Eur J Appl Physiol (1995) 70: 13–19

ORIGINAL ARTICLE

Albert G. Crenshaw · Stefan Karlsson · Jorma Styf
Tomas Bäcklund · Jan Fridén

Knee extension torque and intramuscular pressure of the vastus lateralis muscle during eccentric and concentric activities

Accepted: 25 July 1994

Abstract The objectives of this study were to determine whether the occurrence of delayed onset muscle soreness (DOMS) for the vastus lateralis muscle was associated with elevated intramuscular pressure (IMP); and to assess, whether high eccentric forces occurred at an increased muscle length (as determined by joint angle). Therefore, peak knee extension torque, peak IMP of the vastus lateralis muscle, and the joint angle at which peak torque (JAPT) occurred were determined in eight male subjects during repetitive eccentric and concentric activities until fatigue occurred. Peak torque was significantly higher for eccentric compared to concentric activity ($P < 0.01$) and declined significantly for both activities ($P < 0.01$) throughout the protocols. When comparing the start (prior to fatigue) to the end (fatigue state), mean torque for eccentric activity declined from 191 to 147 (N·m) and for concentric activity declined from 166 to 104 (N·m). In contrast, peak IMP was not significantly different between the types of activity and did not change significantly with time. At the start and the end, the mean IMP remained constant for eccentric activity at 54 mmHg (7.2 kPa) but for concentric activity was 78 mmHg (10.4 kPa) and 96 mmHg (12.8 kPa), respectively. All the subjects, however, experienced DOMS of the vastus lateralis muscle exclusively for the eccentric activity leg. The JAPT was not different between activity types and did not change significantly with time; however, a significant interaction between activity type and time was observed ($P = 0.01$). For eccentric activity JAPT (0° = fully extended leg) was 81° (1.38 rad) and 79° (1.34 rad) and for concentric activity was 76° (1.29 rad) and 83° (1.41 rad) at the start and the end, respectively. From our studies we concluded that during eccentric activity the magnitude of IMP for the vastus lateralis muscle did not reflect the high muscles forces; therefore it would appear that IMP was not an etiologic indicator of DOMS, and that JAPT measurements did not offer an explanation for the high forces which were associated with eccentric activity.

Key words Delayed onset muscle soreness
Isokinetic activity · Joint angle · Knee joint extension
Fatigue

A.G. Crenshaw (✉)
Department of Anatomy, Umeå University, S-90187 Umeå, Sweden

S. Karlsson · T. Bäcklund
Department of Biomedical Engineering, Umeå University, S-90187 Umeå, Sweden

J. Friden
Department of Hand Surgery, Umeå University, S-90187 Umeå, Sweden

J. Styf
East Hospital, Department of Orthopaedics, Gothenburg, Sweden

Introduction

The occurrence of delayed onset muscle soreness (DOMS) 24 to 48 h after unaccustomed exercise has been the focus of an abundance of experimental studies (for reviews, see Ebbeling and Clarkson 1989; Smith 1991). Although the exact mechanism remains unknown, it has now been well established that the pain is most prevalent following exercise that entails a large component of eccentric muscle activity. It has also predominantly been accepted that structural muscle damage caused by high tension associated with eccentric activity leads to these symptoms (Fridén et al. 1983; Newham et al. 1983). The explanations as to why these high tensions occur and the magnitudes reached for individual muscles in humans are also poorly understood. Dynamic torque measurements over a joint are often used as estimators of the muscle contraction force. In most cases, several muscles contribute to torque development and, therefore, this parameter may not be suitable for determining contraction force for specific muscles.

Intermuscular pressure (IMP), the fluid pressure created by a muscle during contraction, has been shown to correlate linearly with the force of contraction during isometric (Sadamoto et al. 1983; Sejersted et al. 1984; Sjøgaard et al. 1986) and isokinetic exercise (Aratow et al. 1993). In the latter study, IMP was correlated with ankle joint torque ranging from zero to maximum for a single concentric action and for a single eccentric action; however, IMP comparisons between actions were not performed. At present, only one study has assessed IMP differences between eccentric and concentric exercise. Fridén et al. (1986) have found a higher mean IMP for eccentric activity of the tibialis anterior muscle (compared to concentric); subsequently, DOMS was found to occur following eccentric activity. It has therefore been implied that IMP is a reflection of the high muscle tensions responsible for DOMS for this lower leg muscle. Whether this relationship holds true for other muscles, especially those in which DOMS more commonly occurs (e.g. vastus lateralis), is not known.

