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ISOMETRIC KNEE EXTENSION STRENGTH AS A FUNCTION OF JOINT ANGLE, MUSCLE LENGTH AND MOTOR UNIT ACTIVITY

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Dysfunction of the knee extensor muscles is a frequently encountered problem in clinical practice. Apart from nervous lesions and certain inhibitory mechanisms, operative procedures interfering with the length or the lever of the muscle group may result in a long-standing muscular insufficiency. To some extent, development of certain operative methods, e. g. shortening osteotomy of the femur, patellectomy, and tibial osteotomy, have advanced more rapidly than has our knowledge concerning the biomechanics of the muscles involved.

Usually the contraction force of a muscle cannot be measured directly. From a functional point of view, contraction force in a muscle is less important than the torque (moment of force) it can produce around a given axis. In isometric contraction against an external resistance, the external torque can easily be measured and is equal to the resisting force multiplied by the lever of this force in relation to the axis chosen. Knee extension strength might thus be defined as the maximum external torque of the quadriceps muscles.

Previous studies on the relationship between strength and joint angles have demonstrated a variation of the knee extensor torque between 0 and 90 degrees of flexion (Clarke et al. 1950, Houtz et al. 1957, Williams & Stutzman 1959). The results rather uniformly indicate a minimum of extensor strength in the extended position and a maximum at 50 to 70 degrees of flexion. This variation of the torque has been suggested to be due to several factors. The *lever of the quadriceps,* i. e. the perpendicular distance of the force resultant in the quadriceps tendon from the axis chosen, varies somewhat with the position of the knee joint and the patella (Figure 1). However, this varia-

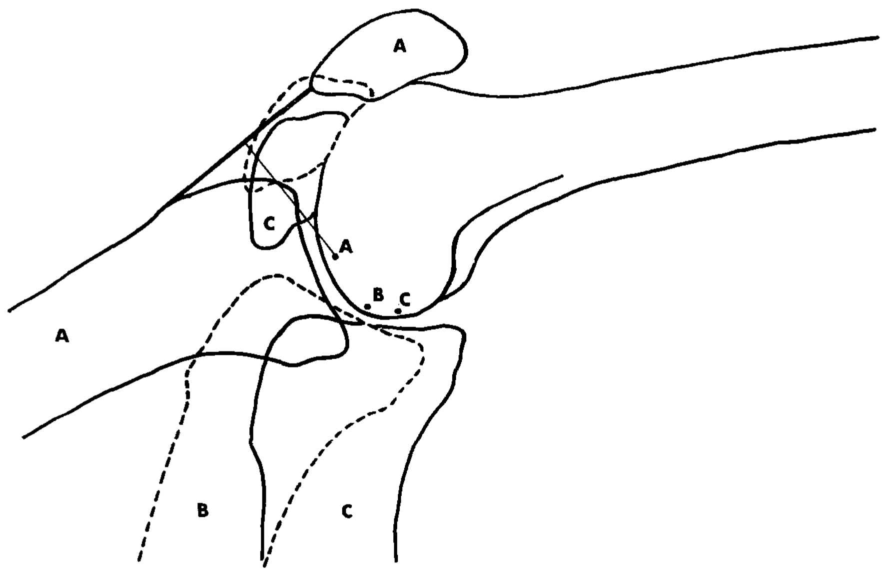


Figure 1. X-ray tracings of the knee of one of our subjects in three different positions, showing contact points corresponding to positions A, B and C and lever of quadriceps force in position A. The contours of the femoral condyles do not coincide, and only one contour is shown. Then "points of contact" lie between the condyles and represent the intersection of the contact line with a sagittal plane between the condyles. In studying the moments produced by forces around the knee joint, the customary axis of motion is not well suited for calculations. The lever lengths in positions A, B and C are 46, 47 and 43 millimeters respectively.

tion appears to be less than is often assumed. According to measurements reported by Lindahl & Movin (1967) the lever a_Q (Figure 2) varies approximately 25 per cent between 10 and 90 degrees of flexion. The variation of the torque in the above-mentioned studies amounted to at least 50 per cent.

