Pain and fatigue after concentric and eccentric muscle contractions

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Summary

1. Normal subjects performed a step test in which the quadriceps of one leg contracted concentrically while the contralateral muscle contracted eccentrically.

2. Maximal voluntary force and the force:frequency relationship were altered bilaterally as a result of the exercise, the changes being greater in the muscle which had contracted eccentrically. Recovery occurred over 24 h.

3. Electromyographic studies using three sites on each muscle showed an increase in electrical activation during the exercise only in the muscle which was contracting eccentrically. Recovery followed a time course similar to that of the contractile properties.

4. Pain and tenderness developed only in the muscle which had contracted eccentrically. Pain was first noted approximately 8 h after exercise and was maximal at approximately 48 h after exercise, at which time force generation and electrical activation had returned to pre-exercise values.

5. Eccentric contractions cause more profound changes in some aspects of muscle function than concentric contractions. These changes cannot be explained in simple metabolic terms, and it is suggested that they are the result of mechanical trauma caused by the high tension generated in relatively few active fibres during eccentric contractions.

Key words: eccentric contractions, low-frequency fatigue, muscle pain.

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Abbreviations: EMG, electromyograph; IEMG, integrated electromyograph.

Introduction

Muscle pain occurring 24–48 h after unaccustomed exercise is a phenomenon familiar to most individuals, but the mechanisms responsible for its production are uncertain. Asmussen [1] first indicated that eccentric contractions (those in which the muscle is lengthened during contraction) are particularly associated with pain and soreness. In the intervening period many workers have found this to be an interesting model as it is well established that both the metabolic cost [2–5] and the electrical activity required to produce a given tension [6–9] are less under eccentric conditions than concentric. Komi [10], however, reported the relationship between the integrated electromyograph (IEMG) and percentage of maximum force to be similar whichever type of contraction was used. The fact remains that eccentric rather than concentric contractions predispose to delayed onset, post-exercise pain that is not accounted for in terms of metabolism.

The 'torn tissue' hypothesis of Hough [11] suggested that pain resulted from structural damage in the muscle; de Vries [12] proposed tonic spasms in localized motor units and both Komi [13] and Asmussen [1] put forward overstretching of the connective tissue elements as the cause of pain.

Repetitive, fatiguing isometric and dynamic contractions have been shown to produce specific, long-lasting alterations in contractile properties of muscle such that the force:frequency curve is shifted to the right and electrical

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stimulation at low frequency (1–20 Hz) results in decreased force generation when compared with the fresh muscle, but the force generated by high-frequency stimulation is relatively preserved [14]. This type of fatigue, termed 'low-frequency fatigue', has been demonstrated in the quadriceps, adductor pollicis, diaphragm [15] and sternomastoid [16]. Although the underlying mechanism is not clear, it was assumed that the amount of low-frequency fatigue produced in a muscle was related to the work done by that muscle. Recent work [17] has revealed that eccentric contractions caused greater low-frequency fatigue than concentric.

In this study, normal subjects have performed a step test in which the quadriceps muscle of one leg worked concentrically and the contralateral muscle worked eccentrically. The effects of these two types of contraction on the IEMG, voluntary force and contractile properties of the muscle have been investigated. The degree and distribution of tenderness over the surface of the muscle has been measured [18] in an attempt to define the painful tissue.

Methods

Subjects

Four healthy, normal subjects performed the experiments, three males and one female, the age range being 31–45 years (mean 36·25 years).

Step test

Subjects performed a step test for 15 or 20 min, using a 46 cm step. The stepping pattern was designed so that the quadriceps of one leg contracted concentrically (stepping up) throughout the test, while the contralateral muscle contracted eccentrically (stepping down). A rate of 15 cycles/min was used and an electronic metronome provided audible timing clicks, so that each stepping phase lasted 1 s. During the exercise period a total height of 103·5 m was ascended. Subjects were encouraged to fully control each eccentric contraction and as far as possible to maintain a constant stepping rate.

Force measurements

The force produced by electrically stimulated and maximal voluntary isometric contractions was measured by using previously described techniques [19].

The force:frequency characteristics of the muscle were monitored by percutaneous stimulation at 1 Hz (for 5 s) and 10, 20, 50 and 100 Hz (for 2 s) by using square wave pulses of 50 μs.

Maximal voluntary force measurements and electrical stimulation of the quadriceps muscles of both legs were carried out before exercise, then 2, 10 and 30 min and 1, 5, 24 and 48 h after exercise.

