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Skeletal Muscle Tension, Flow, Pressure, and EMG During Sustained Isometric Contractions in Humans*

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Summary. In five healthy males sustained isometric torques during elbow flexion, knee extension, and plantar flexion correlated positively with intramuscular tissue pressure (MTP) in the range 0–80% of the maximal voluntary contraction (MVC). During passive compression of the muscle at rest 133-Xenon muscle clearance stopped when MTP reached diastolic arterial pressure (DAP) indicating that the muscle vascular bed was occluded. However, during sustained contractions this relation between DAP, flow and MTP was not seen. In two cases 133-Xenon clearance from M. soleus did not stop in spite of an 80% maximal contraction and MTP stayed below DAP. In other cases MTP would reach as high as 240 mm Hg before clearance was zero. In the deeper parts of the muscles MTP during contraction was increased in relation to the more superficial parts. The mean values for the %MVC that would stop MBF varied between 50 and 64% MVC for the investigated muscles. Mean rectified EMG (MEMG) showed a high correlation to MTP during sustained exhaustive contractions: When MEMG was kept constant MTP also remained constant while the exerted force decreased; when force was kept constant both MEMG and MTP increased in parallel. This demonstrated that muscle tissue compliance is decreasing during fatigue. Muscle ischemia occuring during sustained isometric contractions is partly due to the developed MTP, where especially the MTP around the veins in the deeper parts of the muscle can be considered of importance. However, ischemia is also affected by muscle fiber texture and anatomical distorsion of tissues.

Key words: Isometric exercise – Intramuscular pressure – Muscle flow – Muscle compliance – Mean voltage EMG

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Introduction

It has been demonstrated that intramuscular tissue pressure (MTP) is positively related to muscle force exerted. Hill (1948) measured a MTP of 100 to 300 mm Hg in the frog and suggested that similar pressures would develop in any size of muscle. Sylvest and Hvid (1959), however, showed that MTP reached 1,025 mm Hg in M. vastus medialis of man. Other studies state that pressures developed during contraction in different muscles were different and showed important variations when measurements were repeated (Edwards et al. 1972; Møller et al. 1979; Saltin et al. 1981). When MTP increases during dynamic and sustained contractions, MTP is interfering with muscle blood flow (MBF) (Bonde-Petersen et al. 1975a, b; Møller et al. 1979; Saltin et al. 1981). However, it is not known which level of MTP will occlude the muscle vascular bed in different muscles. During external passive compression by a blood pressure cuff Dahn et al. (1967) observed that MBF stopped when MTP was close to diastolic pressure (DAP) – the Starling valve. However, these experiments were not performed during contraction. It was, therefore, of interest to investigate whether MBF also stopped during exercise when MTP surpasses DAP or if other factors play a role. The purpose of the present experiment was to examine the relationship between MTP, DAP, MBF, during rest and sustained isometric contractions in different muscles. However, MTP and MBF cannot be recorded simultaneously from exactly the same location in the muscle. Therefore, the needle used for MTP recording was subsequently used for the injection of an isotope tracer (133-Xe) for MBF measurements. Thus it was possible to obtain values for MTP and MBF from the same location in the muscle even if this was not obtained simultaneously. Another purpose was to see how MTP varied with fiber recruitment during exhaustive exercise, where the additional recruitment of motor units can be estimated from mean rectified electromyography (MEMG).

Material and Methods

Five healthy males participated in the experiment. Informed consent was obtained.

Muscle force exerted was measured on a strain-gauge dynamometer (Darcus 1951; Bonde-Petersen 1960) constructed to measure torques of different muscle synergies. With this dynamometer, forces during elbow flexion, knee extension, and plantar flexion were measured in kp × m (1 kp = 9.81 N).

Intramuscular tissue pressure (MTP) was measured in mm Hg (1 mm Hg = 133,3 Pa) with a miniature pressure transducer (Statham P37), connected to a strain-gauge bridge amplifier (Bryans 40550). The output from the pressure transducer was recorded on one channel of a two-channel recorder (Servogor 320) while the signal from the torque dynamometer was recorded simultaneously on the other channel. The male Luer-fitting of the pressure transducer was mounted with a needle and introduced into the muscle at a certain angle to the skin surface in such a way that the direction of the needle supposedly would be near parallel to the muscle fibers and that contraction would cause no pain. During contraction muscle tissue would plug the tip of the needle due to the increased MTP. This was prevented by having an infusion pump (Harvard) flushing the needle by isotonic saline infused at a slow rate (Edwards et al. 1972) through a fine bore inlet to the pressure transducer. Preliminary studies showed infusion rate and size of the needle to be important for the development

of pain during measurements. An infusion rate of 5.2 or 2.6 μl/s and a needle 72 mm long and 1.2 mm o.d. (0.8 mm i.d.) seemed to satisfy the needs for a painless recording. However, during contraction the recording of MTP at this relatively low rate of infusion showed a slow response with a rise time of about 10 s from 0 to 150 mm Hg (Fig. 1). This rise time could be minimized by increasing the infusion rate, but as this would also cause pain we decided to use the infusion rate of 2.6 μl/s. Also the size of the o.d. of the needle was important. E.g. in the soleus muscle a needle of 1.2 mm o.d. caused pain. Therefore, in this muscle a needle of 0.6 mm o.d. and 40 mm long was used. This substantially diminished the pain.