During eccentric activity the muscle is first activated and then passively stretched to a desired length. This passive stretching has been believed to add to the tension already created by activation (Stauber 1989). Therefore, it is suggested that not only would peak eccentric force be greater but would also occur at a longer muscle length than for peak concentric force. For dynamometric studies, joint angle has often been inferred as a reflection of muscle length (Hortobágyi and Katch 1990). The joint angle at peak torque during a protocol that generates DOMS has not been investigated. An understanding of this relationship might provide an insight into the mechanism of the tension generated during eccentric activity and to subsequent soreness symptoms.

The purpose of this study was to assess whether high force eccentric activity was associated with an elevation in IMP and subsequent DOMS for the vastus lateralis muscle. Therefore, we determined the magnitudes of IMP for the vastus lateralis muscle and knee joint torque throughout repetitive eccentric and concentric activities. An additional objective was to determine the joint angle at which peak torque (JAPT) occurred throughout our eccentric and concentric protocols.

Methods

System validation tests

A five-channel chart recorder (Mingograf 7, Siemens-Elema, Solna, Sweden) equipped with a disposable fluid-filled transducer (Sorenson, Transpec II, Abbott Laboratories, North Chicago, Ill., USA) was used to measure intramuscular pressures and a computerized dynamometer (Biodex Corporation, Shirley N.Y., USA) was used to measure and report torque and joint position values. Signals from the dynamometer and chart recorder were first directed through a low-pass 10-Hz anti-aliasing filter and then acquired by a data acquisition (DA) processor (DAP 800/2, Microstar Laboratories, Bellevue, Wash., USA). The DA processor was equipped with a microprocessor and connected in parallel with a host personal computer (PC) which was used for real time data display. The data were buffered before logging to the PC which allowed the PC to momentarily perform other functions. The processor contained an eight-channel 16-bit analogue to-digital converter. One channel each was assigned to pressure, torque, and joint position and the sampling frequency was 20 Hz for all parameters. Data were initially acquired and logged as arbitrary units in ASCII format, but could also be displayed with DAP view software (Microstar Laboratories) graphically in real time and with appropriate units on the host PC. Therefore, the data were simultaneously acquired in real time and stored for manipulation or downloading for graphical or statistical analyses.

To determine accuracy and linearity of the DA, pressures between 0 and 140 mm Hg (0 and 18.7 kPa) were applied with a fluid column and a torque of 30 (N · m) was applied by attaching a weight to the arm of the dynamometer. All values were accurately displayed on the chart recorder and the dynamometer. A linear regression analysis incorporating changes in fluid pressure compared to changes in the units of the DA was performed. These calibration procedures allowed conversion of the arbitrary units within the DA to millimetres of mercury (kilopascals) for pressure and to newton metres for torque.

To test for drift by the DA system with time for pressure and for torque at three time periods, (1) zero pressure and torque were applied for 1 min, (2) 60 mm Hg (8.0 kPa) and 30 (N · m), respectively, were applied for 3 min, and (3) zero values were again applied for 1 min. Pressure and torque calibrations were applied simultaneously. The DA sampled continuously at 20 Hz and the variability for each time period was expressed as drift in actual units [millimetres of mercury (kilopascals) for pressure and newton metres for torque].

The linearity of the DA response to torque changes was determined by measuring a series of isometric contractions of one of the investigators. After being secured in the dynamometer and while the knee was at 90 ° (1.53 rad) of flexion, the subject performed a maximal voluntary contraction (100%) for knee extension. This was followed by 75%, 50%, and 25% of the maximal value. The subject could easily determine these levels by viewing the video monitor. A linear regression analysis incorporating changes in the torque measured by the dynamometer and the signals recorded by the DA was performed.

Joint angle linearity was tested between 0 ° (0 rad, full knee extension) and 120 ° (2.04 rad) of knee flexion. A linear regression analysis was performed and correlation coefficients were determined.

Experimental design

Subjects

Eight healthy males subjects (age 21–40 years) who were moderately active participated in the study. The subjects ranged in height from 175 to 184 cm and in body mass from 67 to 85 kg. The study was approved by the Ethics Committee of Umeå University and was performed after each subject signed informed consent.