Electromyography

Areas over rectus femoris, vasti medialis and lateralis on each leg were prepared by abrasion and alcohol swabs to lower the skin resistance to less than 5 kohm. These areas were marked so that identical sites would be used on subsequent testing. Silver/silver chloride cup electrodes were filled with electrode jelly and taped in place. Unipolar recordings were made from these sites and amplified with reference to an electrode placed over the lower lumbar spine in the midline. Signals were amplified (S.E. Labs, type 4901) and band pass filtered between 0·2 Hz and 10 kHz, and displayed on a u.v. oscillograph and recorded on light-sensitive paper. The six raw signals were integrated over 300 ms periods and similarly displayed. Recordings were made from these sites at intervals during stepping.

In order to investigate any changes in activation patterns as a result of the exercise, electrical activity of the three muscles on each leg was recorded during active, submaximal contractions during knee extension from 90° to full extension, which was held for 2 s, with a 3 kg weight attached to the foot. These recordings were made before and at intervals after exercise.

To study the relationship between muscular activity and joint angle during stepping and the submaximal knee extension tests, electronic goniometers were used. A rotary potentiometer with a linear response was mounted as the pivot between two long Perspex arms. The goniometers were placed laterally on each leg with the potentiometer sited over the fulcrum of the knee joint and the Perspex arms taped in place along the femur and fibula. A signal, proportional to the knee angle, was displayed on the u.v. oscilloscope with the EMG and simultaneously recorded. Rate of knee extension was kept as constant as possible during the test by displaying to the subject a signal proportional to angular velocity.

Measurement of severity and distribution of muscle tenderness

A polythene sheet marked with a grid of intercepts 2 cm apart, to be used as test sites, was wrapped around the thigh, the skin of which was marked to ensure constant positioning in subsequent tests. A round-ended, wooden probe (2 cm diameter) was attached to a strain gauge and the amplified force signal was displayed on a u.v. oscillograph. At each test site, a gradually increasing force was applied up to a maximum of 40 N. The subject was asked to indicate verbally when the sensation of pressure changed to one of discomfort, whereupon the probe was immediately withdrawn. If no indication was given at a deflection on the oscillograph proportional to 40 N, tenderness was considered not to be present at that site. Each site was tested in a defined order, enabling a record to be made of the degree of tenderness over the whole surface of the muscle. From these records maps were drawn showing the degree and distribution of muscle tenderness. Although the accuracy of localization by muscle nociceptors is not well defined, the fact that the receptive areas of mechanical nociceptors are spot-like [20] and also that subjects are well able to localize the sites of contusions and needle biopsies in muscle suggests that the degree of localization is adequate to indicate the sites of muscle trauma.

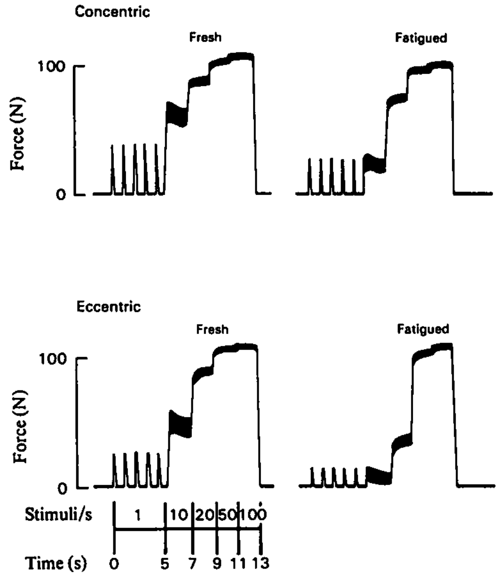

FIG. 1. Force generation in response to electrical stimulation at 1, 10, 20, 50 and 100 Hz in the quadriceps before and 10 min after a 20 min period of stepping in which one muscle contracted concentrically and the other eccentrically. Female subject, 32 years.

Results

No significant difference was found between the 15 and 20 min exercise periods, therefore the following are combined results of both periods.

Force changes

(a) Maximal voluntary force. Maximal voluntary force was reduced in both legs after exercise, the reduction being significant only in the muscle which had contracted eccentrically when pre-exercise values were compared with those at 2 and 10 min after exercise ($P < 0{\cdot}001$). Force did not recover to pre-exercise values until 24 h after exercise.

