

Length and moment arm of human leg muscles as a function of knee and hip-joint angles

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Summary. Lengths of muscle tendon complexes of the quadriceps femoris muscle and some of its heads, biceps femoris and gastrocnemius muscles, were measured for six limbs of human cadavers as a function of knee and hip-joint angles. Length-angle curves were fitted using second degree polynomials. Using these polynomials the relationships between knee and hip-joint angles and moment arms were calculated. The effect of changing the hip angle on the biceps femoris muscle length is much larger than that of changing the knee angle. For the rectus femoris muscle the reverse was found. The moment arm of the biceps femoris muscle was found to remain constant throughout the whole range of knee flexion as was the case for the medial part of the vastus medialis muscle. Changes in the length of the lateral part of the vastus medialis muscle as well as the medial part of the vastus lateralis muscle are very similar to those of vastus intermedius muscle to which they are adjacent, while those changes in the length of the medial part of the vastus medialis muscle and the lateral part of the vastus lateralis muscle, which are similar to each other, differ substantially from those of the vastus intermedius muscle. Application of the results to jumping showed that bi-articular rectus femoris and biceps femoris muscles, which are antagonists, both contract eccentrically early in the push off phase and concentrically in last part of this phase.

Key words: Muscle length changes – Joint angle – Moment arm – Lower limb

Introduction

With the present interest in modelling the skeletomuscular system of the lower extremities (e.g. Gregoire et al. 1984; Bobbert et al. 1987), it is desirable to quantify the relationship between the length of the muscle ten-

don complexes and joint angles. This is particularly important for poly-articular muscles for which even the direction of length change is unknown during some specific movements, due to the opposing effects on muscle length of changes of the angles of the joints they span.

Frigo and Pedotti (1978) schematized the locomotor apparatus by modelling muscles as linear connections between the midpoints of their origins and insertions. Joints were represented as hinges. This simplification allowed the calculation of estimates of moment arm and length changes in the muscle tendon complex. Grieve et al. (1978) studied such length changes of the triceps surae muscle in the lower limbs of human cadavers. Their methods avoided any of the simplifications of muscle and joint geometry, as well as a choice of axis of rotation. In the present work, these methods were applied to other leg muscles with the aim of determining lengths of the heads of human quadriceps femoris muscle, of biceps femoris muscle and of gastrocnemius muscle as a function of lower limb joint angles.

Methods

Experimental procedure. The study was performed on six legs of five human cadavers (two males, three females). The limbs were separated from the rest of the body at the level of the fourth lumbar vertebra. The pelvis was separated in the median plane. Skin, fascia lata and muscle fascia were removed. The quadriceps femoris muscle, biceps femoris muscle (BF) and gastrocnemius muscle (G) were dissected. Of the quadriceps muscle the following parts were distinguished: rectus femoris muscle (RF), vastus intermedius muscle (VI), vastus medialis muscle medial part (VMM) and lateral part (VML) and vastus lateralis muscle medial part (VLM) and lateral part (VLL). The muscles studied were cut transversely at standard locations (Table 1). Other muscles that did not influence the position of the muscles studied were removed. Those muscles that, if removed, would have influenced the muscles studied were left in position but were cut to make joint movement possible. To obtain sufficient range of motion of the knee and hip joints, small incisions were made in the joint capsules. Subsequently Bandafix, a wide mesh elastic gauze bandage, was slipped

Table 1. Locations of transverse section of muscles

Rectus femoris:	10 cm distal of spina iliaca anterior inferior, and 2 cm proximal of basis patellae
Vastus medialis:	3.5 cm proximal of basis patellae
Vastus lateralis:	4 cm proximal of basis patellae
Vastus intermedius:	5.5 cm proximal of basis patellae
Gastrocnemius:	10 cm proximal of insertion on the calcaneus
Biceps femoris:	10 cm distal of tuber ischiadicum, and 13 cm proximal of insertion at caput fibulae