Muscle blood flow (MBF) was measured during histamine induced vasodilation by the local isotope clearance technique (Kety 1949) using 133-Xe (Holzman et al. 1964; Lassen et al. 1964). The amount of 0.1–0.2 ml of isotonic saline containing 100–200 μCi 133-Xe and about 5–10 μg of histamine (Lindbjerg 1965) was injected into the muscle through the needle used for pressure measurements, after the pressure measurements were performed, and before the needle was withdrawn. The disappearance rate was then recorded by external counting using a scintillation detector and a rate meter (Meditronic) connected to the two channel recorder. Counts of 100–1,000/s were obtained.

Electromyography (EMG) was recorded by a DISA (Type 15C 01) electromyograph containing a mean voltage unit for recording of MEMG. The EMG signals were picked up by surface electrodes (5 by 10 mm) placed on the skin overlying the muscle belly investigated. The EMG and MEMG signals were recorded on a strip chart recorder (Brush, Clevite 220).

Heart rate (HR) was monitored by an ECG-scope (S & W Diascope DS 521) to survey the subject, and blood pressure was measured by sphygmomanometry during exercise as often as possible, which meant at least 30 s intervals. Mean arterial blood pressure (MAP) was calculated as (DAP) + $^1/_3$ pulse pressure.

Blood pressures were measured on the upper arm by a sphygmomanometer, and systolic, mean and diastolic arterial pressures (SAP, MAP, and DAP, respectively) noted.

Muscle cross sectional areas were measured in one subject (YS) from computer tomography (CT) scans performed on upper arm-, thigh-, and calf muscles. These scans were then examined to identify the different muscle synergies investigated, the areas of which were measured by planimetry.

Conventional statistical methods were used. A significance level of 0.05 was accepted.

Experimental Procedure

Two experimental series were performed. Experiment I: Relative muscle force exerted (%MVC), MTP, and MBF were measured in five subjects in M. biceps brachii during elbow flexion, in M. vastus lateralis and M. rectus femoris during knee extension, and in M. gastrocnemius lateralis and M. soleus during plantar flexion. Further, MAP was measured during sustained contractions at different force levels. Experiment II: %MVC, MTP, and MEMG were measured during sustained contractions of the same muscles in four of the subjects.

Experiment I. The five muscles chosen were investigated in a random order. The experiments were carried out at no specific time of the day. During the experimental session the subject was placed in the sitting position with underarm, leg, or foot, respectively, placed in suitable holders and with elbow-, knee-, or ankle joint at an angle of 90 degrees. MVC was measured as the maximum of 3 trials. The subject was then resting for 15–20 min while the pressure needle was prepared and introduced in position. If the needle caused pain during contraction it was withdrawn and reinserted until the subject experienced no pain. The first part of this experimental protocol consisted of sustained contractions at various levels of force relative to MVC. The force exerted was recorded on the two channel strip chart potentiometer recorder, which was placed in such a way that the subject was able to keep the desired force level by a visual feed back. On the other channel MTP was recorded (Fig. 1). There was a certain delay in the MTP signal, caused by the relatively slow injection speed used. Therefore, the contraction was sustained until a stable reading of the MTP pressure signal was obtained, which in general ment 10–30 s. After a few min rest, the contraction was repeated at another force level. During one series of measurements about 10 contractions were