Intramuscular pressures

After instilling local anaesthesia superficial to the fascia, catheters were inserted into the vastus lateralis muscle while the knee was fully extended. The insertion site was 15-cm proximal to the lateral femoral condyle. The catheter was directed at an angle of 20 ° (0.34 rad) to the skin toward the patella parallel to the direction of the fibres. The catheter tip was inserted to a depth of 40 mm from the skin. The catheter was connected to a microcapillary infusion system set at a rate of 1.5 ml $\cdot$ h^{-1}. Further details of catheter insertion and use of this system have been described in a previous study (Styf and Körner 1986). All catheter insertions were performed by the same person using the same orientation to minimize placement errors. Catheter position and patency were confirmed first by palpation and then by each subject performing a maximal isometric contraction for knee extension with the knee joint at 90° (1.53 rad) of flexion. During contraction, peak IMP and torque values were recorded and the mean was determined (n = 8) as an expression of overall group strength.

Exercise protocol

Following catheter insertion, each subject performed repetitive eccentric activity (forced lengthening of a muscle that is contracted) for knee extension in one leg on one occasion and concentric activity (active contraction resulting in the shortening of a muscle) in the other leg on another occasion.The activities were performed at least 1 week apart. Right and left legs and the order of activities were randomly chosen for each subject. This resulted in five of the eight subjects performing eccentric activity with their dominant leg. Torque, joint position and IMP were recorded and displayed simultaneously by the data acquisition system at a sampling rate of 20 Hz. Figure 1 shows the experimental setup and the flow of data signals. Eccentric actions consisted of the subjects trying forcefully to maintain extension throughout the full range of motion while the dynamometer was motor driven from 30° (0.51 rad) to 120° (2.04 rad) and then relaxing while the leg was returned to 30° (0.51 rad). Concentric actions consisted of forcefully extending the leg from 120° (2.04 rad) to 30° (0.51 rad) and then relaxing while the dynamometer was motor driven to return to 120° (2.04 rad). Our initial choice for this range of motion was based on studies that have indicated that soreness symptoms (or damage) are enhanced if contractions begin when the muscle is under some tension and the contractions are maintained for an extended range of motion (Newham et al. 1988; Fridén and Lieber 1992). We thereby confirmed the generation of soreness symptoms in a pilot study. The dynamometer was set so that an equal velocity [60° (1.02 rad) $\cdot$ s^{-1}] was used for both activities. Therefore, each contraction lasted for 1.5 s. The subjects were encouraged to perform maximal contractions until they were fatigued or were unable to continue due to discomfort of pain. Fatigue was determined at the discretion of the subjects as the point when they were unable to continue. Due to problems with catheter kinking, data from two subjects during eccentric activity and from one subject during concentric activity were discarded.

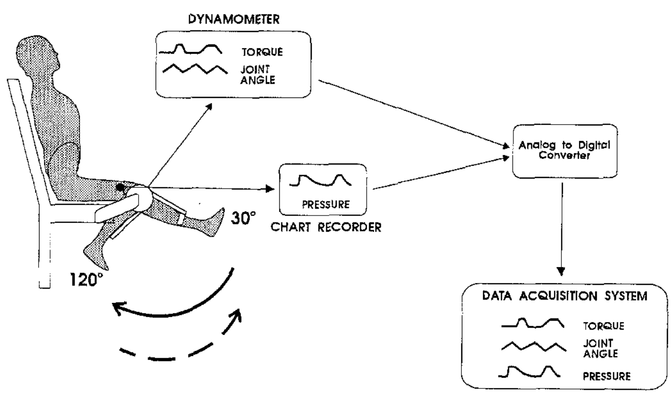

Fig. 1 Diagram showing the experimental setup and the flow of signals to the data acquisition system. Eccentric activity of the vastus lateralis muscle was performed from 30° (0.51 rad) to 120° (2.04 rad) (*solid line arrow direction*) and concentric activity was performed form 120° (2.04 rad) to 30° (0.51 rad) (*dashed line arrow direction*). Velocity for both activities was 60° (1.02 rad) $\cdot$ s^{-1}. The reference angle was 0° (0 rad) with the leg fully extended. The subjects were seated in the exercise device with a 110° (1.87 rad) angle between the alignment of the spine and the femur to minimize resistance by antagonistic muscles when extended ranges of motion were reached

Data selection and processing

The data were extracted from the DA system, converted to appropriate units, and for each contraction an algorithm was used to identify peak torque and its associated joint angle for each subject. Figure 2 shows a portion of one subject's original exercise tracings. The enlarged tracing demonstrates how the joint angle was selected. Peak IMP for each contraction was also identified and was selected independent of peak torque. To illustrate the relationship between IMP and torque, the coefficient of millimetres of mercury per newton metres was calculated.