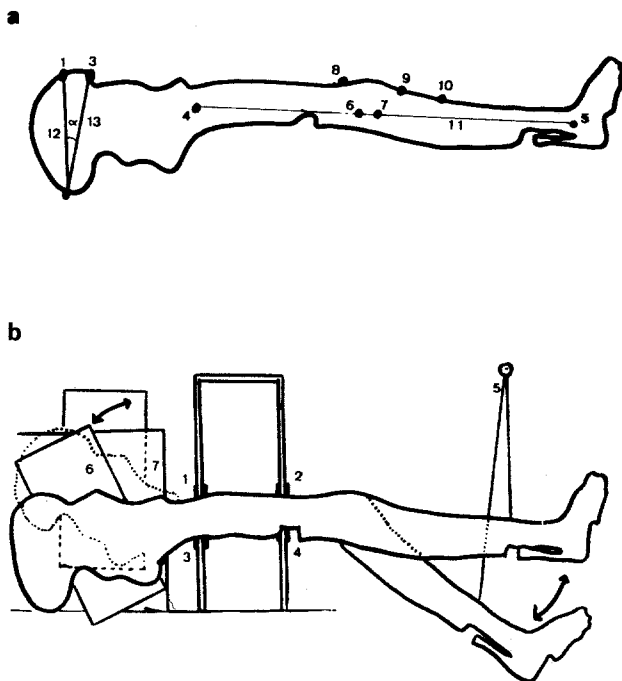


Fig. 1. Diagram of experimental set-up. **a** Positions of markers on the lateral side of the leg: 1, spina iliaca anterior superior (SIAS); 2, spina iliaca posterior superior (SIPS); 3, extra marker for determining hip joint angle; 4, most lateral aspect of trochanter major; 5, most lateral aspect of malleolus lateralis; 6, most distal aspect epicondylus lateralis femoris; 7, most proximal aspect condylus lateralis tibialis; 8, middle part of patella; 9, tuberositas tibiae; 10, extra marker for determining knee joint angle; 11, line between markers on trochanter major and malleolus lateralis, used for setting the reference position of the leg; 12, line between SIAS and SIPS; 13, vertical line (i.e. horizontal line when standing erect); in the reference position, an angle of 15° existed between lines 12 and 13. **b** Mounting frame and methods of changing joint angles: 1-4, clamps fixing the femur; 5, pulley; 6, plastic board attached to the pelvis; 7, part of reference frame

around the leg to hold the muscles together, much like a general fascia.

Experimental set-up. The legs were mounted in a special frame which had been constructed for this study. The femur was clamped to the frame, while the tibia and pelvis could be moved. The leg was positioned in the reference position corresponding to the posture of standing erect using markers on the frontal and lateral sides of the leg (Fig. 1a). In the reference position, the angle between the lines connecting the most lateral aspect of the tro-

chanter major and the most distal aspect of the epicondylus lateralis femoris with the line connecting the most lateral aspect of the malleolus lateralis and the most proximal aspect of the condylus lateralis tibialis was 0°. This position was referred to as 0° of knee flexion. For the hip joint, the reference position was defined by imposing an angle of 15° between the line connecting the spina iliaca anterior superior and the spina iliaca posterior superior and the vertical line. This position was referred to as 0° of flexion. In the reference position, the line between the spina iliaca anterior superior and the apex patellae (frontal plane) was maintained parallel to the sagittal plane.

A diagram of the experimental set-up is shown in Fig. 1b. Changes in hip-joint angle were brought about by moving a board with the pelvis firmly attached to it along another board that was part of the frame. Changes of knee-joint angle were made by allowing gravity to bend the leg, by easing off a cord connecting the tibia and the frame. With respect to the reference angles in the standard position the knee-joint angles studied ranged from 0° to 90° of flexion for the knee and from -15° to 60° of flexion for the hip. Knee- and hip-joint angles were changed in steps of approximately 5° as indicated by a goniometer. A photographic slide was taken at each position. In postexperimental analysis of the slides, the exact angle was determined. As the angle of one joint was varied, the other joint was fixed in the standard position.

The distances between the edges of the transverse cuts of each muscle or head at each joint angle represent ΔL_{oi} , the length of the muscle tendon complex relative to reference length. These distances were measured using a pair of compasses, a ruler and a Vernier caliper. For the vastus lateralis and medialis muscles these distances were determined at both the medial and lateral edges of the cut. Lengths were expressed as percentages of the segment length. Upper segment length was defined as the distance between the most lateral part of the trochanter major and the most distal point of the condylus lateralis femoris. Lower segment length was defined as the distance between the most proximal point of the epicondylus lateralis tibialis and the lateral tip of the malleolus lateralis. Segment lengths are shown in Table 2.

Analysis of data. The raw values for length of the muscles were fitted with a second degree polynomial by a method of least squares (Business Graphics, Apple Inc.):

$$\Delta L_{oi} = A_0 + A_1 \Theta_i + A_2 (\Theta_i)^2$$

where ΔL_{oi} represents the origin to insertion length relative to length in the reference position (as percentage of segment length) and Θ_i represents joint angle (in degrees); A_0 , A_1 , and A_2 are constants.