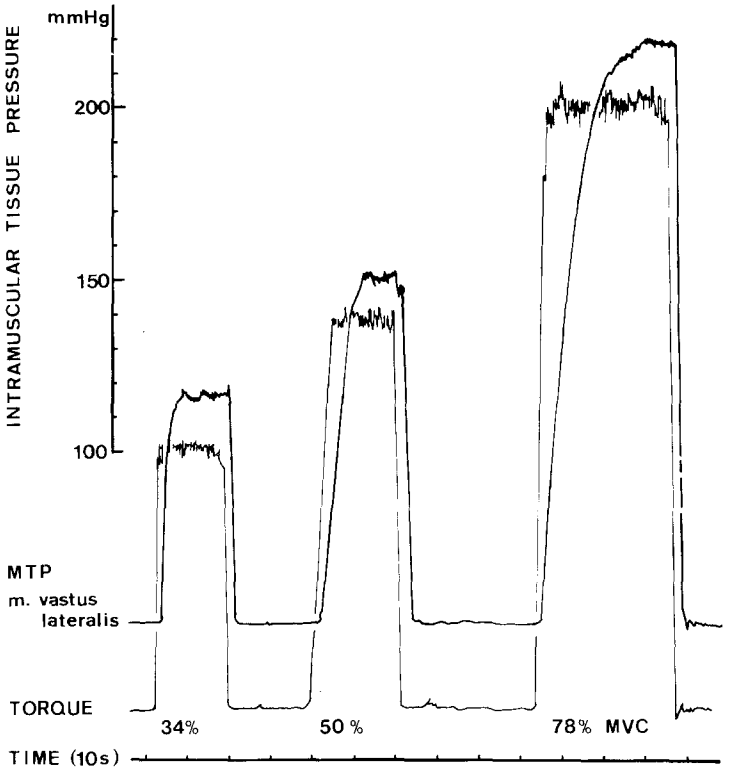

Fig. 1. An example of the tracings obtained when muscle tissue pressure (MTP) and intramuscular tissue pressure were recorded simultaneously from M. vastus lateralis at 34%, 50%, and 78% MVC

performed with simultaneous measurements of blood pressures. Subsequently the miniature pressure transducer was dismounted from the needle which was left in situ and the 133-Xe solution was injected through the needle before this was withdrawn. In this way it was possible to obtain clearance and pressure measurements from exactly the same location in the muscle. The purpose of using 133-Xe clearance was to decide at which relative level of MVC the MBF stopped. This meant that the subject performed sustained contractions at different force levels for brief periods. The clearance curve was observed until the force level was found above which 133-Xe clearance was zero. In this way the clearance method was used as a semiquantitative method, and no flow values were calculated (Fig. 2).

Experiment II. MTP and MEMG were recorded during sustained contractions at 35%, 50%, and 65% MVC kept for 2 min or until fatigue. In one series of contractions muscle force exerted was kept constant and in another series MEMG was kept constant by visual feed back. In this way it was possible to study the relationship between MTP and recruitment pattern of motor units.

Results

Preliminary results: In order to see if the rate of infusion in the pressure transducer was of importance for the obtained pressure, two rates of infusion were used: 2.6 and 5.2 µl/s. These infusion rates caused an off-setting by

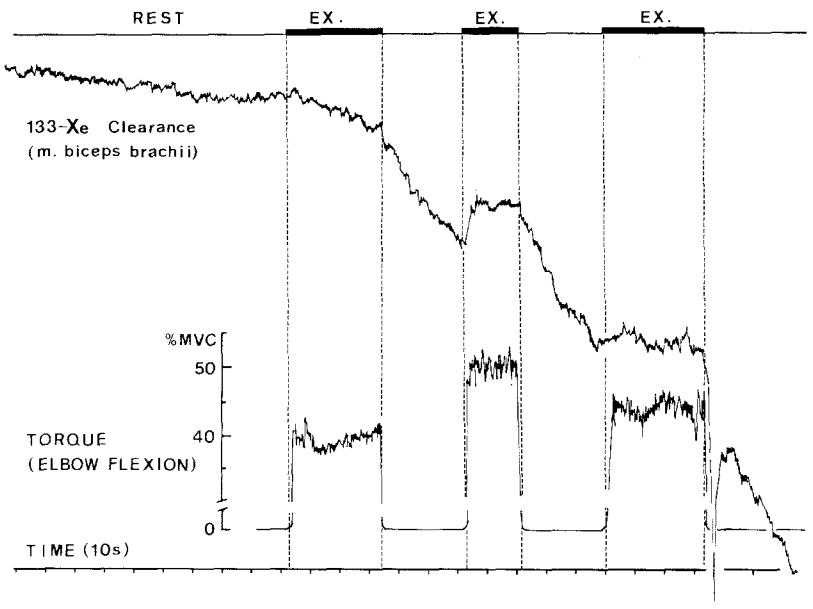

Fig. 2. Logarithmic plot of 133-Xe clearance curve from M. biceps brachii during elbow flexion. From bottom to top the y-axis represents 1 decade. The torque exerted indicated in % MVC. Time axis 10 s divisions. EX. indicates periods of sustained static contractions. Three such periods are indicated at 40, 50, and 45% MVC respectively. The 133-Xe clearance curves demonstrate that at 40% MVC a certain flow was present at a higher than resting level, followed by and even more pronounced hyperaemia during the recovery period before the next contraction performed at 50% MVC. This level of contraction evidently stopped the flow which was then further enhanced during the subsequent recovery period. During the contraction at 45% MVC, a slight clearance could be noticed. This experiment shows that the % MVC sufficient to arrest muscle blood flow is 50% MVC

