleus H reflex excitability which was induced by electrical stimulation. Also, their results did not show central fatigue because they used peripheral stimuli and they observed

no signs of peripheral fatigue since they obtained relatively stable M waves.

The present experiments differ from Garland and McComas, in the use of both electrical and voluntary fatigue in anterior tibial muscles, rather than soleus. The anterior tibial muscles fatigued even if the blood flow was not occluded with a blood pressure cuff. On the other hand the recruitment curve for anterior tibial H reflexes was smaller than soleus compared to their maximal M waves (see figure 37 and 38 in section 3.8).

Comparison of the results in sections 3.6 - 3.12, shows there was no significant difference between electrical and voluntary activity of anterior tibial muscles in terms of fatigue developed or anterior tibial H reflex excitability changes. This proves there is no central fatigue. However, electrical exercise of anterior tibial muscles produced rather greater depression of soleus H reflexes than did voluntary exercise of the same duration. This is almost certainly associated with a greater fatigue produced by electrical stimulation in these experiments. Electrical exercise activates the largest and most easily fatigued motor units whilst voluntary exercise activates the smaller more fatigue resistant units. Thus for equivalent exercise periods it is not difficult to see how the fatigue related effects might be larger after electrical exercise. In addition, as seen in section 3.10 of the results the maximal force dropped progressively during 9 minutes voluntary contraction of quadriceps muscle group the H reflexes amplitude were reduced progressively during similar time.

The development of fatigue was quite clear during the experiments. As can be noted in sections 3.6 to 3.12 during either voluntary or electrical exercise the force decreased and the half relaxation time increased more than 70%. These changes are associated with the developing fatigue. The amount of force developed during electrical exercise was about 30% of MVC. This was similar to voluntary contraction procedure. The similar forces are to those used by Bigland-Ritchie et al. (1986b). In their experiments, human quadriceps and soleus muscles were exercised by submaximal intermittent isometric voluntary contractions. Their results in quadriceps showed that the central nervous system was capable of full muscle activation, and the reduction of MVC was due to failure of muscle contractile apparatus. However, in soleus muscle the results were less clear. They also reported that the quadriceps EMG associated with a brief MVCs increased during fatigue developed, while the soleus EMG declined.

In the results reported in this thesis the M waves were stable which indicate that there was not any failure of neuromuscular junction. Thus, the changes in H reflex excitability must be due to the central actions of sensory fibres affected by the muscle exercise which will be described in more detail in the section 4.7 of discussion.

Garland and McComas (1990) were also reported the reduction of soleus H reflex excitability. We agree with Bigland-Ritchie et al., (1986b); Garland and McComas, (1990) that the reduction in H reflexes is a reflex phenomenon. The changes were due to inhibitory afferents to motoneurones from receptors in the fatigued muscle.

4.3 Comparison of H reflexes in the anterior tibial and soleus muscles

Soleus is a slow, postural muscle. The soleus motoneurone pool receives strong inputs from Ia afferents and shows strong monosynaptic and H reflexes. The anterior tibial motoneurones receive weaker inputs from Ia afferents and so show weaker H reflexes. In addition, anterior tibial motoneurones are subjected to stronger descending influences (Belanger and McComas, 1981). Thus, anterior tibial muscles needed weak background activity in its muscle to produce reliable H reflexes. This effect was first reported by Upon et al. (1971). The anterior tibial H reflex excitability during equivalent activity of the α motoneurone produced by voluntary movement or a polysynaptic reflexes was investigated by Pierrot-Deseilligny and Bussel (1973). Their results showed that the anterior tibial H reflex amplitude was much greater at the onset of voluntary activity than at the onset of a polysynaptic reflex. Thus, in many types of experiment the anterior tibial motoneurone pool requires some preparatory central excitation before it displays H reflexes. This may be a reduction in presynaptic inhibition of Ia terminals as suggested by Delwaide (1973).

In the experiments described here anterior tibial maximal H reflexes were elicited with lower stimulus intensities than soleus H reflexes. This probably reflects the additional excitation of the anterior tibial motoneurone pool provided by the voluntary contraction.

In addition, the H_{max}/M_{max} ratios in anterior tibial muscles were smaller than soleus. This could be partly attributed to the type of muscle

composition fibres in those muscles. Belanger and McComas in 1981, compared plantarflexor to dorsiflexor muscles in man. Their results showed that plantarflexor muscles had larger twitch torques and slower twitch speeds than dorsiflexors. This shows greater muscle bulk and a higher percentage of slow twitch fibres in plantarflexors. Human muscles have been investigated to find out the type of muscle fibre distribution. Samples, of muscle were obtained at autopsy show that soleus has 87% slow type I fibres whilst anterior tibial muscles have 73% of type I fibres (Johnson et al., 1973). Differences in fibre types look less significant than the differences in reflexes in fatigued muscles.

The differences between anterior tibial and soleus compositions are much greater in cats where, the percentages of slow fibres are much higher for soleus than for anterior tibial muscles (Ariano et al., 1973). Hensbergen and Kernell (1993) reported that cumulative activity times tended to be significantly higher for soleus than anterior tibial.

What is the main reason for the differences between slow and fast fibre types in the different species? Sargeant and Kernell (1993) pointed out that the percentage of slow fibres is much higher in a heavy animal than a light one. It was also suggested that with respect of linearity in body dimensions, force would increase by a power of 2 but weight by a power of 3. Therefore, The percentage of slow fibres in postural muscles is higher for man than for cat.

Thus, differential fatigue of muscles with different fibre types might be much more significant in smaller animals than it is in man.

4.4   Factors determining the size of H response

During the pilot experiments the amplitude of H reflexes was observed to vary systematically. These changes were due to changes in posture, the intensity and frequency of stimuli or the extent of voluntary activity.

Posture

The subject's trunk and limb were fixed in the same position during the experiments so that the effects of body position do not contribute to changes in H reflex amplitude.

Stimulus Intensity

During the experiments, the intensity of stimulation was set to obtain control H reflexes about half maximal amplitude. That level allows easy identification of both excitation and inhibition effects. Alternatively, a wide range of intensities was employed to identify H_{max} and M_{max}. During the experiments the M and M_{max} waves were stable which proves stable stimulation conditions were produced.

Frequency of stimulation

This is a potential problem if H reflex tests are repeated at short intervals. The effect of intervals between 1-10 seconds on soleus H reflex amplitudes are shown in figure 22. The M waves are stable in all traces, whilst in A, B and C, the H reflex amplitude remains relatively constant. In D, with intervals of 2.5 seconds, there is a progressive reduction in amplitude. With repetitions at 1 second intervals (E) almost

no H reflexes can be elicited. The most effective intervals to elicit H reflex were longer than 5 sec which was suitable for subjects.

The constancy of the M wave proves that the depression of H reflexes cannot be attributed to changes in stimulus intensity. Long intervals are necessary to avoid the late 'depression' described by Magladery (Hugon, 1973). Therefore, although long intervals would have been better this would have made the whole experiment too long. Thus, H reflexes were delivered every 5 sec intervals during experiments.

The intensity of voluntary activity

It can be difficult to elicit anterior tibial H reflexes in relaxed muscle, but it easy to elicit reflexes in soleus muscle even when it is relaxed. However, with a background of weak dorsiflexion contraction, we showed that the anterior tibial H reflex can be elicited very constantly and reliably. Figures 24 and 25 in section 3.4 show the effect of precontraction at 5% and 10% of MVC on the anterior tibial M wave and H reflex amplitudes. Contraction had little effect on M wave amplitudes in the range below 1.75 T. Between 1.75 T and 2.5 T, the M wave amplitudes change, with higher forces associated with larger M waves. The maximal M wave amplitudes were constant. These changes in M wave amplitudes could be due to slight movements of the muscle nerve relative to the cathode.