The quadriceps contraction force Q (Figure 2) depends partly on the degree of *motor unit activity* (motor unit recruitment and discharge frequency) and partly on *muscle length* relative to resting length. As shown in the classical length-tension diagram of Blix (1894), using electrical stimulation of frog muscle, a certain length-tension relationship exists that is independent of motor unit activity. Eberhart & Inman (1947) found the same type of length-tension relationship in the biceps brachii of patients with cineplastic amputations. The authors checked motor unit activity by electromyography. At constant myoelectrical activity, active muscle tension has its maximum at resting

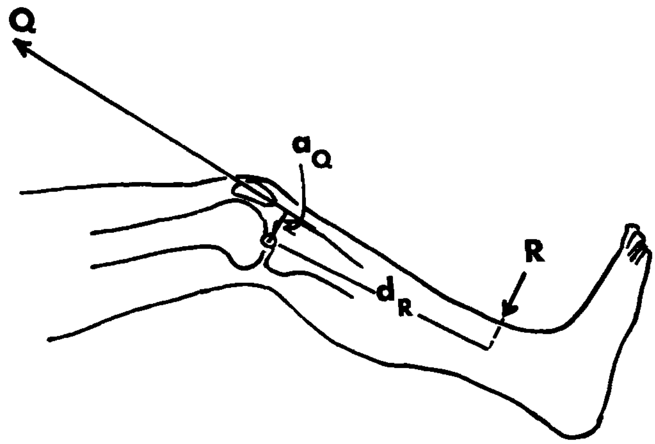


Figure 2. Rotatory equilibrium around the knee joint. Forces necessary for translatory equilibrium are not considered. R *= external resisting force,* d_R *= lever of* R*,* Q *= quadriceps contraction force,* a_Q *= lever of* Q*,* $M_{ext} = R \cdot d_R = Q \cdot a_Q = M_{int}$ *where* M_{ext} *and* M_{int} *are external and internal moments respectively.*

length of the muscle and decreases in the shortened and in the lengthened position.

The present investigation was planned as part of a research program on muscular dysfunction in orthopaedic conditions. It was the purpose to study the relative influence of the variables discussed above on knee extension strength in healthy subjects, with special regard to motor unit activity.

METHOD

The subject was seated on a quadriceps training table (O. Blomqvist, Sweden), leaning slightly backward, with the arms extended and the hands grasping the sides on the table (Figure 3). The thigh was strapped to the table. The leg being tested was attached to a resistance arm which was counterbalanced. The torque was registered through a strain gauge dynamometer, the chain from this being attached to a known constant lever arm. The angle between resistance arm and the lever arm could be altered stepwise.

The clinical degree of flexion during contraction was registered by means of an electric goniometer (Figure 4).

The myoelectrical activity was picked up by surface electrodes (diameter 12 mm) or pairs of subcutaneous needle electrodes (uncoated steel needles) from the vastus medialis and lateralis and the rectus

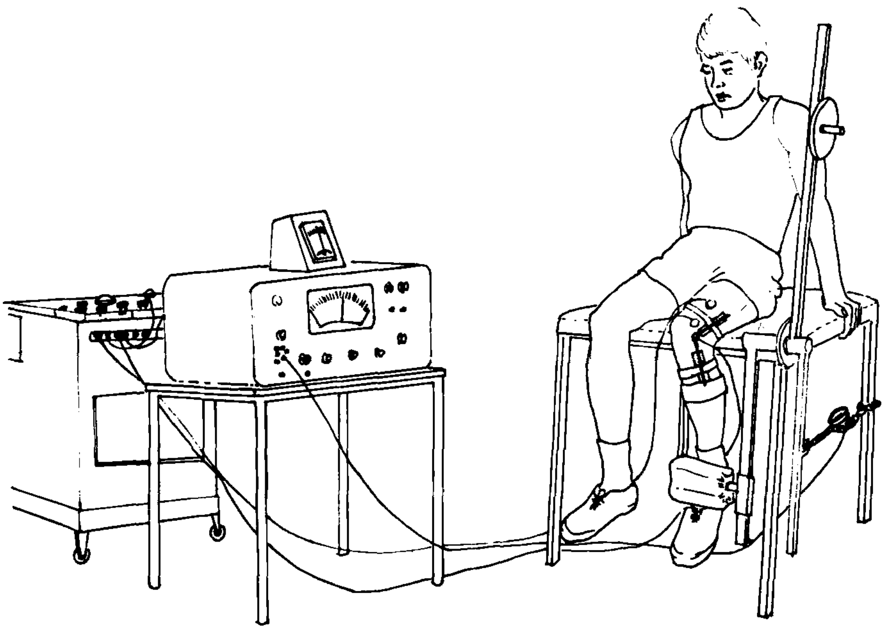


Figure 3. Experimental set-up. During testing the thigh is strapped to the table and the leg is attached to the resistance arm which is counter-balanced. The chain from the dynamometer is attached to a known constant lever arm. The angle between resistance arm and lever arm can be altered stepwise.

femoris, interelectrode distance 10–12 cm. This type of electrodes was chosen in order to record electrical output from an area as large as possible. Different positions of the electrodes along the longitudinal axis of the muscles did not influence the electromyographic records noticeably.