2–10 mm Hg which was then used as the zero-line for MTP. Both during an increased muscle pressure produced passively by a pressure cuff applied around the limb (Fig. 3) and during muscle contraction (Fig. 4) results obtained by the two infusion rates fitted the same rectilinear slope. The pressure recording during increased external pressure (Fig. 3) could also be taken as an in vivo calibration, and showed some variation between individuals but also some deviation from the line of idendity. This is ascribed to geometrical variations and to the fact that the external pressure is transmitted differently to the underlying tissue. Also the location of the needle was of importance as an about 50% lower pressure was found during contraction if the needle was placed more superficially. In general the tip of the needle was located 2–3 cm below the skin surface.

There were some difficulties in deciding the exact level of %MVC that would stop 133-Xe clearance (Fig. 1) even if the clearance method was made more sensitive by adding histamine to the solute. However, we think that the preliminary experiments show that the methods for measuring MTP, %MVC, and "stop flow" were satisfying.

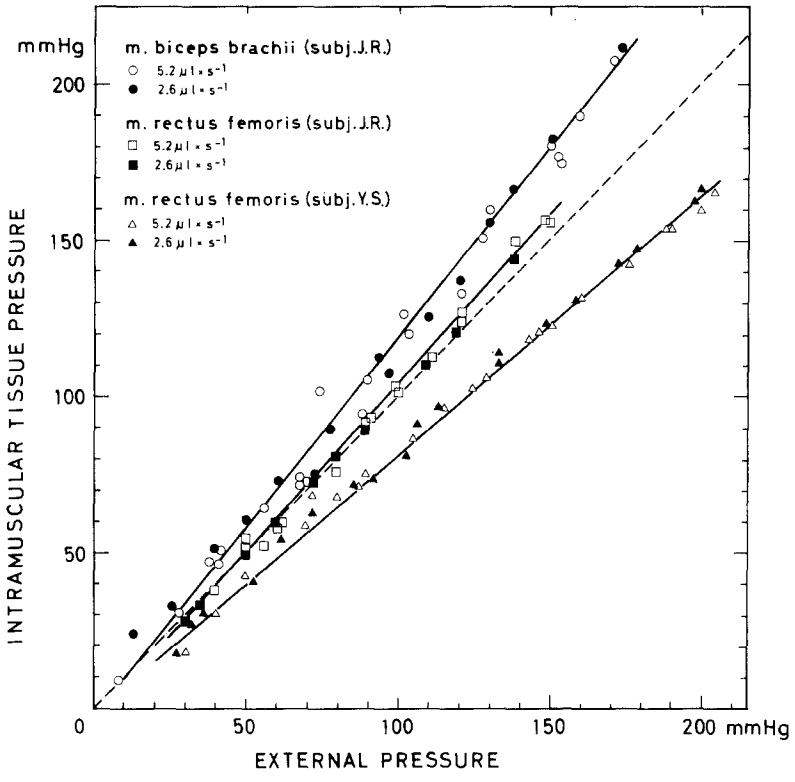

Fig. 3. Relationship between MTP and the pressure applied externally by a cuff to the thigh or upper arm. Two infusion rates of 5.2 and 2.6 µl/s were used

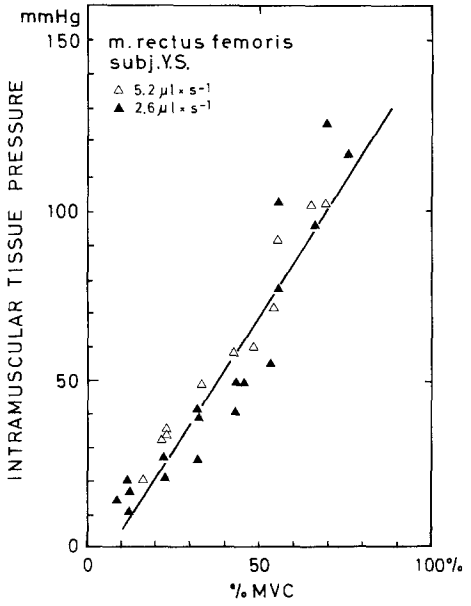

Fig. 4. Relationship between MTP and % MVC of subject YS obtained using two infusion rates of 5.2 and 2.6 µl/s