(b) Stimulated forces. As an index of low-frequency fatigue, we have used the ratio of the forces produced by a low stimulation frequency (10 Hz) to the force produced by a high stimulation frequency (50 Hz), expressed as a percentage (T10/50%).

A significant decrease in T10/50% was found in the quadriceps of both legs ($P < 0{\cdot}001$); the fall was more marked in the muscle which had contracted eccentrically in the exercise period (Fig. 1). The difference of the T10/50% between the two muscles was significant at 2 min ($P < 0{\cdot}02 > 0{\cdot}01$) 10 min ($P < 0{\cdot}025 > 0{\cdot}002$) after exercise and most highly significant 1 h after exercise ($P < 0{\cdot}001$) as the muscle which had contracted concentrically began to recover. Twenty-four hours after exercise there was no significant difference between the two muscles, although when compared with the pre-exercise values, the T10/50% had not fully recovered (Fig. 2).

Electromyography

In both of the two subjects studied no significant increase was seen in the IEMG of the concentrically contracting muscle during the stepping period. In contrast, a progressive increase in the IEMG of all sites monitored was found in the eccentrically contracting muscle throughout the exercise period (Fig. 3).

Similar changes in electrical activation were seen during the submaximal knee extension test when pre- and post-exercise data were compared (Fig. 4); only the muscles which had contracted eccentrically showed increased electrical activation for the generation of a given muscular tension.

There was no significant change in the ratio of the contributions of the three muscle components to that of the total measured quadriceps activity,

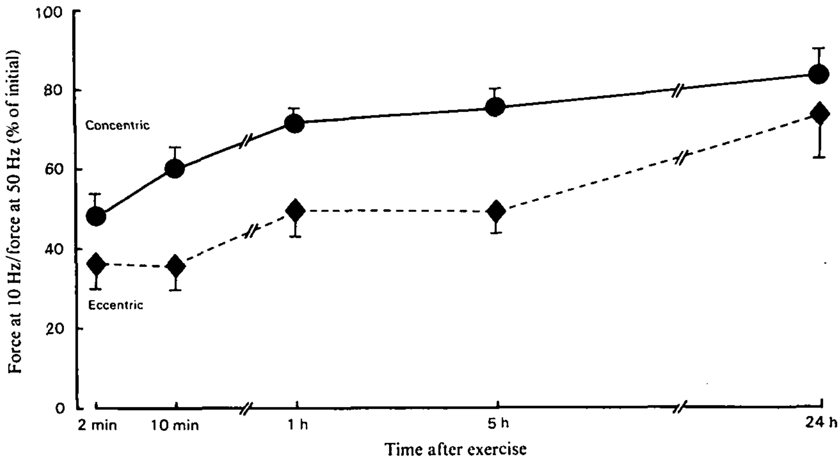

FIG. 2. Changes in the relationship between force generated by 10 and 50 Hz stimulation (expressed as a percentage of pre-exercise values) after 15 or 20 min stepping. Mean values ± SEM are shown for seven subjects.

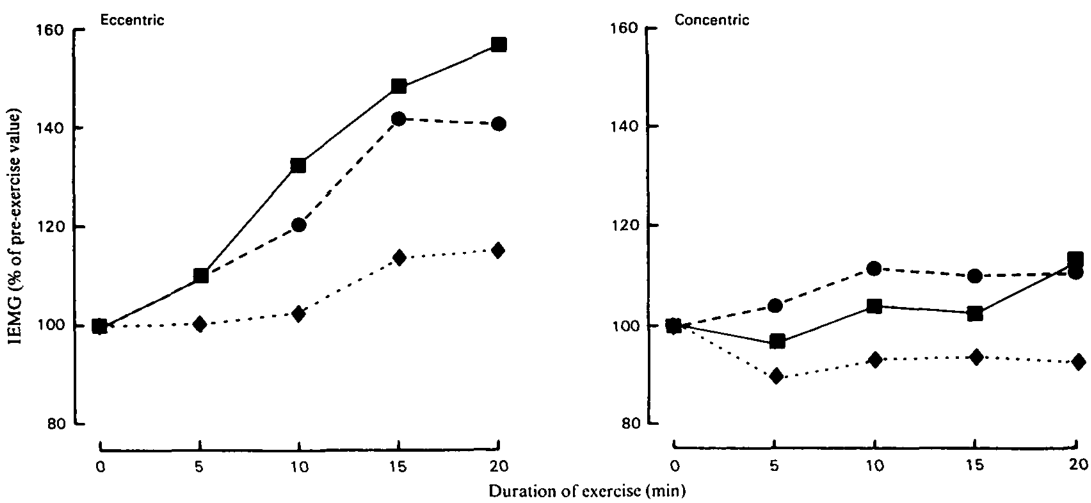

FIG. 3. Integrated electromyogram (IEMG) from three sites of both quadriceps recorded at 5 min intervals during a 20 min period of stepping. Each point is the mean of three consecutive concentric or eccentric contractions and is expressed as a percentage of the pre-exercise value. ■, Rectus femoris; ●, vastus medialis; ♦, vastus lateralis. Male subject, 45 years.