H reflex amplitudes increased significantly with increasing force between T-1.75T. The stability of the M waves over this range suggests the increase in H reflex amplitudes is due to central facilitation rather

than peripheral effect. Further increases in force of contraction more than 10% did not produce a further increase in H reflex amplitude.

The effects of agonist and antagonist contraction on H reflex amplitude

The finding that voluntary contraction of the pre-tibial muscles decreases the amplitude of the soleus H reflex is an old one (Hoffmann, 1918 and Paillard, 1955). That was precisely described in Sherrington's principle of reciprocal innervation. During contraction of a muscle the antagonists do not behave passively but are actively inhibited by central nervous mechanisms (Sherrington, 1947). In cats, electrical stimulation of the Ia afferent fibres of agonist muscles inhibits the motoneurones of antagonist muscles (Lloyd, 1946).

In experiments on soleus, facilitation of H reflexes was observed during voluntary contraction of solus. Inhibition of soleus H reflexes was seen during voluntary activity in anterior tibial muscles. However the facilitation in anterior tibial H reflexes by voluntary contraction was much more than for soleus H reflexes. This could be due to more powerful control from descending pathways on anterior tibial muscles.

Meinck (1980) investigated the effect of amplitude of H reflexes on the ease with which facilitation and inhibition of the human soleus H reflexes could be found. His results showed that the greatest facilitation was observed only if the amplitude of the control reflex was below half-premaximal or, in other terms, if the control reflex was elicited at low stimulus intensity. On the basis of the size principle (Henneman et al., 1965a), such stimuli can be expected to recruit mainly small

motoneurones. This suggestion was first made by Buchthal and Schmalbruch (1970). It seems that small motoneurones have the highest susceptibility to excitatory inputs. Larger motoneurones, which are assumed to be discharged with increasing stimulus intensity, showed either little or no facilitation at low stimuli. This is very similar to observations by Henneman et al. (1965b) in the decerebrate cat.

In contrast to facilitation, inhibition was marked over a wide range of control reflex amplitudes. Their view is in some disagreement with the observations of Henneman et al., (1965b) who noted that inhibition was most prominent in larger motoneurones which show higher recruitment thresholds while smaller ones, exhibiting a lower recruitment threshold, were susceptible to inhibition to a lesser extent.

Hugon (1973) and Desmedt (1973) observed that it is generally inconvenient to test motoneurone excitability using control H reflexes larger than half maximal amplitude. This holds for both facilitation and inhibition. In pools with a higher functional number of small motoneurones the half maximal H amplitude may be elicited at low stimulus intensities than in those with predominantly larger motoneurones. It seems that anterior tibial muscles, which are used in a phasic manner (Garland et al., 1988a) have mostly large motoneurone pools. Garland et al. (1988a) investigated the relationship between stimulus frequency and fatigue on anterior tibial muscles. Their results showed that muscle fatigue depended not only on the number of muscle fibre excitations but also on the impulse frequency.

4.5 M and H waves recruitment curves

The recruitment curves for direct M responses and H reflexes had different shapes. The recruitment curve for M response had sigmoid shape which is determined by the distribution of α motor fibres in the nerve (Hugon, 1973). The largest fibres are recruited at lower stimulus intensities but because they are few in number the M wave has a small amplitude. With increasing stimulus intensity, smaller fibres which are more numerous and have higher thresholds are recruited. Therefore the amplitude of the M response increases rapidly. The smallest fibres which are few and recruited at the highest stimulus intensities, so the amplitude rises very slowly. Ultimately, when all α motor fibres are active the maximum M waves is seen. Further increases in stimulus intensity do not increase the M wave.

But the H waves recruitment curve is different. At low stimulus intensity the amplitude of H reflex increases rapidly in amplitude. Then the amplitude begins to fall, while the M response rises. At higher threshold intensity complete occlusion occurs between antidromic and orthdromic impulses.

At higher stimulus intensity still the F wave appears in most of subjects in these experiments "as described earlier, it is very unlikely H waves were confused with F waves".

4.6   The effects of muscle fatigue on H reflexes

The results in sections 3.6 to 3.12 show significantly greater different effects on soleus H reflexes with electrical and voluntary activity of anterior tibial muscles. The electrical activity produced larger force reductions and so was presumably more effective in producing fatigue than was voluntary activity. Consequently, greater fatigue was associated with reductions in H reflex excitability. In addition, the maximal force dropped progressively during 9 minutes voluntary contraction of quadriceps muscle group and simultaneously the H reflex amplitudes were reduced (figures 42 and 43 in section 3.10).

Control experiments are difficult to perform in experiments of this type. H reflexes are stable when no stimulation is presented but "sham" stimulation is not effective as a control since are subjects aware that the "exercising" muscle is inactive. However, in two subjects the electrical activity of anterior tibial muscles was set at a low intensity because of their very low intensity tolerance level for stimulation. The MVCs were only slightly decreased and the half relaxation times were slightly increased. This shows little fatigue occurred. In these cases the H reflex amplitudes were not changed significantly.

During fatigue the H reflex recruitment curves were decreased in most of subjects, while the M wave recruitment curves were not changed significantly. If changes in the amplitude of M waves were significant, those data were ignored because of the changes in stimulus efficiency.

However, after voluntary activity of quadriceps group muscles in some subjects the M wave recruitment curves were stable but the H wave

recruitment curves were shifted to the right of control value but the amplitude H_{max} was unchanged. This could be due to changes in H reflex threshold stimulus intensity. Hugon (1973) suggested that the shifting of H reflex recruitment while the M waves are stable, indicates a change of H reflex loop excitability.

Garland and McComas (1988) showed that the voluntary EMG activity was decreased following electrical activity of the soleus muscle. In their experiments, the relative stability of maximal M waves suggested that the decline of the voluntary EMG activity could not be due to the loss of excitability of neuromuscular junctions. It was also clear because of their use of direct muscle stimulation that the reduction in the EMG could not be related to central fatigue.

In the other similar experiment, the voluntary EMG activity was decreased after electrically induced activity of the human ankle dorsiflexor muscles (Garland et al., 1988b). Therefore the loss of voluntary EMG activity might be due to decrease in α motoneurone excitability. Testing of this possibility was the main point of this investigation. In this case the anterior tibial muscles were fatigued electrically.

However, Kukulka et al. (1986) also found a reduction in motoneurone excitability by applying a modified H reflex technique like Bussel & Pierrot-Deseilligny (1977). They showed increased recurrent inhibition exerted by Renshaw cells, but they employed maximal voluntary contractions of the soleus in their experiments.

In a different experiment, Garland and McComas (1990) investigated the changes of motoneurone excitability by employing fatiguing electrical

activity of soleus muscle. Their result showed the reduction of soleus H reflex excitability which was induced by electrical stimulation.

The present experiments differed from Kukulka et al. (1986), in using of intermittent voluntary contraction and ischaemia, instead of maximal voluntary contraction and Garland and McComas, in using of electrical fatigue in anterior tibial muscles, rather than soleus.

The present results show that H and H_{max} reflexes in anterior tibial and soleus muscles are reduced after fatiguing exercise of anterior tibial muscles even with normal blood flow. The similar results were also obtained following fatiguing activity of quadriceps group muscles. The relative stability of the M and M_{max} waves whilst anterior tibial and soleus H and H_{max} waves are reduced suggest that this is a reflex phenomenon rather than a change in excitability of neuromuscular junctions.