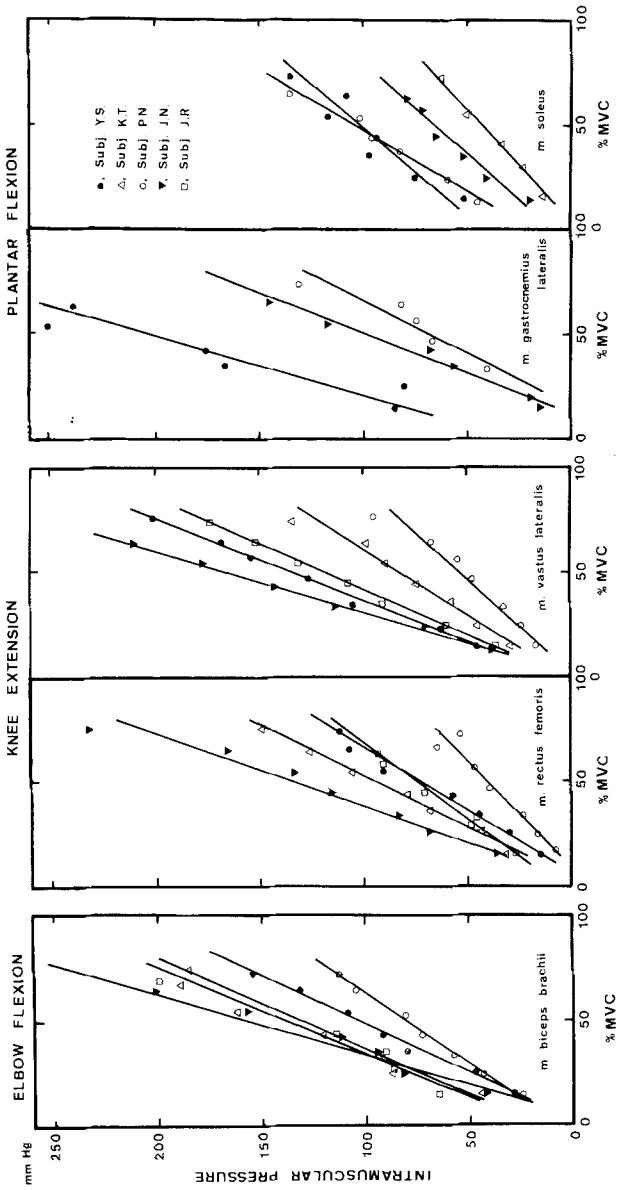

Fig. 5. Relationship between MTP and % MVC for all experiments and subjects

Experiment I. During rest the external pressure that would stop MBF in the investigated muscles was identified having the subject sitting. The difference between this cuff pressure and DAP measured on the upper arm is 3.0, 16.5, and 21.3 mm Hg respectively for the 3 muscles investigated. The differences between DAP and MTP correspond for the thigh muscles to the increase in hydrostatic pressure between arm and thigh, calculated in the sitting position assuming the specific gravity of blood to be 1.055 g/ml. These hydrostatic

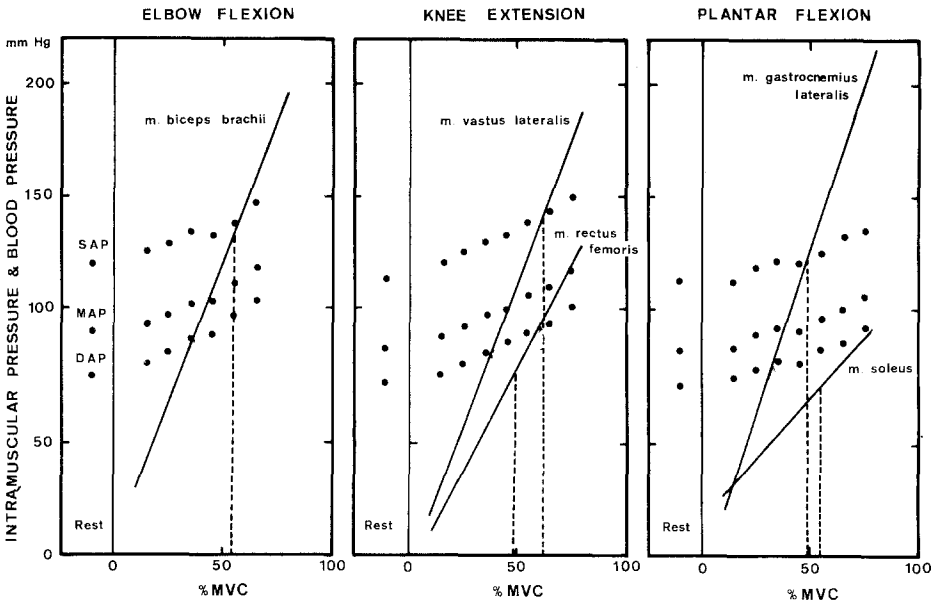

Fig. 6. Mean values for MTP, SAP, MAP, and DAP during contraction of the five muscles investigated. The straight line indicate the MTP as a function of % MVC. The arterial pressures are measured with the cuff method on the upper arm with the subject in the sitting position. The vertical dotted lines indicate the mean % MVC that would stopp muscle blood flow as estimated from the recording of 133-Xe clearance during contraction

pressures were 0, 14, and 23 mmHg for M. biceps, M. rectus femoris, and M. vastus lateralis, respectively and thus correspond fairly well to the measured values.