In addition, subjective soreness ratings (0 = no pain, 10 = severe pain) based on self-palpation were determined for each subject.

Statistical analyses

The total activity time to fatigue averaged 16 min for eccentric (6–28 min) and 12 min for concentric activity (3–25 min). Due to these differences in the total activity time among subjects, and to normalize them, the total time for each subject was divided into ten equal periods. The means for each period for each subject were determined. When presented graphically, the start represented the first 10% and the end represented the last 10%. This procedure allowed us to combine subjects for mean determinations at a common relative time point. A repeated measures analysis of variance (ANOVA) using Statview (1992) statistical programs (Abacus Concepts, Inc., Barkeley, Calif.) was used to determine differences due to activity type (eccentric compared to concentric) and to test changes in time. When the ANOVA proved significant, a post-hoc Fisher's protected least significant difference with multiple student's t-test was used to compare data points during activities to their respective start vales. Significance was set at $P < 0.05$.

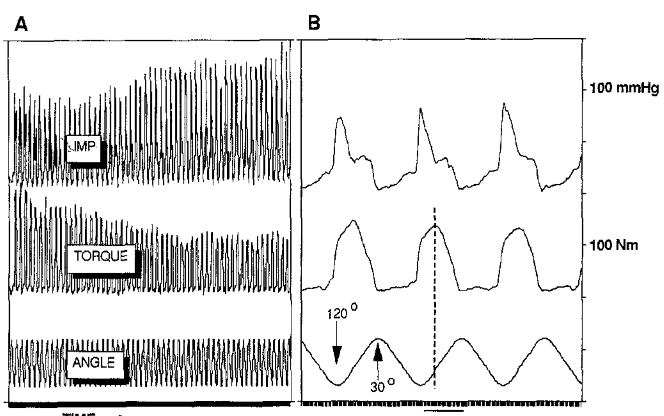

Fig. 2 (**A**) A portion of an original recording from one subject showing multiple contractions during concentric activity. Note the decline in torque and the increase in intramuscular pressure (*IMP*) during time. (**B**) An expanded view of three of these contractions. The *dashed line* indicates the selection of the joint angle associated with peak torque for one of these contractions

Results

System validation

The changes in the calibrated fluid pressure, the torque changes during varying percentages of isometric activity and the joint position changes were recorded accurately and linearly by the DA system. The minimal correlation coefficient was 0.99.

When recording zero pressure and torque continuously for 1 min, calibrated pressure and torque continuously for 3 min, and again recording zero continuously for 1 min, the DA showed a drift of less than 1 mmHg (0.13 kPa) for pressure and 0 N · m for torque at each time period. The manufacture's specification for drift by the pressure transducer was less than 2 mmHg (0.26 kPa) in 8 h and therefore, the drift value we recorded could be thus attributed.

For overall group strength during a maximal voluntary isometric contraction, IMP was 69 (SD 21) mmHg [9.2 (SD 2.8) kPa] and torque was 250 (SD 58)N · m.

Peak torque

Peak torque generated during eccentric activity was significantly higher than during concentric activity ($P < 0.01$). Overall, torque declined significantly with time ($P < 0.01$). Figure 3 demonstrates the relative trends for repetitive eccentric and concentric activities. Torque values declined to a significant point at 60% of the total eccentric activity time and at 20% of the concentric activity time. The decline in torque, however, was not different for the two types of activity ($P = 0.50$, no significant interaction). When relating end values to respective start values, concentric torque declined significantly from 191 (SD 30) to 147 (SD 49) N · m ($P = 0.02$) and concentric torque declined significantly from 166 (SD 32) to 104 (SD 23)(N · m) ($P < 0.01$).

Peak IMP

Peak IMP was not significantly different between activities although it tended to be higher for concentric than for eccentric activity ($P = 0.06$). There was also no effect on IMP due to activity time ($P = 0.48$) and no interaction between type of activity and time ($P = 0.81$). Figure 4 demonstrates the relative trends for repetitive eccentric and concentric activities. For eccentric activity IMP was 54 (SD 24) mmHg [7.2 (SD 3.2) kPa] and 54 (SD 25) mmHg [7.2 (SD 3.3) kPa], $P = 0.95$, and for concentric activity IMP was 78 (SD 31) mmHg [10.4 (SD 4.1) kPa] and 96 (SD 46) mmHg [12.8 (SD 6.1) kPa], $P = 0.99$, for the start and end, respectively.