Muscle moment arms as a function of knee and hip joint angles were calculated, according to Bobbert et al. (1987) by the following equation:

$$d = (A_1 + 2 A_2 \Theta_i) \times 180/\pi$$

where moment arm (d) is expressed as a percentage of segment length and Θ_i is expressed in degrees; A_1 and A_2 are the same constants as above.

Table 2. Segment lengths of six limbs of five human cadavers

Cadaver	Upper segment length (mm)	Lower segment length (mm)	Side
A	406	376	right
B	380	352	right
B	384	344	left
C	416	394	right
D	421	391	left
E	398	357	right

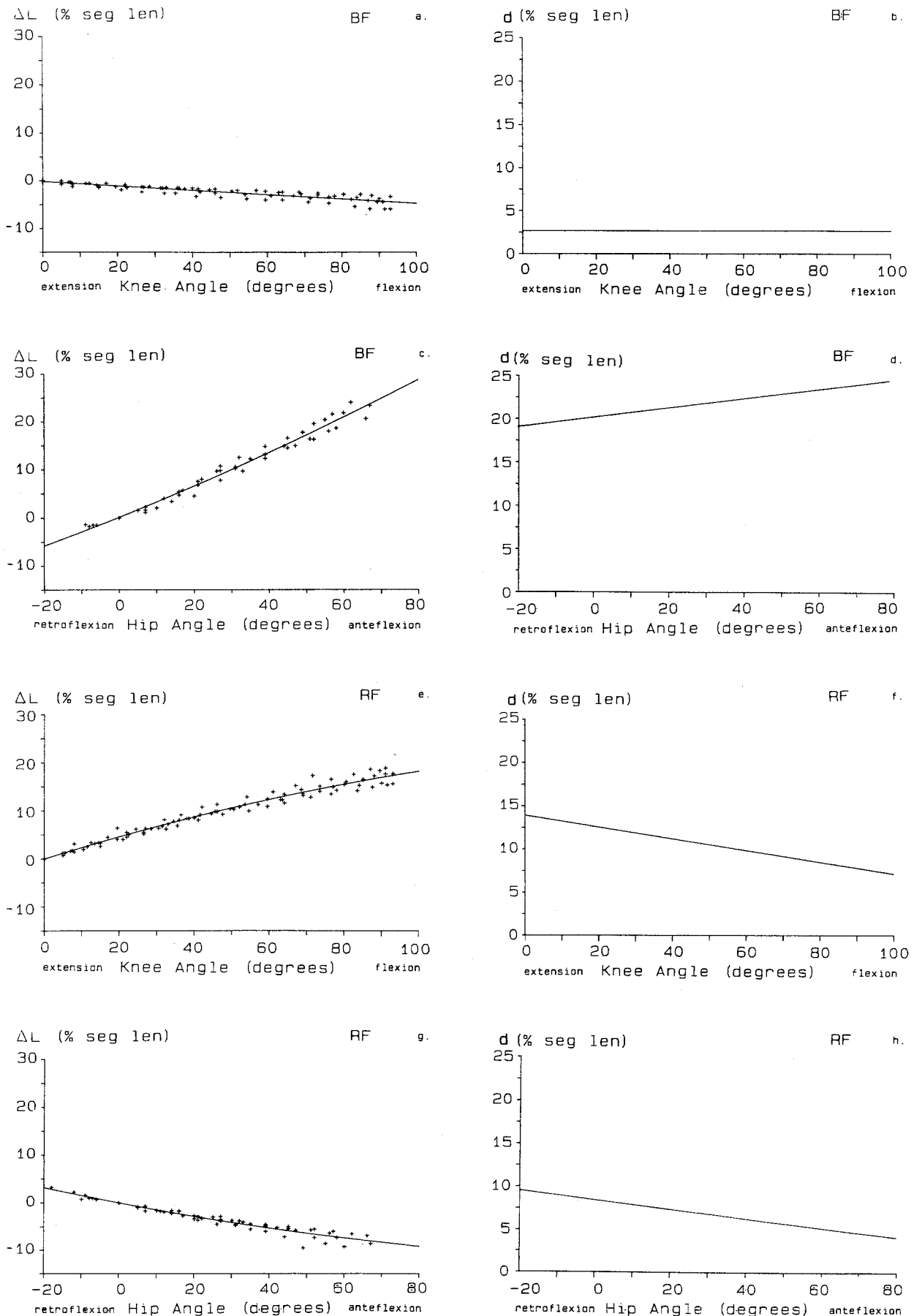


Fig. 2. Length of muscle tendon complex (ΔL) and moment arm (d) of bi-articular muscles as a function of knee and hip angle. **a** and **b** Biceps femoris (BF) at the knee joint; **c** and **d** BF at the

hip joint; **e** and **f** rectus femoris (RF) at the knee joint; **g** and **h** RF at the hip joint

Results

The ΔL_{oi} values as well as the moment arm are shown as a function of joint angle in Figs. 2, 3 and 4. The coefficients of the best-fit parabolas for length-angle curves are given in Table 3.