4.7 The source of changes in reflex

The reduction in H reflex excitability associated with muscle fatigue could be due to many reasons each possibility is discussed sequentially below:

Decrease in descending excitatory input from motor cortex

The first possible cause of a reduction in H reflexes might be due a depression of activity of descending pathways. Garland and McComas (1990) did not reject this reason. In their experiments interpolated twitches were employed during fatigue process which did not show any central function. In addition, after fatiguing activity of anterior tibial muscles, the reduction in H reflexes of those muscles were observed during a constant level of precontraction (10% of MVC) which showed the motoneurone's excitability was maintained constant. A similar result was demonstrated by Duchateau and Hainaut (1993). Rather, in keeping with the suggestion of Duchateau et al. (1993), the result presented in this thesis support the view that reduced central drive is not be the cause of fatigue.

Decrease in muscle spindle output

A second possibility for the reduction of H reflexes might be due a reduction in the net excitatory input from spindle primary endings. The time course for reduction of H reflex was slow in the present experiments. Recent work has also shown that spindle output does fall in fatigue (Macefield et al., 1991). But that this has a faster time course

than the observed changes in the H reflex reduction . In addition, the reduction in anterior tibial H reflexes were also observed during a constant level of precontraction (10% of MVC) in those muscles which should ensure the motoneurone pool excitability was maintained constant.

Adaptation in motoneurone excitability

In the present investigation the H reflexes were elicited in anterior tibial and soleus muscles by electrical stimulation of the common peroneal and tibial nerves. It was observed that during the electrical and voluntary fatigue process in anterior tibial muscles and also following voluntary activity of quadriceps muscle, the normalised H reflex amplitude was decreased, even when the blood flow were normal. The reduction was increased when the normal blood flow occluded. However, with normal blood flow the rate of development of fatigue was slower. Kernell and Monster (1982a, b) working with in anaesthetised cats, suggested that the adaptation of the motoneurone discharge rates occur during constant excitability drive. During these investigations the time course of fatigue was relatively slow, it took 30 seconds at least to see the reduction of H reflexes and also no sign of recovery was seen when the cuff was kept inflated. In the Kernell's experiment late adaptation occurred during the first 30 seconds of sustained stimulation. Therefore the motoneurone adaptation could not be the cause of reduction in H reflexes. In addition, Enoka and Stuart in (1992) suggested that there is no adaptation of the motoneurone during sustained maximal voluntary contractions.

Recurrent inhibition

Another possible explanation of the reduction of H reflexes following fatiguing activity might be stronger recurrent inhibition. The time interval between the end of fatiguing activity and the measurements of the H reflexes was at least 30 seconds. This relatively long period of motoneurone inactivity makes the reduction of H reflex excitability as a result of recurrent inhibition rather unlikely. In addition, soleus H reflexes also reduced following fatiguing in anterior tibial. This cannot be due to recurrent inhibition, since soleus was not active during the tests.

Presynaptic inhibition of the Ia terminals

Soleus H reflexes were decreased (see sections 3.7 and 3.9) not only after fatiguing activity of anterior tibial muscles but also after voluntary activity of quadriceps group muscles. This relatively extensive pattern of connection suggests that Presynaptic inhibition of the Ia terminals might be responsible for the changes in the soleus H reflexes

Excitability of α motoneurones during contractions of ankle extensor muscles were investigated in the cat (Zytnicki et al., 1990). Their results showed that during a series of gastrocnemius twitches at rate of 10/sec, contraction induced inhibitory potentials in α motoneurones due to activation of homonymous Ib afferent fibres. These rapidly subside before the end of the series. In contrast, excitatory potentials which are due to activity of primary afferent fibres during relaxation persisted. They suggested that presynaptic inhibition of homonymous Ib afferent fibres during muscle contractions is likely to be the main reason for

declining of autogenetic inhibition. However, the present results showed stronger inhibition in soleus motoneurones following activity of antagonist muscles compare to weaker effect of this experiment. Figure 49 shows simply a diagram of presynaptic (A), Postsynaptic (B) and Renshaw inhibition (C).

A   B   C

Ia

α
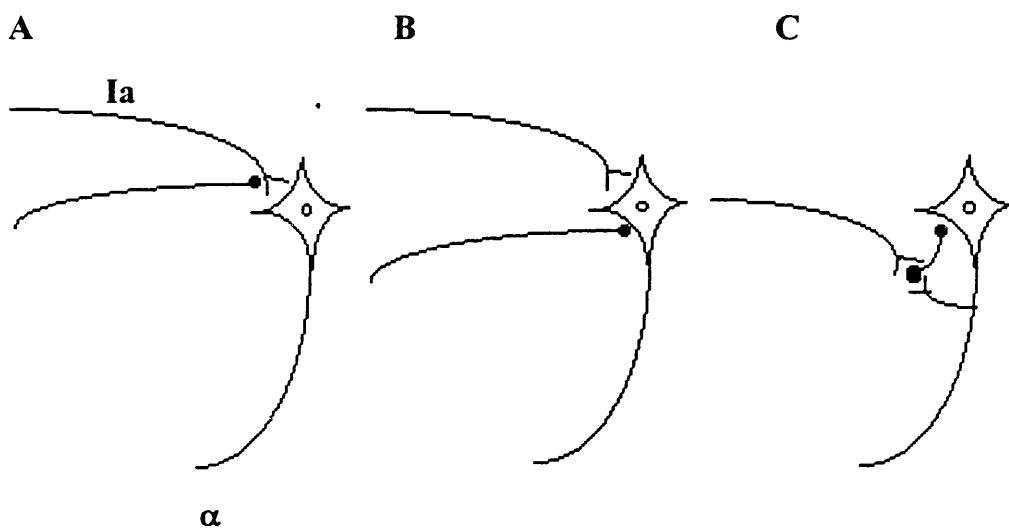
Figure 49. This diagram shows presynaptic inhibition (A), Post synaptic inhibition (B) and Renshaw inhibition (C).

Voluntary muscle relaxation was also investigated in human soleus muscle by means of a H reflex technique (Enoka et al., 1980; Scheippati and Crenna, 1984; Scheippati, 1987). The amplitude of the soleus H reflex is clearly reduced during and following the relaxation phase. The H wave showed a depression over a 50 seconds period following contraction. It was suggested that, when an agonist muscle relaxed from a contraction, presynaptic inhibition of the Ia afferent fibres originating from the spindles of the relaxing muscle is the main mechanism

responsible for the H reflex inhibition (Scheippati, 1987). However, during the present experiments the time course of fatigue was relatively slow.

Effects of cutaneous afferents

Cutaneous afferent input following electrical stimulation might have participated to affect motoneurone excitability, but it is known that these influences are more likely to be excitatory than inhibitory (Hagbarth, 1960; Delwaide et al., 1981; Crenna et al., 1982). In the present results, using blood pressure cuff around the midthigh, it was possible that the pressure exerted by the cuff might have reduced the H reflexes. However, we have not found a significant difference between control H reflexes and the reflexes found with cuff pressure.