For amplification and integration a DISA electromyograph (type 13 A 69) was used. The electromyogram, the strain gauge tension and the joint angle were recorded simultaneously by a 4-channel Mingograph (Elema, Sweden). A recording during maximum voluntary contraction is shown in Figure 5. The mean amplitude of the integrated electromyogram was measured using a planimeter.

Registration was performed in each subject at 5 different angles between 10 and 90 degrees of flexion. In the *first part* of the investigation, knee extensor torque and electromyogram were recorded during *maximum voluntary contraction*. The maximum value of 3 consecutive contractions of 3 to 5 sec duration was measured. In the *second part*, measurement of the torque was repeated at *constant motor unit*

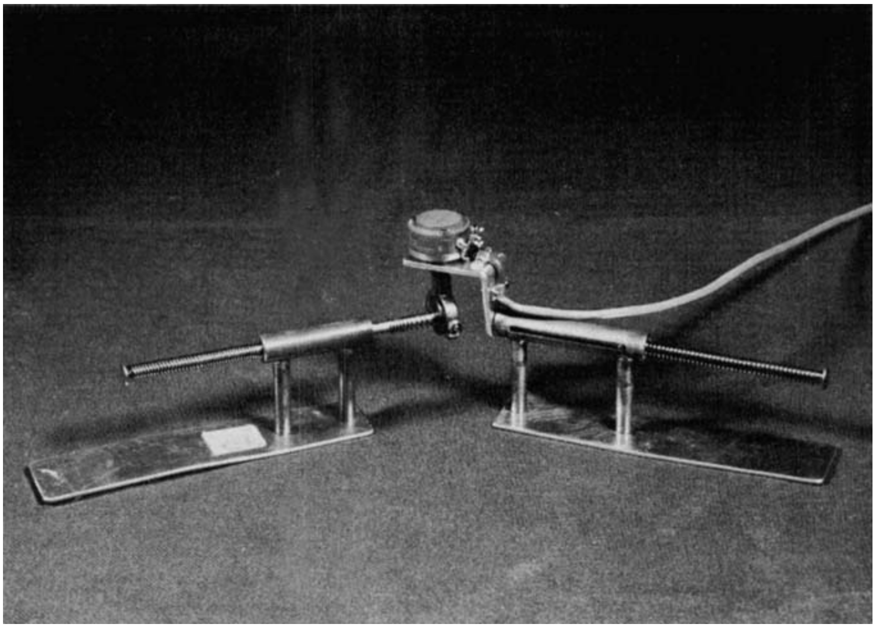


Figure 4. Electrogoniometer.

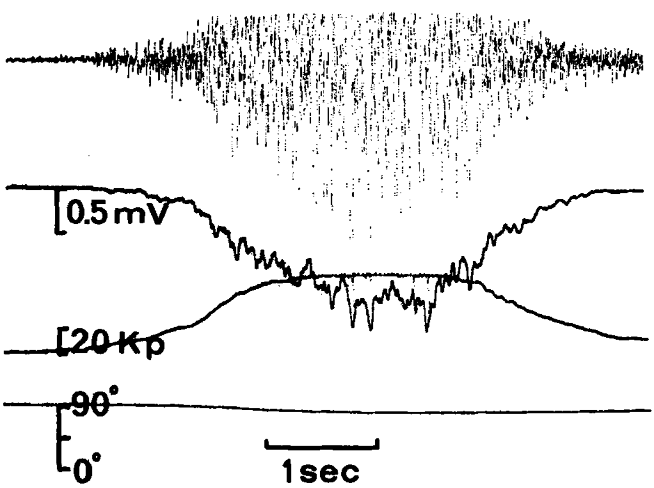


Figure 5. Example of simultaneous recording during maximum isometric contraction. From above: non-integrated EMG, mean voltage, strain gauge tension and joint angle.

activity, i. e. at constant EMG output. In order to obtain a constant amplitude of the myoelectrical activity, the integrated mean amplitude was made visible for the subject being tested by means of an indicator instrument, which was connected to the mean voltage input of the Mingograph. After some training most subjects were able to keep the indicator at a constant pre-set value during each contraction, which had to be submaximal. The mean value of the torque was calculated from 2 consecutive contractions which on the Mingograph record showed the correct EMG amplitude. Electromyographic recording during constant myoelectrical output was performed with the electrodes placed over the rectus femoris muscle only. In order to study the reproducibility of the torque values at constant myoelectrical activity, 5 subjects were re-examined at three different angles during one session. The joint angle could be reproduced with a difference of at most 5 degrees. The standard deviation of the torque was then found to amount to 4 per cent.