The effect of changing the hip angle on BF length was much larger than that of changing the knee angle (Fig. 2). This was caused by a difference of moment arms at the hip and knee joints. For RF the reverse was

true but the differences were not as striking. The moment arm of BF was found to remain constant throughout the whole range of knee flexion (Fig. 2) as was the case of VMM (Fig. 3).

Changes in the length of VML as well as VLM are very similar to those of VI to which they are adjacent, while those changes in length of VMM and VLL, which are similar to each other differed substantially from those of VI (Fig. 3).

For RF, a comparison of results for the left and

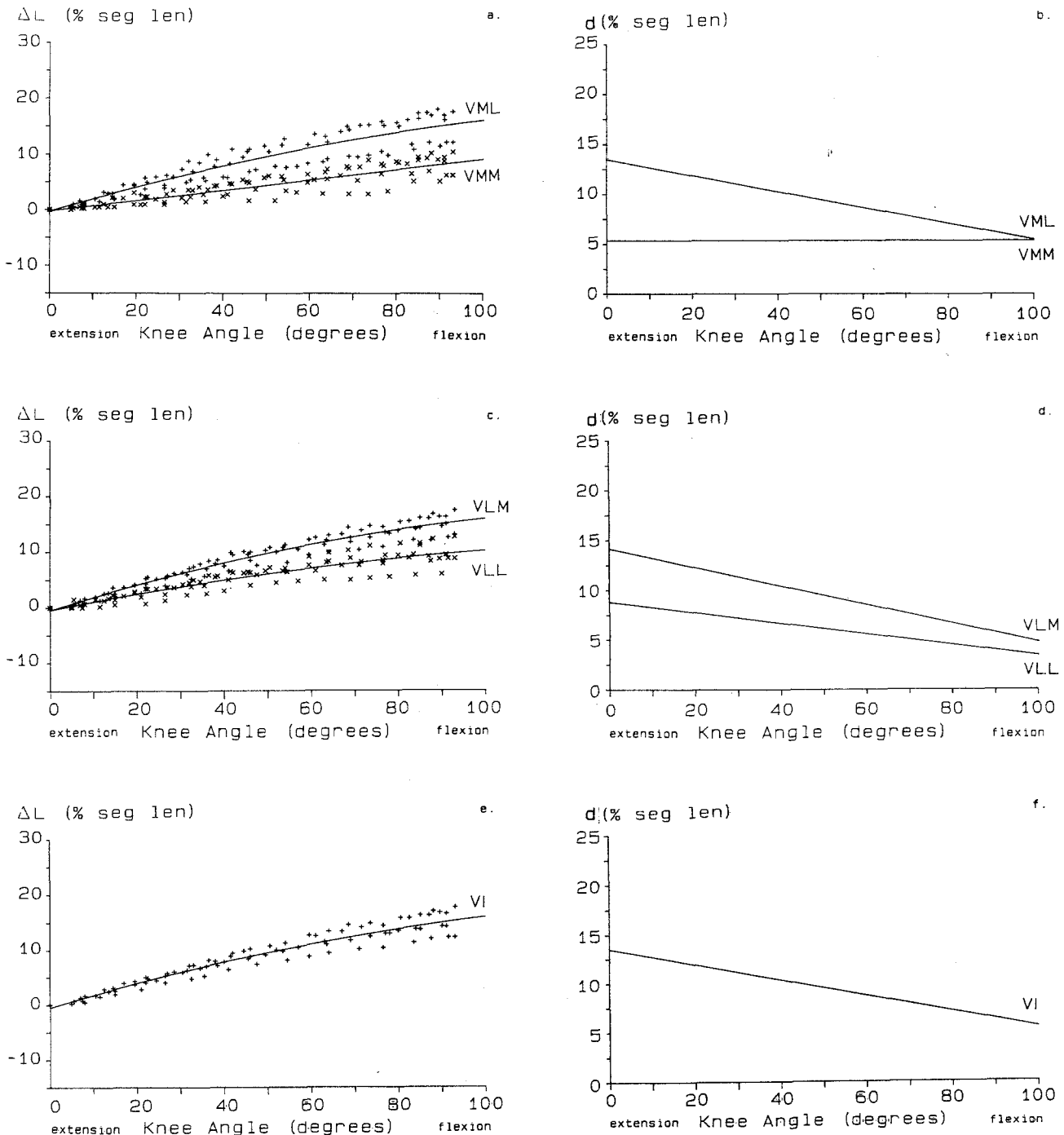


Fig. 3. Length of muscle tendon complex (ΔL) and moment arm (d) of muscles of the vasti as a function of knee angle. **a** and **b** Vastus medialis muscle [medial (VMM) and lateral (VML)

parts]; c and d vastus lateralis muscle [medial (VLM) and lateral (VLL) parts]; e and f vastus intermedius muscle (VI)