Inhibition from metabolically sensitive receptors

The small diameter thinly myelinated afferent fibres (Group III) and unmyelinated fibres (Group IV) from muscle mainly respond to mechanical and metabolic changes in the fatigue process. Approximately half of the small diameter afferents have been shown to respond to noxious chemical, mechanical and thermal stimuli, (Kniffki et al., 1981). Other small afferents are activated by moderately innocuous stimuli such as stretch, contraction and touch (Kniffki et al., 1981). Group III and IV afferents can be activated by chemical agents associated with muscle pain, i.e. bradykinin and potassium (Mense, 1977), lactate and phosphate (Kniffki et al., 1978). Most of these increase in concentration during fatigue.

Bigland-Ritchie et al. (1986a) reported that the motoneurone firing rates associated with maximal voluntary contraction after fatiguing activity remained depressed whilst the limb was kept ischaemic, and recovered within 3 minutes following the return of blood flow. They suggested that a peripheral reflex phenomenon from the fatigued muscle is the main reason for the EMG reduction. Receptors which are sensitive either to the mechanical or to the metabolic state of the muscle must explain this. In the other experiment Garland and McComas (1988) showed that release of blood pressure cuff was associated with decreasing of muscle pain which could be due to wash-out of accumulation of metabolic products. Similar results were obtained by Garland and McComas (1990). They also observed greater reduction in reflex excitability in fatigue experiment than in the existence of ischaemia alone. When the cuff was kept inflated the MVCs and H reflexes did not recover, but they were restored to control value within 10 minutes of releasing the cuff. However, the pain was relatively severe after voluntary fatigue while the ischaemia cuff was inflated and this may have influenced the H reflexes. In the results reported in this thesis, the same reduction was observed in anterior tibial H reflexes even though the blood flow were normal.

The role of small diameter afferent fibres in reflex inhibition was investigated during human muscle fatigue by Garland (1991). The sciatic nerve was compressed by placing a wooden bar distal to the ischial tuberosity to block the contribution of large myelinated afferents before fatigue experiments. It was suggested that any reflex inhibition is mediated by smaller diameter afferents supplying the fatigued muscle.

She also concluded that mechanical changes mediated reflex inhibition, because the reductions in EMG remained while the cuff were inflated. She concluded that activity in the smaller diameter afferents fibres is the main reason for inhibition of the H reflex.

These observations together with Bigland-Ritchie et al., (1986a); Garland and McComas (1990), show that the changes in H reflexes are almost certainly due to inhibitory afferents from receptors in the fatigued muscle.

How might these effects be used to regulate movements during sustained activity?

The performance of muscle changes continuously as fatigue develops. The fatigue process reduces the force produced by the muscle and slows the rate of contraction and relaxation. If consistent movements are to be made, there must be some change in nervous system behaviour to compensate for this. Thus the compensation might be increasing the firing rate of active motor units, recruiting fresh motor units or recruiting motor units earlier in a repeated movement. Any of these changes would be expected to be associated with increased motoneuronal excitability and thus should be reflected in increased H reflexes. This was never observed in the experiments.

The observed reduction in H reflexes is closer to the observed slowing in the firing rate of individual motor units seen during sustained contractions (Bigland-Ritchie et al., 1986a). The effect of this is to maintain the tetanic state by a lower rate of firing as the contractile speed slows. The motor unit remains tetanised though its force production is reduced. Thus the slowing of rate appears to avoid over stimulation and so save energy, rather than to preserve force output. The slowing of individual motor units is thought to be reflex in origin and mediated by small diameter muscle afferents.

Thus, there seems to be some feedback, originating from the peripheral sources or changes in descending commands. The overall changes during repeated low force activity can essentially lead to an increase in motoneurone excitability. However, H reflex excitability is reduced following these type of activities. This might suggest either drop out of

units after they had lost almost all capacity to generate force (Bigland-Ritchie, 1993), or progressive failure of neuromuscular transmission (Fuglevand and Enoka, 1993).

It seems to be some area in the central nervous system to regulate a motor performance associated with a sustained activity. Enoka and Stuart (1992) assessed the effort associated with performing a task by requiring subjects to match forces. It seems that subjects' judgements are based on the effect required to generate a force rather than the absolute magnitude of the force that is exerted. This judgement is referred to as the sense of effort and is distinct from the force sensation associated with contraction.

This suggests a greater involvement of higher centres in force maintenance as fatigue develops.

4.8 Conclusion

The results show that H reflexes in anterior tibial and soleus muscles are reduced after fatiguing exercise in anterior tibial muscles even with normal blood flow.

Maximal H reflexes in soleus are reduced after severe fatiguing voluntary contractions in its antagonist anterior tibial muscles.

Soleus H reflexes can also be reduced after relatively severe fatiguing activity in its antagonist quadriceps group muscles.

There seems to be a reflex inhibitory system active during fatigue, which decreases the motoneurone excitability in conjunction with the reduction in force. This reflex is mediated, due to metabolic or chemical changes which could be mediated by small diameter afferent fibres from fatigued muscles. This agree with Garland and McComas (1990) who stated that the relative stability of the M and M_{max} waves and the H and H_{max} reflexes were decrease, suggests that this reduction could be a reflex phenomenon rather than neuromuscular junction failure.

4.9   Future plan

This project might be extended to clinical investigations, for example in the spinal cord or cerebral injuries such as paraplegic or hemiplegic patients. In such cases, where there is reduced descending control on motoneurone pool activity, the spinal mechanisms could be studied in relative isolation.

The motoneurone excitability could be used as an indicator of muscle fatigue during gait training in paraplegics. One of the biggest problems in using FES during swing phase of gait training of paraplegics is muscle fatigue. Because they need to use this device for along periods and as we know these patients do not have connection or co-ordination between central and peripheral pathways. Therefore, the muscle will act separately from the nervous system. However, fatigue is very different in these patients due to disuse atrophy.

The other group of patients who might be investigated are those who have muscular or neuromuscular disease. The fatigue protocol could be applied as an indicator for these kind of diseases. It is known that myopathic patients fatigue very quickly. Therefore, it would be useful to know how the time course of fatigue and H reflex reductions are linked in these patients.

One of the common treatments in physiotherapy is the activation of antagonist muscles to reduce the limitation of joint motion caused by

spasticity. In that treatment, the spastic muscle is fatigued, helping to increase the range of movements. However, it is not clear how this happens. If the fatigue protocol is used in those patients it may be possible to find out if the effect is due to changes in the motoneurone excitability.

Transcranial magnetic stimulation of the motor cortex can be used to measure cortical excitability produces. The modulation of EMG response following transcranial magnetic stimulation was investigated during the short and long latency stretch reflex by Day et al. (1991). Their results showed that the motor cortex excitability is increased for a period which is close to the period of long latency stretch reflex following the onset of muscle stretch.

Using of magnetic stimulation of the motor cortex during fatiguing activity of muscle, it might be possible to differentiate between spinal reflex and cortical mechanisms in a reducing motorneurone excitability.

5. References

Aiello, I., Serra, G., Migliore, A., Tugnoli, V., Roccella, P., Cristofori, M. C. and Manca, M. (1983b). Diagnostic use of H reflex from vastus medialis muscle. *Electromyography Clinical Neurophysiology* **23**, 159-166.

Andrews, C. J. and Johnson, J. R. (1986). Clinical anatomy. In: *Electrodiagnosis: an Anatomical and Clinical Approach.* Edited by J. C. Andrews and R. J. Johnson. J. B. Lippincott Company, Philadelphia, 79-196.

Andrews, C. J., Johnson, R. F. and Bruyninckx, F. L. (1986). Common injuries and entrapment syndromes involving the peripheral nerves. In: *Electrodiagnosis: an Anatomical and Clinical Approach.* Edited by J. C. Andrews and R. J. Johnson. J. B. Lippincott Company, Philadelphia, 271-351.