IMP to torque coefficient

The IMP to torque coefficient was significantly higher for concentric compared to eccentric activity ($P < 0.01$). Overall, the coefficient increased significantly with time ($P < 0.01$). Also, there was a significant interaction between type of activity and time ($P < 0.01$). Figure 5 demonstrates the relative trends for repetitive eccentric and concentric activities. For eccentric activity the values were 0.28 (SD 0.13) and 0.42 (SD 0.26) mmHg · (N · m)$^{-1}$, ($P = 0.17$) and for concentric was 0.50 (SD 0.20) and 0.94 (SD 0.45) mmHg · (N · m)$^{-1}$, ($P = 0.03$) for the start and end, respectively.

JAPT

The JAPT was not significantly different between activities ($P = 0.79$) or with time ($P = 0.18$). There was, however, a significant interaction between the type of activity and time ($P = 0.01$). The angle for peak eccentric

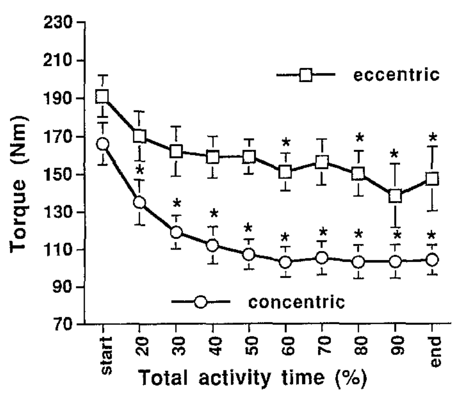

Fig. 3 Torque during repetitive eccentric and concentric activities. *Each data point* represents the means and SEM of eight subjects; *indicates a significant change from respective start values

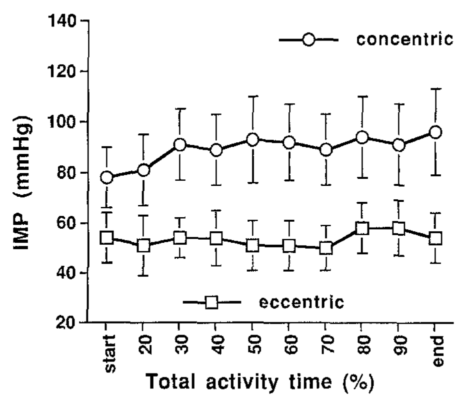

Fig. 4 Intramuscular pressure (*IMP*) during repetitive eccentric and concentric activities. *Each data point* represents the means and SEM of six subjects for eccentric and seven subjects for concentric activities

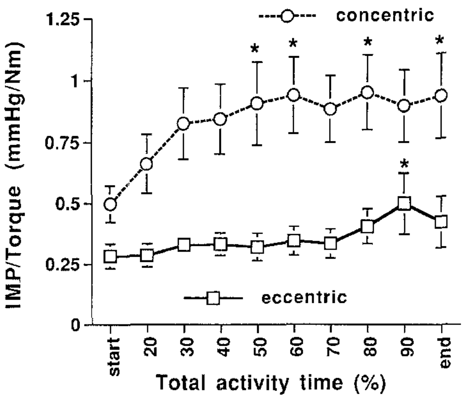

Fig. 5 Coefficient of intra muscular pressure (*IMP*) to torque (in millimetres of mercury per newton metres) during repetitive eccentric and concentric activities. *Each data point* represents the means and SEM of six subjects for eccentric and seven subjects for concentric activities; *indicates a significant change from respective start values

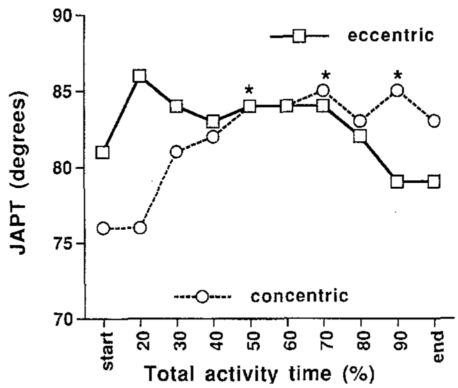

Fig. 6 Joint angle at peak torque (*JAPT*) during repetitive eccentric and concentric activities. *Each data point* represents the means of eight subjects (error bars are omitted for clarity). *Indicates a significant change from respective start values for concentric activity only. No change was detected for eccentric activity

torque remained virtually the same, whereas, the angle for peak concentric torque tended to increase with time. Figure 6 demonstrates the relative trends for repetitive eccentric and concentric activities. The JAPT for eccentric activity was 81 (SD 7)° [1.38 (SD 0.12) rad] and 79 (SD 9)° [1.34 (SD 0.15) rad], $P = 0.59$, and for concentric activity was 76 (SD 6)° [1.29 (SD 0.10) rad] and 83 (SD 7)° [1.41 (SD 0.12) rad], $P = 0.07$, for the start and end, respectively.