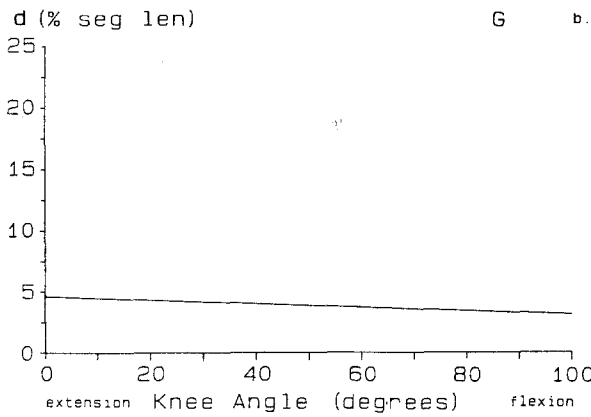
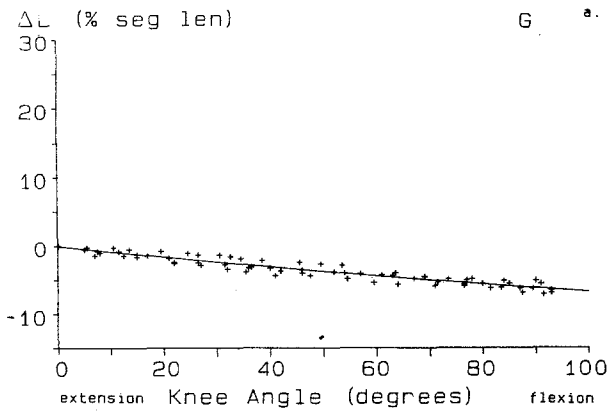


Fig. 4. Length of muscle tendon complex (ΔL) (a) and (b) moment arm (d) of gastrocnemius muscle (G) as a function of knee joint angle

right legs of one cadaver is shown in Fig. 5. It can be seen that raw data as well as fitted curves are very much alike, a result which was typical for all the muscles studied.

To test if, in the case of bi-articular muscles, length changes could indeed be considered the algebraic sum of changes caused by changing joint angles independently, some measurements were performed at a hip angle of 45° , in addition to those performed at 0° . Figure 6 shows that for RF the results are quite comparable. A similar result was found for BF.

Discussion

To compare our methods with those of Grieve et al. (1978), we also studied G . Comparison of fitted curves is shown in Fig. 7. The similarity between our results and those of Grieve et al. (1978) is also apparent from a comparison of the coefficients in the polynomial: A_0 equalled -0.08268 in the present work and 0.0 in the work of Grieve et al. For A_1 and A_2 , these values were -0.08028 vs -0.07987 and 0.00013 vs 0.00011 , respectively.

In the literature, no data are available concerning length changes of individual parts of the quadriceps fe-

Table 3. Coefficients and normalized standard errors (NSE) of fitted polynomials relating length of muscle tendon complex (in % segment length) to joint angle

Muscle	Joint	Constants			NSE
		A_0	A_1	A_2	
BF	knee	0.19826	-0.04600	-0.00000	0.45841
BF	hip	0.16644	0.31078	0.00061	0.14640
RF	knee	-0.02345	0.24222	-0.00059	0.17173
RF	hip	-0.01966	-0.15041	0.00044	0.25853
VML	knee	-0.29879	0.23517	-0.00070	0.35819
VMM	knee	-0.20848	0.09449	0.00001	0.44745
VLL	knee	-0.43341	0.15349	-0.00047	0.39248
VLM	knee	-0.50954	0.24677	-0.00082	0.22301
VI	knee	-0.51106	0.23557	-0.00070	0.25196
G	knee	-0.08268	-0.08028	-0.00013	0.29348

BF, Biceps femoris muscle; RF, rectus femoris muscle; VML, vastus medialis muscle lateral part; VMM, vastus medialis muscle medial part; VLL, vastus lateralis muscle lateral part; VLM, vastus lateralis muscle medial part; VI, vastus intermedius muscle; G, gastrocnemius muscle