Andrews, C. J. and Bruyninckx, F. L. (1986). H reflex and F wave. In: *Electrodiagnosis: an Anatomical and Clinical Approach.* Edited by J. C. Andrews and R. J. Johnson. J. B. Lippincott Company, Philadelphia, 353-358.

Angel, R.W. and Hofmann, W. W (1963). The H-reflex in normal, spastic, and rigid subjects. *Archives of Neurology* **8**, 591-596.

Ariano, M. A., Armstrong, R. B. and Edgerton, V. R. (1973). Hind limb muscle fibre populations of five mammals. *Journal of Histochemistry and Cytochemistry* 21, 51-55.

Bathien, N. and Guiheunec, P. (1974). L' exploration des polinevrites chroniques par la technique du reflex H. Rev. *EEG Neurophysiology Clinical* 4, 587-595. .

Belanger, A. Y and McComas, A. J. (1981). Extent of motor unit activation during effort. *Journal of Applied Physiology* 51(5), 1131-1135.

Bellemare, F., Woods, J. J., Johansson, R. S. and Bigland-Ritchie, B. (1983). Motor unit discharge rates in maximal voluntary contractions of three human muscles. *Journal of Neurophisiology* 50, 1380-1392.

Bergmans, J., Delwaide, P. J. and Gadea-Ciria, M. (1978). Short latency effects of low threshold muscular afferent fibres on different motoneuronal pools of the lower limb in man. *Experimental Neurology* 60, 380-385.

Bessou, P and Laporte, Y. (1961). Etude des recepteurs musculaires innerves par les fibres afferents du groupe III (fibres myelinisees fines) chez le chat. *Archs Ital. Biol.* 99, 293-321.

Bigland-Ritchie, B. and Lippold, O. C. J. (1979). Excitation frequency and muscle fatigue: Electrical responses during human voluntary and stimulated contractions. *Experimental Neurology* **64**, 414-427.

Bigland-Ritchie, (1981). Human muscle function and fatigue In: *Human Muscle Fatigue: Physiological Mechanisms*, edited by R. Porter and J. Whelan. London: Pitman, 130-148.

Bigland- Ritchie, B., Johansson, R. S., Lippold, O. C. J. and Woods, J. J. (1982). Changes of single motor unit firing rates during sustained maximal voluntary contractions. *Journal of Physiology.* **328**, 27-28P.

Bigland-Ritchie, B. and Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle and Nerve* **7**, 691-699.

Bigland- Ritchie, B., Johansson, R. S. and Lippold, O. C. J.(1986a). Reflex origin for the slowing of motoneurone firing rates in fatigue of human voluntary contractions. *Journal of Physiology* **379**, 451-459.

Bigland- Ritchie, B., Furbush, F. and Woods, J. J. (1986b). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. *Journal of Applied Physiology* **61**(2), 421-429.

Bigland- Ritchie, B. (1993). Regulation of motoneurone firing rates in fatigue. In: *Neuromuscular Fatigue,* edited by A. J. Sargeant and D. Kernell, 147-155.

Buchthal, F. and Schmalbruch, H. (1970). Contraction times of twitches evoked by H reflexes. *Acta Physiologica Scandinavica* **80**, 378-382.

Bulbulian, R. and Darabos, B. L. (1986). Motor neuron excitability: the Hoffmann reflex following exercise of low and high intensity. *Medicine and Science in Sports and Exercise* **18**, 697-702.

Burke, D. Gandevia, S. and McKeon, B. (1983). The afferent volleys responsible for spinal proprioceptive reflexes in man. *Journal of Physiology* **339**, 535-552.

Burke, D., Adams, R. W. and Skuse, N. F. (1989). The effects of voluntary contraction on the H reflex of human limb muscles. *Brain* 112, 417-433.

Bussel, B. and Pierrot-Deseilligny, E. (1977). Inhibition of human motoneurones, probably of Renshaw origin, elicited by an orthodromic motor discharge. *Journal of Physiology* **269**, 319-339.

Carew, T. J. (1985). The control of reflex action. In: *Principles of Neural Science*. Edited by E. R. Kandel and J. H. Schwartz, second edition. Elsevier, 457-468.

Carew, T. J. and Claude, C. (1985). Muscle and muscle receptors. In: *Principles of Neural Science.* Edited by E. R. Kandel and J. H. Schwartz, second edition. Elsevier, 443-446.

Carpenter, R. H. S. (1991). Nerves. In: *Physiological Principles of Medicine Series.* Edited by R. H. S. Carpenter, second edition, Edward Arnold 20-48.

Cavallari, P., Fournier, E., Katz, R., Malmgren, E, Pierrot-Deseilligny, E. and Shindo, M. (1985). Cutaneous facilitation of transmission in Ib reflex pathways in the human upper limb. *Experimental Brain Research* **60**, 197-199.

Crenna, P., Schieppati, M. and DeCurtis, .(1982). Long-latency, nonreciprocal reflex responses of antagonistic hind limb muscles after cutaneous nerve stimulation in the cat. *Experimental Neurology* **76**, 58-71.

Davies, T. W. (1985a). Reciprocal inhibition of proprioceptive reflexes in man revealed by a threshold shift technique. *Neuroscience Letters* **60**, 375-380.

Davies, T. W. (1985b). Position-dependent modulation of human recurrent inhibition. *Neuroscience Letters* (Suppl.), **21**, S35.

Day, B. L., Marsden, C. D., Obeso, J. A. and Rothwell, J. C. (1984). Reciprocal inhibition between the muscles of the human forearm. *Journal of Physiology* **349**, 519-534.

Day, B. L., Riescher, H., Struppler, A., Rothwell, J. C. and Marsden, C. D. (1991). Changes in the response to magnetic and electrical stimulation of the motor cortex following muscle stretch in man. *Journal of Physiology* **433**, 41-57

Dehen, H., Willer, J. C. and Cambier, J. (1976). Le reflexe H du muscle pedieux: Etude chez le sujet normal at au cours des neuropathies alcooliques latentes. *Rev Neurol. Paris* **132**, 859-868.

Delwaide, P. J. (1973). Human monosynaptic reflexes and presynaptic inhibition, an interpretation of spastic hyperreflexia. In: *Human Reflexes, Pathological of Motor System, Methodology of Human Reflexes. New Development in Electromyography and Clinical Neurophysiology*, edited by J. E. Desmedt. Karger: Basel. Vol. 3, 508-522.

Delwaide, P. J., Crenna, P. and Fleron, M. H. (1981). Cutaneous nerve stimulation and motoneuronal excitability. I: Soleus and tibialis excitability after ipsilateral and controlaterl sural nerve stimulation. *Journal of Neurology Neurosurgery Psychiatry* **44**, 699-707.

Delwaide, P. J. and Toulouse, P. (1983). The Jendrassik manoeuvre: Quantitative analysis of reflex reinforcement by remote voluntary muscle contraction. In: *Motor control mechanisms in health and disease, Advance in Neurology*, edited by J. E. Desmedt. Raven Press: New York. Vol. 39, 661-669.

Delwaide, P. J. (1984). Contribution of human reflex studies to the understanding of the pyramidal syndrome, in Shahani (ed). *Electromyography in CNS Disorders: Central EMG.* Boston, Butterworths, 77-109.

Deschuytere, J. and Rosselle, N. (1971). Electrophysiological study of discharges from spinal origin in the anterolateral muscles of the leg in normal adults. *Electromyography* 11, 331-363.