Soreness symptoms

On the 2nd day after exercise, all the subjects complained of stiffness and soreness in the mid-portion of the vastus lateralis muscle exclusively for the leg that had performed the eccentric protocol. This area was considerably swollen as assessed by the subjects. Soreness and swelling were also present for some subjects in the area of the rectus femoris muscle but this was not as pronounced (except for one subject). Subjective soreness ratings ranged from 5 to 8 for the eccentric activity leg and from 0 to 3 for the concentric activity leg.

Discussion

Our results indicated that during repetitive isokinetic activity

1. Eccentric muscle activity was associated with higher knee extension torques and with DOMS of the vastus lateralis muscle
2. The higher knee extension torques generated by eccentric muscle activity were not associated with increased IMP of the vastus lateralis muscle
3. High force eccentric activity did not occur at a greater joint angle compared to concentric activity.

Torque

The higher eccentric torque values relative to concentric torque are in agreement with previous studies (Singh and Karpovich 1966; Koml and Rusko 1974; Westing et al. 1988; Colliander and Tesch 1989). Also, the decline in torque agrees by extrapolation to other studies that have used different muscle groups, different velocities of contractions or a limited number of contractions (usually 40–50 repetitions) as an expression of fatigue (Komi 1973; Thorstensson and Karlsson 1976; Gray and Chandler 1989). The soreness symptoms suffered by all subjects as an exclusive result of eccentric activity supported our model as a reliable system for analysing parameters associated with DOMS, especially when muscle function and intramuscular pressure parameters are emphasized.

Intramuscular pressure

It has been shown that IMP increases linearly with joint torque and muscle force output for isometric and for a particular isokinetic action (Sadamoto et al. 1983; Sejersted et al. 1984; Sjøgaard et al. 1986; Aratow et al. 1993). It is also known that muscle tensions developed during eccentric activity are higher than during concentric activity (Singh and Karpovich 1966). Although we found higher torque for eccentric activity, there was no significant difference in IMP between activities. In contrast, we actually observed that for IMP there was a tendency for concentric activity to be higher than eccentric (nearly significant; $P = 0.06$) throughout the protocols. This relationship was best emphasized by the higher IMP per unit torque for concentric activity demonstrated in Fig. 5. In contrast, in a study which compared activities for the leg anterior compartment but did not measure joint torque, IMP was higher during eccentric activity and this activity was followed by DOMS (Fridén et al. 1986). For that study, the protocol involved ankle joint rotation throughout the full range of motion. The difference between their results and our findings is probably most related to differences in compartmental compliance. The leg anterior compartment has a low compliance and is surrounded by a tight fascia whereas the thigh anterior compartment, which includes the vastus lateralis muscle, is much more compliant. During eccentric activity, the muscle as well as the fascia are stretched and thereby contribute to increased IMP especially when an extended range of motion is reached. The IMP in the leg anterior compartment in the previous study was probably more responsive to this increase than in the thigh anterior compartment for our study. In addition, we have observed in support of this no IMP differences between an eccentric and a concentric action of the tibialis anterior muscle when a limited range of motion was used (unpublished observations). Therefore, we conclude that it is misleading to relate directly changes in IMP solely to the force of contraction. The fact that all the subjects in our study experienced DOMS following eccentric activity only, but without higher IMP values, would seem to indicate that IMP magnitudes during exercise are not a reflection of DOMS occurrence in the vastus lateralis muscle.

Certain mechanical aspects of muscle contractions suggest that IMP for a concentric action may in fact be larger than for an eccentric action. Mazzella (1954) has observed that IMP increases with the increasing number of fibres in activity which would suggest that IMP would be higher for concentric activity since it has been shown that more motor units are activated than for eccentric activity (Bigland-Ritchie and woods 1976). According to some other investigators, IMP during a contraction increases with the extent of fibre curvature (Hill 1948; Sejersted et al. 1984). This paraphrases the law of Laplace which was eloquently applied by Serjersted et al. (1984) to explain why IMP in a curved fibre (as for concentric activity) would be greater than for a straight fibre (as for eccentric activity).