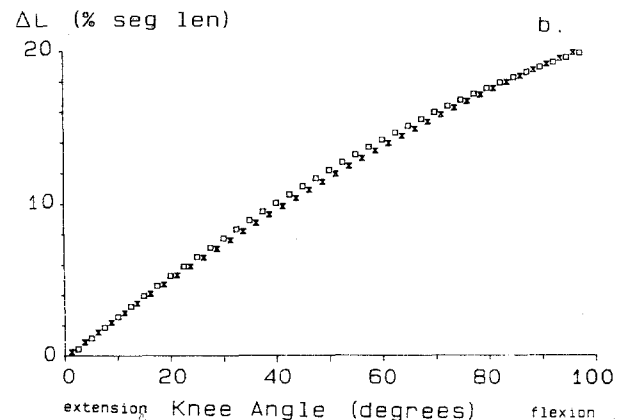
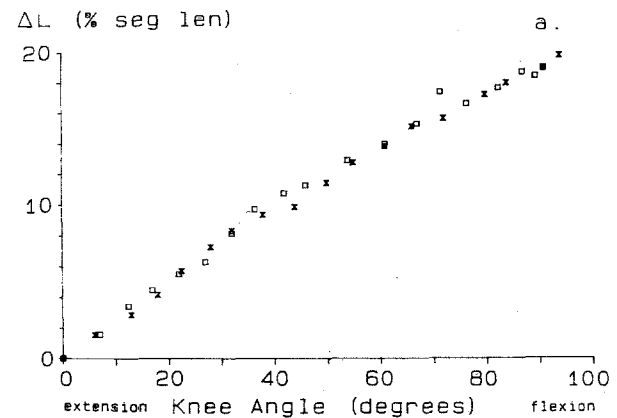


Fig. 5. Comparison of raw data (a) and fitted second degree polynomials (b) of length of muscle tendon complex (ΔL) of the rectus femoris muscle as a function of the knee angles of right and left legs of one cadaver

moris muscle. Frigo and Pedotti (1978) distinguished RF and the vasti muscles, viewing the latter as one part. Other authors (e.g. Lindahl and Movin 1967; Harding

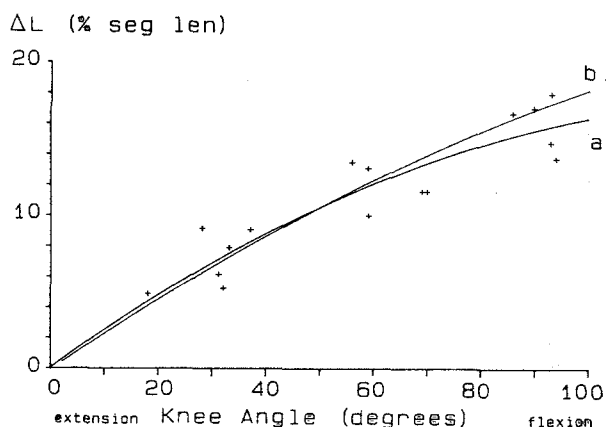


Fig. 6. Comparison of length of muscle tendon complex (ΔL) of the rectus femoris muscle as a function of knee angle measured at two different hip angles. Polynomial *a.* at a hip angle of 45° fitted to the raw data (+). For comparison, polynomial *b.* represents results obtained with a hip angle of 0° (see also Fig. 2e)

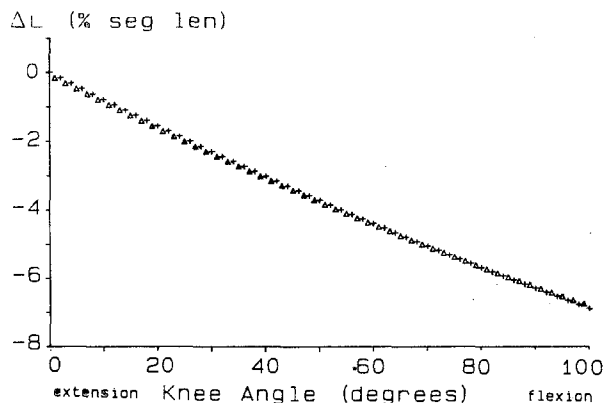


Fig. 7. Comparison of polynomials, describing length of muscle tendon complex (ΔL) of the gastrocnemius muscle as a function of knee joint angle, as obtained by Grieve et al. (+, 1978), to that of the present study (Δ)

et al. 1977; Wendt and Johnson 1985) considered the quadriceps femoris muscle as a single extensor mechanism as did Baratta et al. (1988). Harding et al. (1977) stimulated the quadriceps femoris muscle lengthening by a turnbuckle and reported a length change of 70 mm as a consequence of knee flexion from 0° to 90° . A similar value is reported by Lindahl and Movin (1967). Wendt and Johnson (1985) found a mean total excursion of the quadriceps femoris muscle of 66.2 mm. These length changes would correspond to a RF length change of 17% of mean upper segment length which agrees quite well with our findings.