in either leg, during stepping, in the immediate post-exercise phase or during the period when the leg was painful. The simultaneous recording of joint angle and IEMG during stepping (Fig. 5) in the concentrically contracting muscle showed that the main peak of electrical activity occurs during the stepping up phase, with a smaller burst as the opposite muscle lowered the body weight to the ground, to be supported by the former.

The eccentrically contracting muscle showed two peaks in each cycle which were approximately similar in amplitude to each other, and shorter in duration than the main peak in the concentrically contracting muscle. One peak occurred during the eccentric contraction itself, and the other at the time when the same leg was taking part of the body weight after the opposite leg had raised the body up on the step.

The submaximal extension test showed an increase in IEMG at all knee-joint angles be-

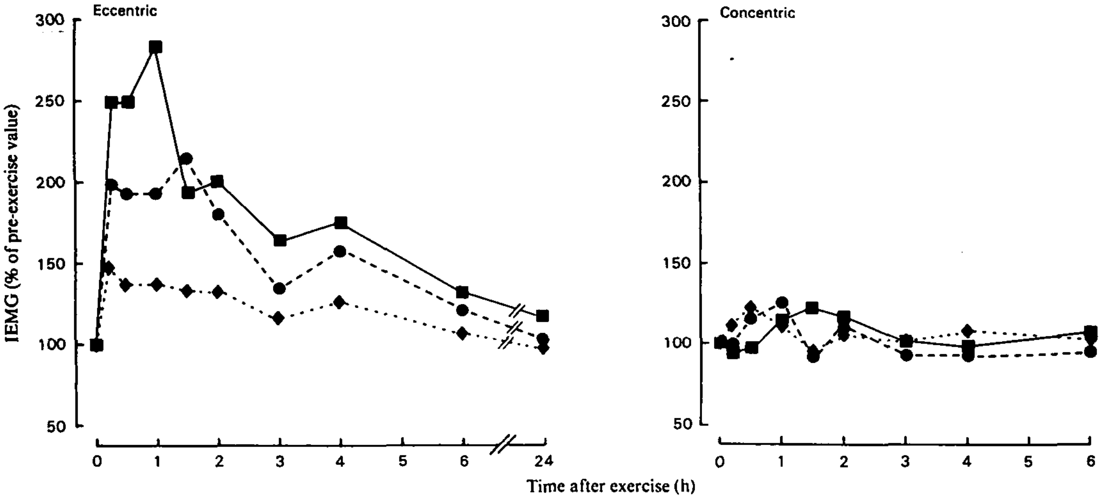

FIG. 4. Integrated electromyograph (IEMG) from three sites of both quadriceps during a submaximal knee extension held for 2 s, after a 20 min period of stepping. Each value is expressed as a percentage of the pre-exercise value. See Fig. 3 for explanation of symbols. Male subject, 45 years.

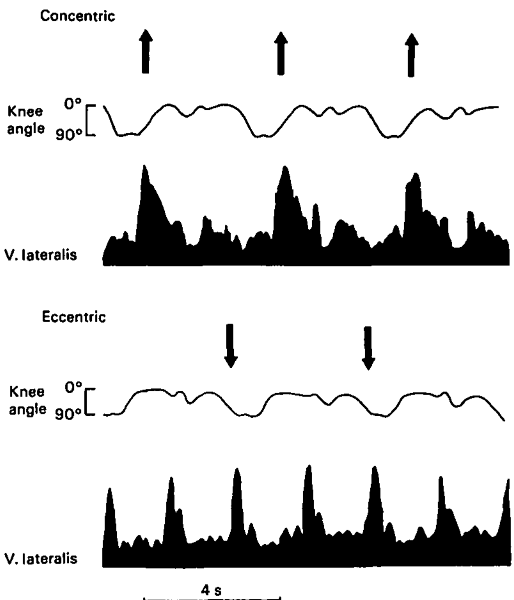

FIG. 5. Simultaneously recorded knee angles and IEMG from vastus lateralis of both legs during stepping.