In the present study, peak IMP during maximal eccentric, concentric, and isometric activities [approximately 100 mmHg (13.3 kPa)] were lower than has previously been reported for isometric activity of the vastus medialis muscle (Sejersted et al. 1984). It has been demonstrated in the previous study, that the muscle contraction pressure increases linearly with increasing depth within the muscle. The authors have also cited architectural differences as a factor in determining IMP. Since the vastus medialis and the vastus lateralis muscles have been described as architecturally similar (Wicklewicz et al. 1983), the large discrepancy between the previous study and our findings is probably most related to differences in catheter depth. It is important to note that our measurements were performed at the same level as biopsies from a previous study which indicated structural damages to the vastus lateralis muscle presumably caused by high muscle tensions (Fridén et al. 1983).

Joint angle for peak torque

Contrary to our hypothesis, the consistently higher torques for eccentric activity did not occur at a greater joint angle compared to concentric activity. Our study constituted the first, to the authors' knowledge, that compares eccentric and concentric JAPT for knee extension. A similar JAPT relationship between eccentric and concentric activity was reported for the elbow extensors by Singh and Karpovich (1966) who have found that JAPT was the same for both activities. However, for the elbow flexors, these authors found that JAPT was larger for concentric activity. Hortobágyi and Katch (1990), on the other hand, reported a larger JAPT for elbow extension during eccentric activity and an opposite pattern for flexion.

Overall, JAPT in the current study [range 76° (1.29 rad) to 83° (1.41 rad)] was higher than has previously been reported for concentric knee extension when compared with a similar population (age and exercise frequency) tested at the same angular velocity (Thorstensson et al. 1976; Kannus and Beynnon 1993). The range of motion for the previous studies, however, was between 0° (0 rad) and 90° (1.53 rad) and for our study between 30° (0.51 rad) and 120° (2.04 rad). The JAPT values we found were more closely related to those obtained when testing high level athletes (Osternig et al. 1983; Kemp and Anderson 1989).

The JAPT throughout eccentric activity remained the same, that is it occurred at the same point in the range of motion. However, JAPT throughout concentric activity tended to increase, that is it occurred earlier in the range of motion, as subjects approached fatigue. Differences that have been demonstrated between eccentric and concentric activities in motor unit activity (Bigland-Ritchie and Woods 1976; Nardone and Schieppati 1988; Nardone et al. 1989), fatigue patterns (Gray and Chandler 1989) and muscle activation patterns (Westing et al. 1991; Nakazawa et al. 1993) may also account for the JAPT profile differences we found.

In summary, this study showed that high force eccentric activity of the vastus lateralis muscle led to DOMS but *was not* associated with elevations in IMP. Therefore, the magnitudes of IMP was not an etiologic indicator of DOMS. High force eccentric activity was not associated with a greater JAPT, therefore, this parameter did not offer an explanation for these high forces.

Acknowledgements We wish to thank Tomas Ekman, Ulf Ranggård, Torsten Sandström and Lena Söderberg for their excellent technical assistance. We also wish to thank our subjects and the facilities provided by Professor Ronny Lorenzon at the Sports Medicine Department of Umeå University. This work was supported by the Swedish Sports Research Council, the Swedish Medical Research Council (12 × -3934 and 9098) and the Medical Faculty of the University of Umeå.

References

Aratow M, Ballard RE, Crenshaw AG, Styf J, Watenpaugh DE, Kahan NJ, Hargens AR (1993) Intramuscular pressure and electromyography as indexes of force during isokinetic exercise. J Appl Physiol 74:2634–2640

Bigland-Ritchie B, Woods JJ (1976) Integrated electromyogram and oxygen uptake during positive and negative work. J Physiol (Lond) 260:267–277

Colliander EB, Tesch PA (1989) Bilateral eccentric and concentric torque of quadriceps and hamstring muscles in females and males. Eur J Appl Physiol 59:227–232

Ebbeling CB, Clarkson PM (1989) Exercise-induced muscle damage and adaptation. Sports Med 7:207–234

Fridén J, Lieber RL (1992) Structural and mechanical basis of exercise-induced muscle injury. Med Sci Sports Exerc 24:521–530

Fridén J, Sjöström M, Ekblom B (1983) Myofibrillar damage following intense eccentric exercise in man. Int J Sports Med 4:170–176

Fridén J, Sfakianos PN, Hargens AR (1986) Muscle soreness and intramuscular fluid pressure: comparison between eccentric and concentric load. J Appl Physiol 61:2175–2179