MATERIAL

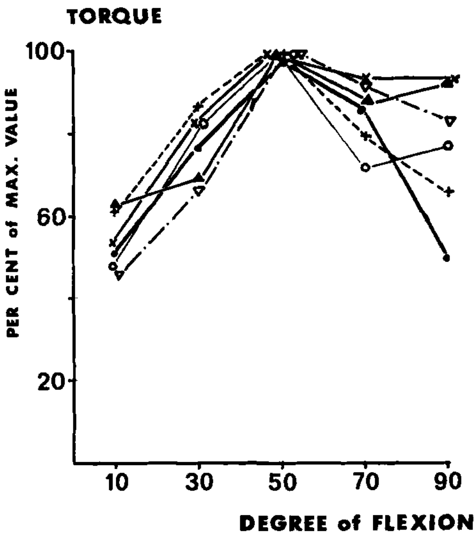
The material consisted of 19 healthy subjects in the age group 20 to 43 (15 females and 4 males). Fifteen subjects were studied at maximum voluntary contraction; 6 performed contractions with constant EMG output.

RESULTS

The main results are shown in Figures 6 through 8. Figures 6 shows the individual torque curves of 6 subjects. The curves tend to coincide at 50 degrees of flexion, where they all show a definite maximum. In more extended positions, the torque values decrease rather uniformly, which is in contrast to the scattering of values at 90 degrees of flexion. At 10 degrees of flexion, the average torque is reduced to about 50 per cent of maximum value (Figure 7).

At *maximum* voluntary contraction of the quadriceps, the average amplitude of the integrated electromyogram increased as the knee was held in a more flexed position, but the quantitative relationship between different subjects varied considerably. In addition, there was some difference between the subjects with regard to the slope of the curve. In contrast to the shape of the torque curve, the curves of the integrated EMG show an increase through the whole range of motion

Figure 6. Knee extension torque during maximum effort, individual curves.



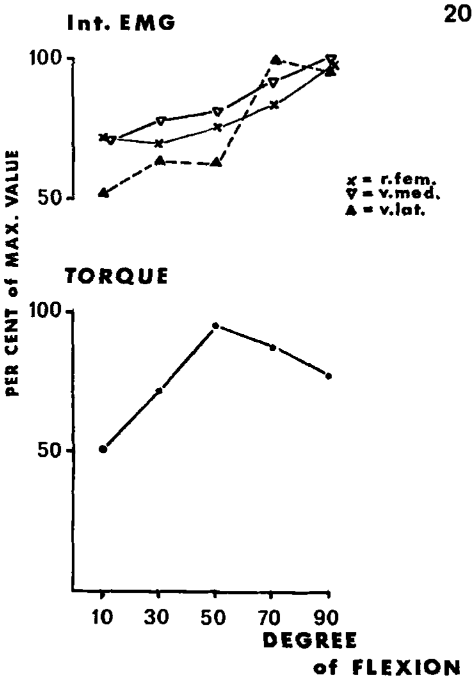


Figure 7. Integrated electromyogram (mean voltage) and torque during maximum effort, summation curves.

tested. The vastus medialis, vastus lateralis and rectus femoris muscles differ very little from each other in this respect.

When motor unit activity is kept constant, the average torque curve differs little from that of maximum voluntary effort (Figure 8). The maximum is shifted to a flexion angle slightly smaller and as flexion is increased from 50 to 90 degrees, torque falls to about 60 per cent of the maximum value.