As is the case with the quadriceps muscles no data are known to us concerning length changes in the muscle tendon complex with changing joint angles or moment arms for individual muscles of the hamstring group. Frequently this group is studied as a single muscle. The moment arm of BF at the hip joint takes on values ranging from 17% to 21% of segment length, for

joint angles between -20° and 60° . These values correspond to the calculated moment arms of the hamstrings in the study of Nemeth (1985). At the knee joint, values of the moment arm of BF found in the present study differed considerably from accepted values in the literature. Rasche and Burke (1976) mentioned a moment arm of 34 mm for the hamstrings at the knee joint. Smidt (1973) calculated the moment arm of the hamstrings to vary from 25 mm at 0° of knee flexion to 41 mm at 45° of flexion. Baratta et al. (1988) calculated similar values. We found BF moment arm at the knee to be fairly constant at levels of approximately 2.5% of upper segment length, corresponding to a mean moment arm of approximately 1 cm. This value is much smaller than those discussed above. Even though our results were not influenced by a choice of axis of rotation, they may have been affected by possible differences between the in vivo situation and cadaver material, relative to the degree of freedom of movement of the biceps tendon. This would have had little effect on the value found for the moment arm with the knee fully extended as the muscle belly would have been aligned with the tendon but the effect could be greater as the knee is flexed and the tendon would follow a more curved path. Further work on this subject seems to be required.

To give an example of the application of our results, particularly for bi-articular muscles, we calculated length changes as well as contraction velocities of RF and BF during the push off phase of vertical two-legged counter movement jumps (Fig. 8) using data from previous experiments in our laboratory (Van Soest et al. 1985). In that work origin to insertion lengths and contraction velocities of RF were calculated on the basis of angles and angular velocities obtained from high speed film analysis, by assuming fixed moment arms (4.4 cm and 3.9 cm at hip and knee joint, respectively). The pattern of these previous findings is qualitatively similar to our present results (compare Fig. 3 of van Soest et al. 1985 to the present Fig. 8b): early in the push off RF is performing an eccentric contraction at moderate velocities; at approximately $t = -150$ ms the contraction becomes concentric and rises within 100 ms to peak velocities, followed by smaller velocities as take-off approaches. However, our present results show values for peak velocity for RF equal to approximately 115% segment length, which for the subjects of van Soest et al. (1985), having an upper leg length of 47.8 cm (unpublished observations), would amount to a velocity of approximately $55 \text{ cm} \cdot \text{s}^{-1}$. It is clear that, in the work of van Soest et al. (1985), RF peak contraction velocity was underestimated considerably because of underestimation of moment arms at both hip and knee joints (see also Fig. 2f, h). A similar argument can be made for the maximal eccentric contraction velocity.

Considering the co-ordination and type of contraction of RF and BF, the following can be observed using our present data: early in the push-off phase (for approximately 30 s) both RF and BF muscle tendon complexes are contracting eccentrically, despite the fact that they are antagonists. This paradox can be explained as follows. For BF the shortening effects of hip