Deschuytere, J. and Rosselle, N. (1973). Diagnostic use of monosynaptic reflexes in L5 and S1 root compression. In: *Human Reflexes, Pathological of Motor System, Methodology of Human Reflexes. New Development in Electromyography and Clinical Neurophysiology*, edited by J. E. Desmedt. Karger: Basel. Vol. 3, 360-366.

Deschuytere, J. and Rosselle, N. (1974). Identification of certain EMG patterns of the spinal cord reflexive activity in man. Electrophysiological study of discharges from spinal origin in the forearm flexors in normal adults. *Electromyography Clinical Neurophysiology* 14, 497-511.

Deschuytere, J., Dekeyser, C., Deschuttere, M. and Rosselle, N. (1983). H reflexes in muscles of the lower and upper limbs in man. In: *Motor Control Mechanisms in Health and Disease, Advance in Neurology*, edited by J. E. Desmedt. Raven Press: New York. Vol. **39**, 951-960.

Desmedt, J. E. (1973). A discussion of the methodology of the triceps surae T and H reflexes. In: *Human Reflexes, Pathological of Motor System, Methodology of Human Reflexes. New Development in Electromyography and Clinical Neurophysiology*, edited by J. E. Desmedt. Karger: Basel. Vol. **3**, 773-780.

Deuschl, G., Schenck, E. and Luncking, C. H. (1985). Long latency responses in human thenar muscles mediated by fast conducting muscle and cutaneous afferents. *Neuroscience Letters* **55**, 361- 366.

Donaldson, S. K. B. and Hermansen, L. (1978). Differential, direct effects of H^+ on Ca^{+2} activated force of skinned fibres from soleus, cardiac and adductor magnus muscles of rabbits. *Pflugers Archiv* **376**, 55-65.

Duchateau, J. and Hainaut, K. (1993). Behaviour of short and long latency reflexes in fatigue human muscles. *Journal of Physiology* **471**, 787-799.

Dudel, J. (1985). Excitation of nerve and muscle. In: *Fundamentals of neurophysiology*. Edited by R. S. Schmidt, third edition. Springer-Verlag 19-68.

Eccles, R. M. The central action of antidromic impulses in motor nerve fibres. (1955). *Pfluger's Arch* **260**, 385-415.

Eccles, R. M. and Lundberg, A. (1959). Synaptic actions in motoneurones by afferents which may evoke the flexion reflex. *Archive of Italian Biology* **97**, 199-221.

Edwards, R. H. T., Hill, D. K., Jones, D. A. and Merton, P. A. (1975). Metabolic changes associated with the slowing of relaxation in fatigued mouse muscle. *Journal of Physiology* **251**, 287-301.

Edwards, R. H. T., Hill, D. K., Jones, D. A. and Merton, P. A. (1977). Fatigue of long duration in human skeletal muscle after exercise. *Journal of Physiology* **272**, 769-778.

Edwards, R. H. T, (1981). Human muscle function and fatigue. In: *Human Muscle Fatigue: Physiological Mechanisms*, edited by R. Porter and J. Whelan. London: Pitman, 1-18.

Enoka, R. M., Hutton, R.S. and Eldred, E. (1980). Changes in excitability of tendon tap and Hoffmann reflexes following voluntary

contractions. *Electroencephalography and Clinical Neurophysiology* **48**, 664-672.

Enoka, R. M. and Stuart, D. G. (1985). Henneman's 'size principle' current issues. In: *The Motor System in Neurobiology*, edited by E. V. Evarts, S. P. Wise and D. Bousfield. Elsevier Biomedical Press. 30-35.

Enoka, R. M. and Stuart, D. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology* 72(5), 1631-1648.

Erlanger, J. and Gasser, H. S. (1938). Electrical signs of nervous activity. University of Pennsylvania Press, Philadelphia.

Fabiato, A. and Fabiato, F. (1978). Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiac and skeletal muscles. *Journal of Physiology* **276**, 233-255.

Fisher, M. A. (1992). H reflexes and F waves: Physiology and clinical indications. *Muscle and Nerve* **15**, 1223-1233.

French, J. H., Clark, D. B., Butler, H. G. and Teasdall, T. F. (1961). Phenylketonuria: Some observations of reflex activity. *Journal of Pediatry* **58**, 17-22.

Fuglevand, A. J. and Enoka, R. M. (1993). Fatigue-related impairment of neural drive to muscle. In: *Neuromuscular Fatigue,* edited by A. J. Sargeant and D. Kernell, 189-194.

Garland, S. J., Garner, S. H. and McComas, A. J. (1988a). Relationship between numbers and frequencies of stimuli in human muscle fatigue. *Journal of Applied Physiology* **65** (1), 89-93.

Garland, S. J., Garner, S. H. and McComas, A. J. (1988b). Reduced voluntary electromyography activity after fatiguing stimulation of human muscle. *Journal of Physiology* **401**, 547-556.

Garland, S. J. and McComas, A. J. (1988). H- reflex inhibition following fatigue of human soleus muscle. *Physiologist* **30**, 200P.

Garland, S. J. and McComas, A. J. (1990). Reflex inhibition of human soleus muscle during fatigue. *Journal of Physiology* **429**, 17-27.

Garland, S. J. (1991). Role of small diameter afferents in reflex inhibition during human muscle fatigue. *Journal of Physiology* **435**, 547-558.

Gassel, M. M. (1963). A study of femoral nerve conduction time. *Archives Neurology. Chicago* **9**, 607-614.

Godaux, E. and Desmedt, J. E. (1975). Human masseter muscle: H and tendon reflexes. Their paradoxical potentiation by muscle vibration. *Archives Neurology*. Paris **32**, 229-234.

Gogan, P., Gueritaud, J. P., Horcholle-Bossavit, G. and Tyc-Dumont, S. (1977). Direct excitatory interactions between spinal motoneurones of the cat. *Journal of Physiology* 272, 755-767.

Gordon, J. and Ghez, C. (1994). Muscle receptors and spinal reflexes: The stretch reflex. In: *Principles of neural science.* Edited by E. R. Kandel, J. H. Schwartz and T. M. Jessell. third edition. Appleton & Lange, 564-580.

Gottlieb, G. L. and Agarwal, G. C. (1976). Extinction of the Hoffmann reflex by antidromic conduction. *Electroencephalography Clinical Neurophysiology* **41**, 19-24.

Granit, R. (1950). Reflex self-regulation of muscle contraction and autogenetic inhibition. *Journal of Neurophysiology* **13**, 351-372.

Hagbarth, K. E. (1960). Spinal withdraw reflexes in the human lower limb. *Journal of Neurology Neurosurgery Psychiatry* **23**, 222-227.

Henneman, E., Somjen, G. and Carpenter, D. O. (1965a). Excitability and inhibition of motoneurones of different sizes. *Journal of Neurophysiology* **28**, 599-620.

Henneman, E., Somjen, G. and Carpenter, D. O. (1965b). Functional significance of cell size in spinal motoneurones. *Journal of Neurophysiology* **28**, 560-580.

Hensbergen, E. and Kernell, D. (1993). Daily "endurance-demands" in cat's ankle muscles. In: *Neuromuscular Fatigue,* edited by A. J. Sargeant and D. Kernell, 184-185.

Hodes, R. and Gribetz, I. (1962a). H reflexes in normal human infants: Depression of these electrically induced reflexes (EIRs) in sleep. *Proc. Soc. exp. Biol.,* New York **110**, 577-580.