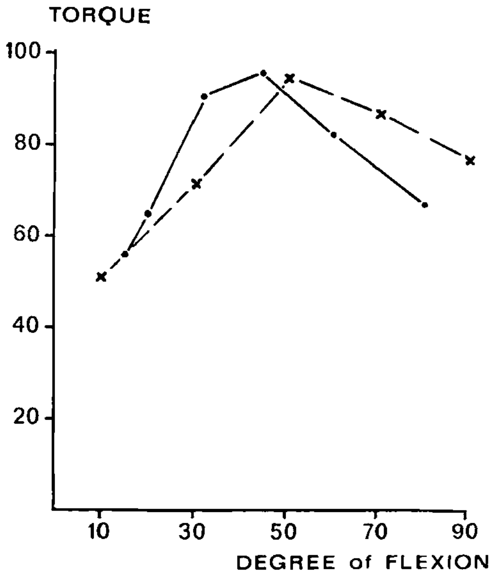


Figure 8. Knee extension torque at constant electromyographic output (· ——— ·) compared to the torque during maximum effort (x – – – x), summation curves.

DISCUSSION

The torque of the external force resisting knee extension is equal to the net sum of the torques caused by forces in internal knee structures such as the quadriceps tendon and the ligaments. It can easily be shown that in isometric knee extension there is no complete equilibrium between the quadriceps force and the external resisting force.

It was shown by Lindahl & Movin (1967) that the anterior cruciate ligament is well suited to provide the remaining force needed for equilibrium. The authors calculated the tension developed in this ligament at different flexion angles. Though a large tension in the cruciate ligament is necessary for the *translatory* equilibrium of forces, its *rotational* effect is quite small compared to that of the quadriceps force (about 5 per cent) and may be disregarded for practical purpose. Thus, we may consider that rotational equilibrium around the knee joint is maintained by the external force causing a flexion moment opposing the extending moment of the quadriceps force (Figure 2). The torque of the knee extensors at maximum voluntary contraction showed a considerable variation within the actual range of motion. The findings are in conformity with previous publications. In the present study the flexion angle for the maximum torque was about 50 degrees. This angle was practically identical for all subjects studied. This is of practical importance since weight-bearing in daily activities often occurs in a semiflexed position of the knee joint, e.g. during ascending and descending stairs.

Differences in myoelectrical activity during maximum effort in different positions appear to be of minor importance with regard to the characteristic shape of the torque curve between 10 and 90 degrees of flexion. This might be ascribed to a nonlinear relationship between averaged EMG and muscle tension. In a study on averaged EMG potential and tension of elbow flexors during isometric contraction, Zuniga & Simons (1969) observed "a marked terminal increase of EMG potential with no consistent increase in tension". This was suggested to be due to an increasing synchronization during maximum effort.

However, the increased electromyographical activity during maximum voluntary contraction in a more flexed position cannot be ascribed to synchronization only. In a study on quadriceps function, Lieb & Perry (1971) recorded electromyographical activity as action potentials per unit time. The authors report that the frequency count at 90 degree position was the highest value in the majority of subjects studied. This argues for a real increase in motor unit recruitment and/or discharge frequency in the more flexed position.

Since in our study the electromyographic findings were practically the same without regard to the position of the electrodes, it seems improbable that the variation of the integrated electromyogram can be ascribed to differences in the relation of the electrodes to the active muscle fibres.

If electromyographical activity is kept *constant* at a submaximal level, the slope of the torque curve is slightly increased toward extended and flexed position. Since the myoelectrical output is the same in all positions, the shape of the torque curve may be ascribed to variations of the lever and of the muscle length only.

It can be calculated from the figures published by Lindahl & Movin (1967) that changes of the lever length may account for at most 25 per cent reduction in the nearly extended position and for about 10 per cent in 90 degrees of flexion. The decrease of torque found in the present study amounted to 50 and 40 per cent respectively. According to Lindahl & Movin, the lever length appears to have its maximum at about 30 degrees of flexion, which is rather close to the angle for maximum torque when differences in motor unit activity are eliminated. It should be borne in mind, however, that the values are not strictly comparable since the joint angle was measured in a different way.

It is a common opinion that the vastus medialis comes into action only during final extension of the knee joint. As appears from the present study, however, this muscle has a pattern of motor unit activity during maximal contraction which is similar to that of the other muscles of the quadriceps within the range of motion studied. The findings are in conformity with those published by Brewerton (1955).

SUMMARY

Simultaneous recording of isometric knee extensor torque, integrated electromyogram from quadriceps muscles, and joint angle was performed in 19 healthy subjects.

The findings indicate that variation of the extensor torque between 10 and 90 degrees of flexion is only slightly affected by variation of maximum motor unit activity.

At constant myoelectrical activity the torque has its maximum at about 40 degrees of flexion. In the nearly extended position and at 90 degrees of flexion the torque is reduced by about 50 per cent. This variation of the torque is much larger than can be explained by lever proportions. Our findings suggest that variation of muscle length is at least of equal importance.

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