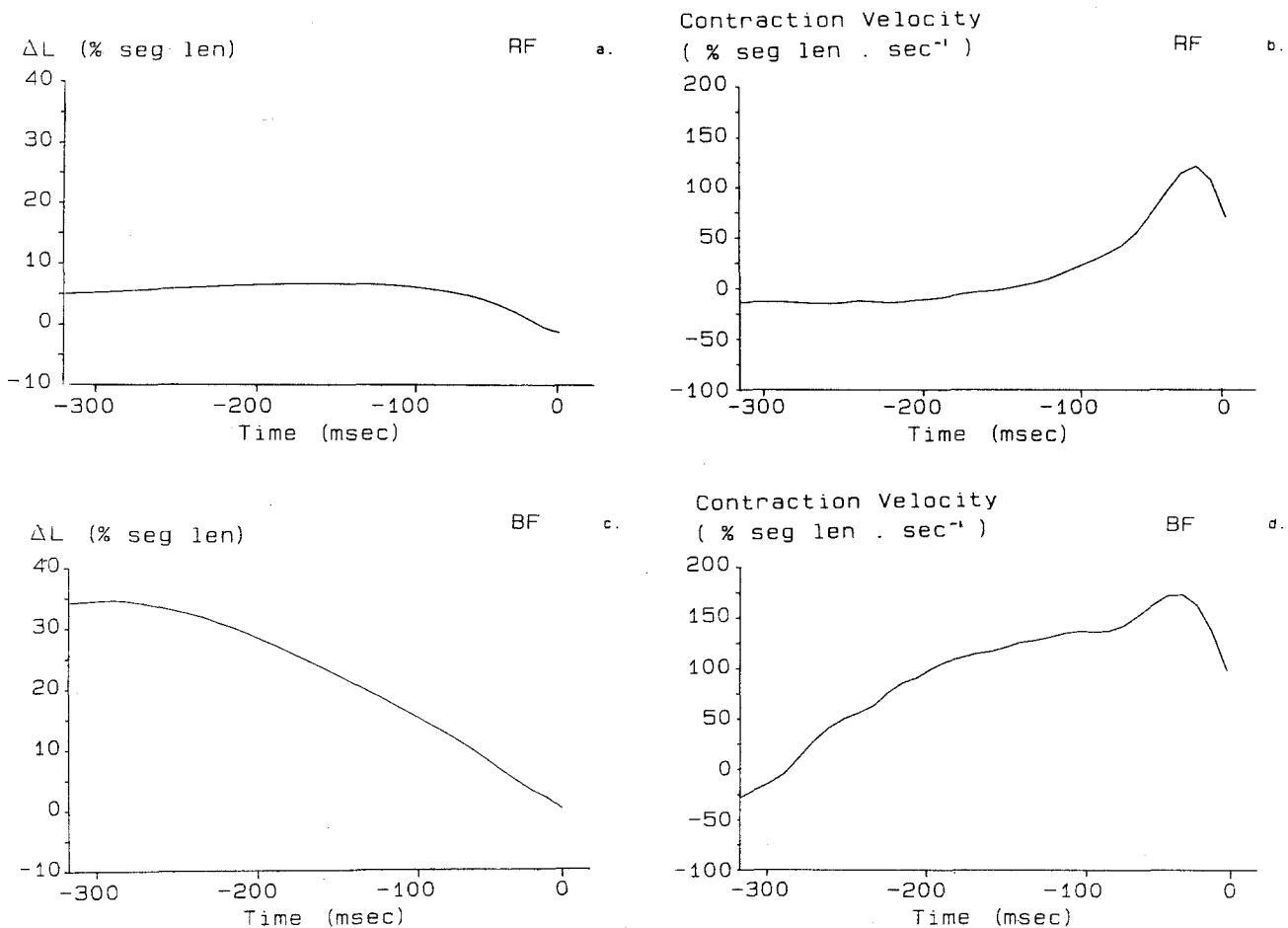


Fig. 8. Length (ΔL) and contraction velocity of rectus femoris (RF) and biceps femoris (BF) muscles, during the push-off phase of counter-movement jumps. These data were calculated using joint angle data of van Soest et al. (1985). Note that for length data (a and c) lengthening of the muscle was defined as

positive. However, in order to facilitate comparison with figures published by van Soest et al. (1985), velocity data (b and d) is presented so that shortening of muscle was defined as a positive velocity

extension are smaller than the lengthening effects of knee extension; for RF the shortening effects of knee extension are smaller than the lengthening effects of hip extension, due to the combination of actual values of angular velocities and moment arms. After this short period, BF is contracting concentrically delivering energy for the elevation of the trunk (i.e. hip extension) while RF is still contracting eccentrically and taking up part of this energy. Towards the end of the push-off (from approximately $t = -150$ ms) both RF and BF contract concentrically. Particularly for RF, contraction velocity rises with increasing slope, which will lead to a decreasing force due to the force velocity characteristics of the muscle tendon complex. As a consequence, elastic energy will be released from the tendinous structures of the muscle.

The mechanical effect of the pattern of length changes of BF and RF described above is that both bi-articular muscles can initiate the concentric parts of their contraction at much higher forces than would be the case if starting isometrically or concentrically. The

work that can be delivered by the muscle fibres, as well as elastic energy released from the tendinous tissues in the concentric phase of the contraction, is increased. Some of the energy delivered at the hip by (poly- as well as mono-articular) hip extensors will be transported to the knee by RF (e.g. Bobbert and van Ingen Schenau 1988).

It should be noted that the results of the present study provide no quantitative information on length changes taking place within the muscle tendon complex (i.e. length changes of tendinous structures and muscle fibres or sarcomeres). Such information is necessary for a complete understanding of movement and would involve taking into account muscle architecture as well as length-force characteristics of tendons and aponeuroses. However, it is clear that more detailed information on length changes in human muscle tendon complexes will allow an increased understanding of the role muscles play in the execution of movement. This seems to be particularly true for the role of poly-articular muscles.

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