MVC showed an important day to day variation. However, during contraction MTP increased rectilinearly proportional to the increase in MVC. The individual pressures varied among muscles and from subject to subject (Fig. 5). Within the measured range of MVC there was no tendency for MTP to level off up to 80% MVC. Although the individual variations in muscle pressures were great, only a small interindividual variation in blood pressures was observed. The relative MVC that arrested MBF is indicated by the dotted vertical lines in Fig. 6. The values were 53 ± 3.2% MVC for M. biceps (n = 5), 64 ± 12% MVC for M. vastus lateralis (n = 5), 50 ± 6.5% MVC for M. rectus femoris (n = 5), 50% for gastrocnemius (n = 3; two subjects were not measured due to pain), and finally 54% MVC for M. soleus (n = 2; 4 subjects were measured, but in two subjects the 133-Xe clearance did not stop even at 80% MVC). Even if the blood pressures at the muscle level are calculated by adding the hydrostatic pressure due to the difference in level between arm and leg muscles, no correlation between diastolic pressure and MTP that would stop blood flow could be obtained.

One subject (YS) was more extensively investigated. Individual values for the correlation between absolute torque measured in Kp × m and MTP were calculated and the slopes indicated in Fig. 7. During knee extension the steeper

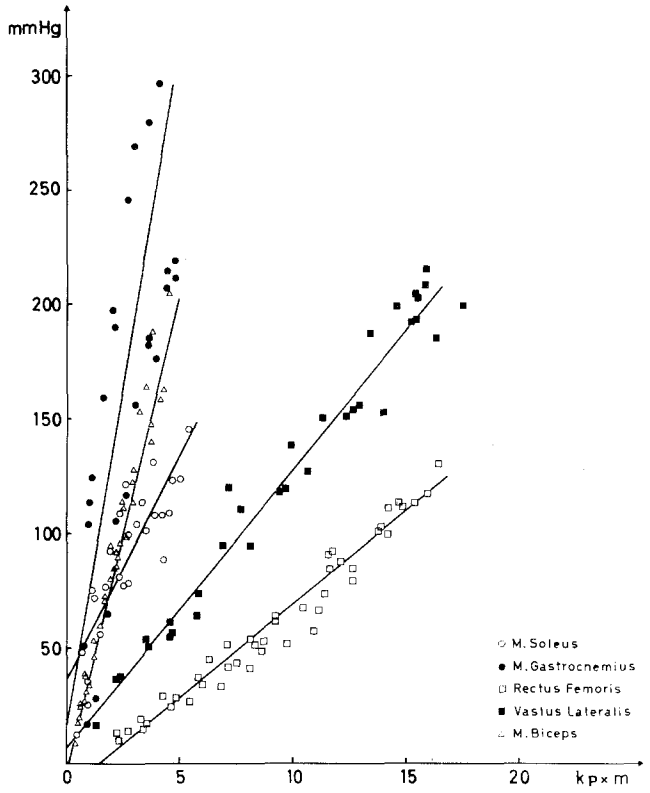

Fig. 7. MTP relative to tension development indicated in Kp × m torque in subject YS in the five muscles investigated

Table 1. MVC, cross sectional area (CT-scanning), and estimated mean intramuscular tissue pressure in elbow flexors (M. biceps caput breve), knee extensors (M. rectus and vastus femoris) and plantar flexors (M. soleus and gastrocnemius). MVC/muscle area and muscle pressure × muscle area/MVC are calculated. The results are from one individual (YS)

Muscle synergy	MVC Kp × m	Area cm^2	MVC per area Kp × m/cm^2	MTP at max MVC mm Hg	MTP × area/MVC mm Hg × cm^2/ Kp × m
Elbow flexors	5.27	9.7	0.54	209	387
Knee extensors	20.05	71.5	0.280	211	754
Plantar flexors	6.81	13.6	0.50	271	542

increase in MTP was seen in M. vastus lateralis compared with M. rectus femoris. The pressure increase in M. gastrocnemius was about the double of that seen in M. soleus, and about equal to that of M. biceps. The results from the study of this subject permitted a calculation by extrapolation of maximum pressures exerted times cross sectional area of muscle, which was measured by CT scanning. This product was divided by the measured maximum torques of the respective synergies (Table 1). The resulting expression varies between 387 for