Hodes, R. and Gribetz, I. (1962b). H reflexes in normal human infants: Effects of sleep, age, and phenobarbital on these electrically induced reflexes (EIRs). *Am. J. Dis. Child* **104**, 490-491.

Hoffmann, P. (1918). Uber die beziehungen der schenreflexe zur willkurlichen bewegun zum tonus. *Z biology* **68**, 351-370.

Hoffmann, P. (1922). *Utersuchung uber die eigenreflexe (schenreflexe) menschlicher muskeln.* Spring: Berlin.

Hoffmann, P. (1934). Die physiologischen Eigenschaften der Eigenreflexe. *Ergebn. Physio* **36**, 15-108.

Hugon, M. (1973). Methodology of the Hoffmann reflex in man. In: *Human Reflexes, Pathological of Motor System, Methodology of Human Reflexes. New Development in Electromyography and Clinical Neurophysiology*, edited by J. E. Desmedt. Karger: Basel. Vol. 3, 277-293.

Hunt, C. C. (1954). Relation of function to diameter in afferent fibres of muscle nerves. *Journal of General Physiology* 38, 117-131.

Iggo, A. (1961). Non-myelinated afferent fibres from mammalian skeletal muscle. *Journal of Physiology* 155, 52-53P.

Ioku, M. (1984). Hand H reflexes demonstrated in patients with central nervous system disorders. *Electromyography Clinical Neurophysiology* 24, 331-339.

Jones, D. A. and Bigland-Ritchie, B. (1986). Electrical and contractile changes in muscle fatigue. In: *Biochemistry of exercise VI*, ed. B. Saltin. International Series on Sports Sciences, Vol 16. Champain, III., Human Kinetics Publishers. 377-392.

Johns, R. J., Grob, D. and Mackel, R. (1957). An electromyographic study of a spinal cord reflex in the normal human arm. *Bull. Johns Hopkins Hospital* 101, 232-239.

Jones, D. A. and Round, J. M. (1992). Fatigue. In: *Skeletal Muscle in Health and Disease*, edited by D. A. Jones and J. M. Round. Manchester University Press, 134-157.

Johnson, M. A., Polgar, J. Weightman, D. and Appleton, D. (1973). Data on the distribution of fibre types in thirty six human muscles an autopsy study. *Journal of the Neurological Sciences* 18, 111-129.

Katirji, M. B. and Weissman, J. D. (1988). The tibial H reflex and the ankle jerk. *Muscle and Nerve* September, 971-972P.

Kentish, J. C. (1986). The effects of inorganic phosphate and creatine phosphate on force production in skinned muscles from rat ventricle. *Journal of Physiology* 370, 585-604.

Kernell, D. and Monster, A. W. (1982a). Time course and properties of late adaptation in spinal motoneurones of the cat. *Experimental Brain Research* 46, 191-196.

Kernell, D. and Monster, A. W. (1982b). Motoneurone properties and motor fatigue: an intracellular study of gastrocnemius motoneurones of the cat. *Experimental Brain Research* 46, 197-204.

Kimura, J. (1983). F wave determination in nerve conduction studies. In: *Motor control mechanisms in health and disease, Advance in*

Neurology, Vol. 39 edited by J. E. Desmedt. Raven Press: New York, 961-975.

Kniffki, K. D., Mense, S. and Schmidt, R. F. (1978). Responses of group IV afferent units from skeletal muscle to stretch, contraction and chemical stimulation. *Experimental Brain Research* **31**, 511-522.

Kniffki, K. D., Mense, S. and Schmidt, R. F. (1981). Muscle receptors with fine afferent fibres which may evoke circulatory reflexes. *Circulation Research.* **48**, I 25-I 31.

Krnjevic, K. and Miledi, R. (1958). Failure of neuromuscular propagation in rats. *Journal of Physiology* **140**, 440-461.

Kukulaka, C. G., Moore, M. A. and Russell, A. G. (1986). Changes in human alpha motoneurone excitability during sustained maximal isometric contractions. *Neuroscience Letters* **68**, 327-333.

Kumazawa, T. and Mizumura, K. (1977). Thin-fibre receptors responding to mechanical, chemical, and thermal stimulation in the skeletal muscle of the dog. *Journal of Physiology,* **273**, 179-194.

Leksell, L. (1945). The action potential and excitatory effects of the small ventral root fibres to skeletal muscle. *Acta Physiologica Scandinavica* **10** (suppl. 31), 1-84.

Liddell, E. G. T. and Sherrington, C. (1924). Reflexes in response to stretch (myotatic reflexes). *Proc. R. Soc. Lon. [Biol]* **96**, 212-242.

Liddell, E. G. T. and Sherrington, C. (1925). Further observations on myotatic reflexes. *Proc. R. Soc. Lon. [Biol]* **96**, 267-283.

Lloyd, D. P. C. (1943). Conduction and synaptic transmission of the reflex response to stretch in spinal cats. *Journal of Neurophysiology* **6**, 317-326.

Lloyd, D. P. C. (1946). Integrative pattern of excitation and inhibition in two-neurone reflex arcs. *Journal of Neurophysiology* **9**, 421-444.

Lloyd, D. P. C. and Chang, H. T. (1948). Afferent fibres in muscle nerve. *Journal of Neurophysiology* **11**, 199-207.

Macefield, G., Gandevia, S. C. and Burke, D. (1989). Conduction velocities of muscle and cutaneous afferents in the upper and lower limbs of human subjects. *Brain* **112**, 1519-1532.

Macefield, G., Hagbarth, K. E., Gorman, R., Gandevia, S. C. and Burke, D. (1991). Decline in spindle support to alpha-motoneurones during sustained voluntary contractions. *Journal of Physiology* **440**, 497-512.

Magladery, J. W. and McDougal, D. B. (1950). Electrophysiological studies of nerve and reflexes activity in normal man: I. Identification of

certain reflexes in the electromyogram and the conduction velocity of peripheral nerve fibres. *Bull. Johns Hopkins Hospital* **86**, 265-290.

Magladery, J. W., McDougal, D. B. and Stoll, J. (1950). Electrophysiological studies of nerve and reflexes activity in normal man: II. The effects of peripheral ischaemia. *Bull. Johns Hopkins Hospital* **86**, 291-312.

Matthews, B. H. C. (1933). Nerve endings in mammalian muscle. *Journal of Physiology* **78**, 1-53.

Mayer, R. F. and Mosser, R. S. (1973). Modulation of human reflexes. In: *Human Reflexes, Pathological of Motor System, Methdology of Human Reflexes. New Development in Electromyography and Clinical Neurophysiology*, edited by J. E. Desmedt. Karger: Basel. Vol. 3, 294 307.

McComas, A. J., Sica, R. E. P. and Upton, A. R. M. (1970). Excitability of human motoneurones during effort. *Journal of Physiology* **210**, 145-146P.

Meinck, H. M. (1980). Facilitation and inhibition of the human H reflex as a function of the amplitude of the control reflex. *Electroencephalography and Clinical Neurophysiology* **48**, 203-211.

Mense, S. (1977a). Nervous outflow from skeletal muscle following chemical noxious stimulation. *Journal of Physiology* 267, 75-88.

Mense, S. (1977b). Muscular nociceptors. *Journal of Physiology. Paris* **73**, 233-240.

Mense, S. and Stahnke, M. (1983). Responses in muscle afferent fibres of slow conduction velocity to contractions and ischaemia in the cat. *Journal of Physiology* **342**, 383-397.

Mense, S. and Meyer, H. (1985). Different types of slowly conducting afferent units in cat skeletal muscle and tendon. *Journal of Physiology* **363**, 403-417.