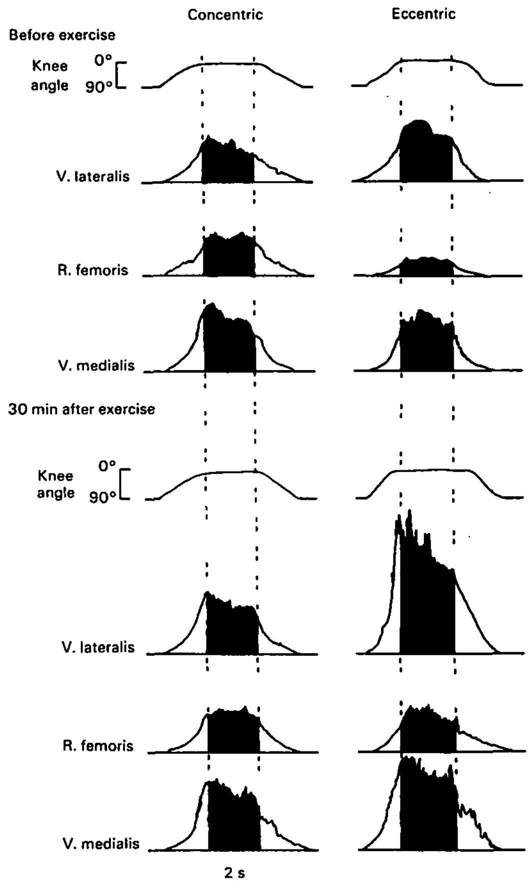

FIG. 6. Integrated EMG from three sites on both quadriceps during knee extension before and 30 min after stepping. Male subject, 45 years.

tween 0 and 90°, in addition to the amount of electrical excitation required to maintain full extension over a 2 s period (Fig. 6).

At no time throughout the testing period was there evidence of spontaneous electrical activity when the muscle was at rest.

Muscle pain and tenderness

Subjective pain was reported by all subjects in

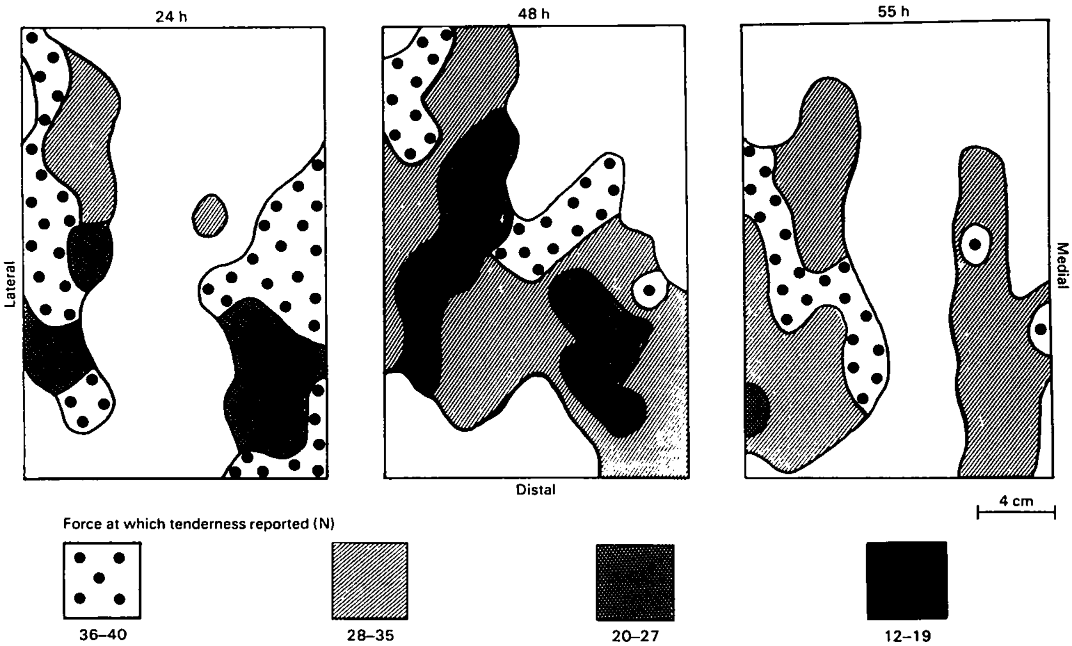

FIG. 7. Distribution and severity of tenderness 24, 48 and 55 h after eccentric contractions in the right quadriceps. Female subject, 32 years.