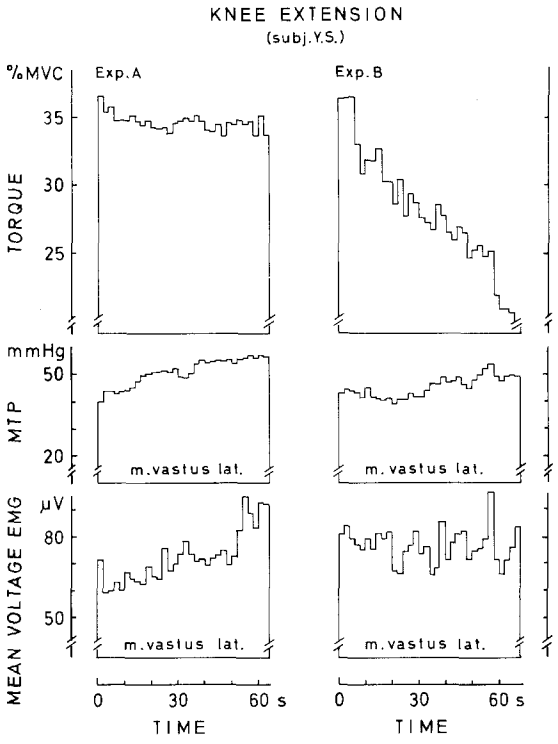

Fig. 8. % MVC, MTP, and mean voltage EMG obtained during sustained knee extension until fatigue in subject YS. MTP and EMG recorded from M. vastus lateralis. In the left hand panel the subject kept muscle tension constant at a 35% MVC level (exp II-A) and in the right hand panels mean voltage EMG was kept constant by a visual feed back

M. biceps during elbow flexion to 754 mm Hg × cm^2/kp × m for knee extension. The great variation in MTP as a function of the developed torque in kp × m seen in Fig. 7 is thus to some extent cancelled out.

Experiment II. In Fig. 8 an example of the relation between muscle tension MTP and MEMG is given in two situations during knee extension. In experiment II-A muscle tension was kept constant and in experiment II-B the mean voltage EMG was kept constant by visual feed back of the subject. The figure demonstrates a clear correlation between MTP and MEMG because in exp. A there is a parallel increase in MEMG and MTP during sustained contraction. This was also demonstrated in exp. II-B as muscle tension exerted decreased while MEMG and MTP both remained fairly constant.

Discussion

The applied method for measuring intramuscular pressure was also used by Edwards et al. (1972). In the present investigation, however, the method was calibrated against known external compression pressures. This new observation shows the method to give reliable results. The method is designed for pressure measurements during exercise, where the tendency to block the tip of the needle is of increasing importance. The injection pressure increases the recorded

Table 2. Intramuscular tissue pressures (MTP) during maximal isometric contractions reported in literature compared with the present results

Reference	MTP at maximum contraction			
	Mean mm Hg	Range, SE mm Hg	*n*	Investigated muscle
For man during voluntary contraction				
Sylvest and Hvid (1959)	160	74– 472	26	M. tibialis anterior
	139	100– 178	2	M. biceps brachii
	479	206–1,025	32	M. vastus medialis
Edwards et al. (1972)	692	–	1	M. vastus lateralis
Møller et al. (1979)	70	11 (SE)	6	M. temporalis anterior
	45	8 (SE)	5	M. masseter
Present study	238	153–326	5	M. biceps brachii
	177	154–284	5	M. rectus femoris
	225	114–348	5	M. vastus lateralis
	123	91–190	4	M. soleus
	256	168–380	3	M. gastrocnemius lateralis
Saltin et al. (1981)	ca. 220	210–310	5	M. vastus lateralis
Hargens et al. (1982)	260	110 (SE)	12	M. vastus medialis
For man during artificial contraction				
Nilsson and Ingvar (1967)	300	–		M. tibialis anterior
For animals				
Hill (1948)	150	100–300		M. gastrocnemius (frog)
Mazella (1953), Mazella and Mendez-Bauer (1954)	150–180	100–300		M. gastrocnemius (rat) M. gastrocnemius (cat)

pressure by about 2–10 mm Hg and the observed pressures, therefore, must be regarded as increments over resting pressures. The method is, therefore, not applicable for absolute measurements during resting conditions. The increase in MTP during contraction is proportional to the exerted force as also found by others (Table 2), and the obtained values in the present investigation were in the range of those described in literature. The variation in MTP recorded due to geometrical variations has also been observed in the rat by Wisness and Kirkebø (1976), and by Saltin et al. (1981), and Hargens et al. (1982) in humans. This has previously been discussed by us (Hermiston and Bonde-Petersen 1975; Møller et al. 1979), where we also emphazised that the direction of the muscle fibres (converging or parallel) will have some implications upon the possibility for the MTP developed during contraction. This is confirmed by the present results, where the smallest pressure increments were found in M. soleus, which has a more parallel fiber course than the other muscles investigated.