Merton, P. A. (1954). Voluntary strength and fatigue. *Journal of Physiology* **123**, 553-564.

Mongia, S. K. (1972). H reflex from quadriceps and gastrocnemius muscle. *Electromyography Clinical Neurophysiology* **12**, 179-190.

Morin, C. Katz, R., Mazieres, L. and Pierrot-Deseilligny, E. (1982). Comparison of soleus H reflex facilitation at the onset of soleus contractions produced voluntarily and during the stance phase of human gait. *Neuroscience Letters* **33**, 47-52.

Paillard, J. (1955). *Reflexes et regulations d'origine proprioceptive chez l'homme*. Arnette: Paris.

Paintal, A. S. (1960). Functional analysis of group III afferents fibres of mammalian muscles. *Journal of Physiology* **152**, 250-270.

Person, R. S. and Kozina, G. V. (1978). Study of orthodromic and antidromic effects of nerve stimulation on single motoneurones of human hand muscles. *Electromyography Clinical Neurophysiology* **18**, 437-456.

Pierrot-Deseilligny, E. and Bussel, B. (1973). A comparison of H reflex at the onset of a voluntary movement or a polysynaptic reflex. *Brain Research* **60**, 482-484.

Pierrot-Deseilligny, E., Morin, C., Bergego, C. and Tankow, N. (1981a). Pattern of group I fibre projections from ankle flexor and extensor muscles in man. *Experimental Brain Research* **42**, 337-350.

Pierrot-Deseilligny, E., Bergego, C., Katz, R. and Morin, C. (1981b). Cutaneous depression of Ib reflex pathways to motoneurones in man. *Experimental Brain Research* **42**, 351-361.

Pinelli, P. and Valle, M. (1960). Studio fisiopatologico dei reflessi muscolari nelle paresi spastiche (sui tests per la misura della spasticita). *Arch. Sci. Med., Torino* **109**, 1-127.

Piper, H. (1912). Die Aktionsstrome menschlicher Muskeln. Die Metodik der Untersuchng am Seitengalvanometer und die Prinzipien der Stromkurvenanalyse. Typenunterchiede der Willkurkontraktion. *Z. biol. tech. Methode* **3**, 52.

Renshaw, B. (1941). Influence of discharge of motoneurones upon excitation of neighbouring motoneurones. *Journal of Neurophysiology* **4**, 167-183.

Renshaw, B. (1946). Central effects of centripetal impulses in axons of spinal ventral roots. *Journal of Neurophysiology* **9**, 190-204.

Romanes, G. J. (1986). *Cuningham's Text book of anatomy*. Edited by G. J. Romanes, fifteenth edition. Oxford University Press.

Rowland, L. P. (1994). Diseases of motor unit. In: *Principles of neural science*. Edited by E. R. Kandel, J. H. Schwartz and T. M. Jessel. Third edition. Appleton & Lange, 244-257.

Sargeant, A. J. and Kernell, D. (1993). Discussion. In: *Neuromuscular Fatigue,* edited by A. J. Sargeant and D. Kernell, 189-194.

Schmidt, R. F. (1985). The structure of the nervous system. In: *Fundamentals of neurophysiology*. Third edition, Edited by R. S. Schmidt. Springer-Verlag 1-18.

Schmidt, R. F. (1985). The physiology of small groups of neurones, reflexes. In: *Fundamentals of neurophysiology*. Third edition, Edited by R. S. Schmidt. Springer-Verlag 103-125.

Shefner, J. and Logigian, E. L. (1994). Conduction velocity in motor, cutaneous afferent, and muscle afferent fibres within the same mixed nerve. *Muscle and Nerve* 17, 773-778.

Sherrington, C. S. (1947). The integrative action of the nervous system, second edition. New Haven: Yale University Press.

Shieppati, M. and Crenna, P. (1984). From activity to rest: gating of excitatory autogenetic afferents from the relaxing muscle in man. *Experimental Brain Research* 59, 448-457.

Schieppati, M. and Crenna, P. (1985). Excitability of reciprocal and recurrent inhibitory pathways after voluntary muscle relaxation in man. *Experimental Brain Research* 59, 249-256.

Shieppati, M. (1987). The Hoffmann reflex: a means of assessing spinal reflex excitability and its descending control in man. *Progress in Neurobiology* 28, 345-375.

Stanley, E. F. (1978). Reflexes evoked in human thenar muscles during voluntary activity and their conduction pathways. *Journal of Neurology Neurosurgery Psychiatry* 41, 1016-1023.

Staubesand. J. (1990). *Sobotta Atlas of human anatomy.* Edited by J. Staubesand, eleventh edition. Urban & Schwarzenberg. Baltimore-Munich.

Stephens, J. A. and Taylor, A. (1972). Fatigue of maintained voluntary muscle contraction in man. *Journal of Physiology* **220**, 1-18.

Taborikova, H. and Sax, D. S. (1968). Motoneurone pool and H reflex. *Journal of Neurology, Neurosurgery and Psychiatry* **31**, 354-361.

Tanaka, R. (1980). Inhibitory mechanism in reciprocal innervation in voluntary movements. In: *Spinal and Supraspinal Mechanisms of Voluntary Motor Control and Locomotion. Progress in Clinical Neurophysiology,* edited by J. E. Desmedt. Karger: Basel. Vol. 8, 117-128.

Thomas, J. E. and Lambert, E. H. (1960). Ulnar nerve conduction velocity and H reflex in infants and children. *Journal of Applied Physiology* **15**, 1-19.

Thomas, C. K., Woods, J. J. and Bigland-Ritchie, B. (1989). Impulse propagation and muscle activation in long maximal voluntary contractions. *Journal of Applied Physiology* **67**, 1835-1842.

Upton, A. R. M., McComas, A. J. and Sica, R. E. P. (1971). Potentiation of 'late' responses evoked in muscles during effort. *Journal of Neurology Neurosurgery Psychiatry* **34**, 699-711.

Verier, M. C. (1985). Alterations in H reflex magnitude by baseline EMG excitability. *Electroencephalography and Clinical Neurophysiology* **60**, 492-499.

Weintraub, J. R., Madalin, K., Wong, M., Wilbourn, A. J. and Mahdad, M. (1988). Achilles tendon reflex and the H response: Their correlation in 400 limbs. *Muscle and Nerve* September, 972P.

Westerblad, H., Lee, J. A., Lannergren, J. and Allen, D. G. (1991). Cellular mechanisms of fatigue in skeletal muscle. *American Journal of Physiology* **261**, 125-136.

Willer, J. C. (1975). Etude de la vitesse de conduction des fibres sensitives Ia chez l'homme normal par la methode du reflex H. *Electroencephalography Clinical Neurophysiology* **38**, 329-330.

Willer, J. C. and Dehen, H. (1977). Le reflexe H du muscle pedieux. Etude au cours des neuropathies alcooliques latentes. *Electroencephalography Clinical Neurophysiology* **42**, 205-212.

Woods, J. J., Furbush, F. and Bigland-Ritchie, B. (1987). Evidence for a fatigued-induced reflex inhibition of motoneurone firing rates. *Journal of Neurophysiology* **58**, 125-137.

Zytnicki, D., Lafleur, J., Horcholle-Bossavit, G., Lamy, F. and Jami, L. (1990). Reduction of Ib autogenetic inhibition in motoneurones during contractions of an ankle extensor muscle in the cat. *Journal of Neurophysiology* **64**, 1380-1389.