Gray JC, Chandler JM (1989) Percent decline in peak torque production during repeated concentric and eccentric contractions of the quadriceps femoris muscle. J Orthop Sports Phys Ther 10:309–314

Hill AV (1948) The pressure developed in muscle during contraction. J Physiol (Lond) 107:518–526

Hortobágyi T, Katch FI (1990) Eccentric and concentric torque-velocity relationships during arm flexion and extension. Eur J Appl Physiol 60:395–401

Kannus P, Beynnon B (1993) Peak torque occurrence in the range of motion during isokinetic extension and flexion of the knee. Int J Sports Med 14:422–426

Kemp L, Anderson T (1989) Measurement of knee extension torque at angular velocities ranging from 60 to 600° per second (abstract). Int J Sports Med 10:380

Komi PV (1973) Relationship between muscle tension, EMG and velocity of contraction under concentric and eccentric work. In: Desmedt JE (ed) New developments in electromyography and clinical neurophysiology. Karger, Basel, pp 596–606

Komi PV, Rusko H (1974) Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work. Scand J Rehabi Med [Suppl] 3:121–126

Mazzella H (1954) On the pressure developped by the contraction of striated muscle and its influence on muscular circulation. Arch Int Physiol LXII:334–347

Nakazawa K, Kawakami Y, Fukunaga T, Yano H, Miyashita M (1993) Differences in activation patterns in elbow flexor muscles during isometric, concentric and eccentric contractions. Eur J Appl Physiol 66:214–220

Nardone A, Schieppati M (1988) Shift of activity from slow to fast muscle during voluntary lengthening contractions of the triceps surae muscles in humans. J Physiol 395:363–381

Nardone A, Ramanò C, Schieppati M (1989) Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. J Physiol 409:451–471

Newham DJ, McPhail G, Mills KR, Edwards RHT (1983) Ultrastructural changes after concentric and eccentric contractions of human muscles. J Neurol Sci 61:109–122

Newham DJ, Jones DA, Ghosh G, Aurora P (1988) Muscle fatigue and pain after eccentric contractions at long and short length. Clin Sci 74:553–557

Osternig LR, Sawhill JA, Bates BT, Hamil J (1983) Function of limb speed on torque patterns of antagonist muscles. In: Matsui R, Kobayashi M (eds) Biomechanics VIII-A. Human Kinetics Champaign, Ill., pp 251–257

Sadamoto T, Bonde-Petersen F, Suzuki Y (1983) Skeletal muscle tension, flow, pressure, and EMG during sustained isometric contractions in humans. Eur J Appl Physiol 51:395–408

Sejersted OM, Hargens AR, Kardel KR, Blom P, Jensen Ø, Hermansen L (1984) Intramuscular fluid pressure during isometric contraction of human skeletal muscle. J Appl Physiol 56:287–295

Singh M, Karpovich PV (1966) Isotonic and isometric forces of forearm flexors and extensors. J Appl Physiol 21:1435–1437

Sjøgaard G, Kiens B, Jørgensen K, Saltin B (1986) Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. Acta Physiol Scand 128:475–484

Smith LL (1991) Acute inflammation: the underlying mechanism in delayed onset muscle soreness? Med Sci Sports Exerc 23:542–551

Stauber WT (1989) Eccentric action of muscles: physiology injury and adaptation. In: Pandolf KP (ed) Exercise and sports sciences reviews. Williams and Wilkins, Baltimore, pp 157–186

Styf JR, Körner LM (1986) Microcapillary infusion technique for measurement of intramuscular pressure during exercise. Clin Orthop 207:253–262

Thorstensson A, Karlsson J (1976) Fatiguability and fibre composition of human skeletal muscle. Acta Physiol Scand 98:318–322

Thorstensson A, Grimby G, Karlsson J (1976) Force-velocity relations and fiber composition in human knee extensor muscles. J Appl Physiol 40:12–16

Westing SH, Seger JY, Karlson E, Ekblom B (1988) Eccentric and concentric torque-velocity characteristics of the quadriceps femoris in man. Eur J Appl Physiol 58:100–104

Westing SH, Cresswell AG, Thorstensson A (1991) Muscle activation during maximal voluntary eccentric and concentric knee extension. Eur J Appl Physiol 62:104–108

Wickiewicz TL, Roy RR, Powell PL, Edgerton VR (1983) Muscle architecture of the human lower limb. Clin Orthop 179:275–283