The applied 133-Xe clearance technique to measure muscle blood flow has previously been videly used, but has been subjected to some critisism because

the results obtained are only about 50% of those expected during exercise (Bonde-Petersen et al. 1975a; Rowell 1974; Cerretelli et al. 1979). It is, therefore, only by some hesitation that we used this method, but not other method is available that with the same ease can give at least an idea of what is happening to the blood flow during isometric contraction. We think that the use of this method is justified in the present experiment where it was used semiquantitatively in order to indicate if the muscle was ischemic or not, i.e. if 133-Xe clearance was zero. This is also corroborated by previous findings by us (Bonde-Petersen et al. 1975b; Hermiston and Bonde-Petersen 1975) where ischemia was found to develop in muscles around 50–60% MVC. In the present experiment the critical relative force at which MBF was zero was 64% in M. vastus lateralis and 50–53% MVC in the other muscles investigated. The present and the above cited experiments are performed in the sitting position, where the hydrostatic pressure is increased. In the recumbent or head down position lower values would of course obtain.

The hypothesis that MBF would stop when MTP reached DAP (the Starling valve) was reconfirmed during rest and concurs with the findings of Dahn et al. (1967). However, they did not measure MTP, which in the present experiment was shown to correspond closely to the applied external pressure in the occlusion cuff. Dahn et al. only investigated M. tibialis anterior, while we extended our investigation to five other muscles. However, the hypothesis did not follow during exercise (Fig. 6). Among other factors that would stop MBF, Gray et al. (1967), have demonstrated that kincking or nipping of arterioles takes place during contraction where they penetrate the fascia due to sliding between the different structures of the muscle belly. The condition for a continued MBF during muscle contraction is thus not only dependent upon the pressure developed around the capillary network of the contracting parts of the muscle. Also the pressure surrounding the veins, often located profoundly around the muscle belly, is of importance. This might be the explanation why MBF was stopped in some cases when MTP was far below DAP, because the pressure in the veins might have created a venous stasis, and thereby stopped the venous outflow from the muscle. In some cases MBF did not stop until MTP reached the local SAP, which could be calculated correcting for the hydrostatic pressure increase arm-leg. In no case did we find any evidence that MBF would continue when MTP surpassed local SAP. Again the deep venous pressure (VP) must be considered of importance. It is also quite natural that the arterial to venous pressure difference – the perfusion pressure (PP) – would play a role. This is modified during external pressure applied at rest because the amount of blood reaching the muscle per heart beat, only constitutes a fraction (about $^1/_6$–$^1/_{10}$) of the capillary blood volume. When once emptied the collapsed capillary bed can not be reopened if MTP is above DAP (= the Starling valve). During exercise a multitude of variables would be considered. All kinds of pumping and squeezing actions would be exerted on the capillary and venous blood rendering local MTP less important to a continuous MBF. This increases the importance of deep VP, and of the finding that MTP increases in the profound parts during contraction.

From this part of the present investigation it is reconfirmed that the critical

PP = DAP−MTP in muscles during rest, but other conditions reign during contraction where the critical PP = SAP−VP in some cases, in other cases PP depends upon distorsion of vessels, suction or squeezing of muscle bellies combined with venous stasis in a non predictable manner.

The CT scans permitted a calculation of MVC, MTP, and muscle area relations. This calculation was based on the assumption that the greatest cross section of an extremity also related to the MVC. The calculations as shown in Table 1 must be compared with the results shown in Fig. 7, where the MTP/MVC slopes varied widely among muscles. The values for MTP × Area/MVC decreased this variation to a factor of approximately 2, but still there was a variation, which must relate to the different anatomical structure of the investigated muscles.

In experiment II of the present investigation MEMG, MTP, and %MVC exerted were recorded simultaneously. This demonstrated that MTP is coupled to MEMG and not to the relative muscle force exerted. It was also obvious that when the muscle fatigued there was an increase in MTP for a given constant force level, and that this increase tracked the electrical activity. When MEMG was kept constant, MTP remained constant, while the exerted force decreased. This relationship between MEMG and MTP has not been demonstrated before, and might indicate that during fatigueing contractions the muscle develops an increasing stiffness, as new motor units are recruited. This indicates that even if MTP is related to muscle tension development and thereby cross-bridge formation it is also the result of other processes in the muscle. The stiffness of the muscle fiber has been mentioned but also osmotic effects building up during contraction might increase MTP, due to increased osmolality in the interstitial space.

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