the quadriceps muscle which had contracted eccentrically in the step test. No pain was noticed in the quadriceps of the opposite leg, although two subjects reported pain in the calf muscles of that leg. The pain was first apparent approximately 8–10 h after exercise and reached maximal intensity between 24 and 48 h after exercise in different subjects. It was also found to be uncomfortable to descend stairs and especially to contract the muscle isometrically in a fully shortened position, although isometric contraction in the mid-length position was less painful.

Strain gauge measurements showed that initially tenderness was primarily located at the distal, medial and lateral parts of the quadriceps and along its lateral margin, with relative sparing of the central and proximal medial regions. At peak intensity the tenderness was more diffuse, but reflected the same pattern. As tenderness diminished a more clear regional localization was again seen as in the early stages of pain (Fig. 7). Both soreness and tenderness had disappeared in all subjects by the fourth day after exercise.

All subjects experienced a feeling of weakness and instability in the immediate post-exercise period only in the muscle which had contracted eccentrically. This sensation was noted at the end of exercise and lasted for approximately 2 h. It was particularly noticeable on performing eccentric contractions, i.e. descending stairs.

Discussion

Despite the relatively low energy cost of eccentric contractions, they are capable of causing more profound changes in some aspects of muscle function, especially the force:frequency curve, than concentric contractions, which clearly cannot be explained in simple metabolic terms.

The fact that greater tension per muscle fibre is generated under eccentric contraction conditions [21, 22] provides a situation where relatively few fibres are recruited and are producing relatively large forces. In this situation the uneven mechanical stresses produced in the muscle and its attachments can be imagined to predispose to physical damage as with the weakest link in a chain.

Mechanical damage to the sarcoplasmic reticulum resulting in less calcium release for each excitatory action potential has been suggested as the cause of low-frequency fatigue [23], and if this is the case it is consistent with our results.

Komi & Rusko [24] reported that with isokinetic exercise at the forearm flexors eccentric contractions cause a greater reduction in maximal voluntary force than concentric contractions, and in contrast to our findings found similar IEMG changes with both types of contraction. They concluded that the differences in force changes were due to extreme mechanical loading of the elastic components during eccentric contractions. This mechanical stress and trauma may well be the explanation of the reduction in maximal voluntary force, increase in electrical activation for a given muscle tension and profound low-frequency fatigue, changes which were all more marked in the muscle which had contracted eccentrically.

The distribution of tenderness revealed that the muscle bellies are relatively spared, and the areas of musculo-tendinous attachment are the main sites of pain and tenderness. These findings are in agreement with the conclusions of Asmussen that the cause of pain is due to over-stretching of elastic non-contractile tissues, which was supported by Abraham [25], who reported rises in hydroxyproline: creatinine ratios at peak muscle soreness with no changes as a result of concentric contractions. The same author was able to correlate myoglobin release with exercise intensity, but not with soreness, and this argues against the theory that the muscle itself is not the sole tissue responsible for this type of muscle pain.

In agreement with other workers we were not able to detect any evidence of localized muscle spasm during pain as reported by de Vries. The relative contribution of rectus femoris, the medial and lateral vasti to the total measured electrical activity of the muscle did not significantly alter during either short-term fatigue or delayed onset pain, thus providing no evidence of changes in recruitment patterns with fatigue or inhibition of painful areas.

An interesting, but poorly defined, phenomenon is the feeling of weakness and instability experienced for a few hours immediately after exercise only in the muscle which had contracted eccentrically. Further work (unpublished) has indicated that this sensation is an indication of pain to follow, and is presumably a reflection of profound low-frequency fatigue with inappropriate forces being generated by the relatively low normal physiological firing frequency [26, 27].

In conclusion, eccentric muscle contractions have marked effects, initially on the contractile properties and force generating capabilities of muscle, and result in pain of delayed onset. These findings are accountable for in terms of the high forces generated by relatively few muscle fibres and the transmission of these uneven forces to the non-contractile tissues with resultant mechanical damage, and are not related to the metabolic energy cost of the contractions. The different time courses of these phenomena may reflect an inflammatory process in the musculo-tendinous areas and/or the different turnover rate of the two tissues.

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