J. Anat. (1991), **176**, 133–137
Printed in Great Britain

Ratios of cross-sectional areas of muscles and their tendons in a healthy human forearm*

ALISON CUTTS, R. McN. ALEXANDER† AND R. F. KER†

Rheumatism and Rehabilitation Research Unit, University of Leeds, LS2 9NZ and † Department of Pure and Applied Biology, University of Leeds, Leeds LS2 9JT

(*Accepted* 4 *December* 1990)

INTRODUCTION

Tendons stretch when their muscles develop tension and recoil elastically when the muscles relax. Their elastic compliance has several consequences for muscle structure and function.

Firstly, there is a consequence for the control of movement (Rack & Ross, 1984). Tendon compliance makes it more difficult to hold a joint in position against a fluctuating force because force fluctuations change the length of the tendon, even if the muscle fibres maintain precisely constant lengths. Thus tendon compliance tends to make control of joint position more difficult. At the same time, it makes it easier to control force (as is necessary, for example, when holding delicate objects), because it reduces the force changes that result from small changes of muscle fibre length.

Secondly, stretched tendons store elastic strain energy which is returned when they recoil. A runner loses and regains kinetic and gravitational potential energy in each step, but much of this energy is stored in the tendo calcaneus and other compliant structures. Thus the work that the muscles have to do is reduced (see Ker *et al.* 1987).

Thirdly, muscle fibres may have to shorten more than would otherwise be necessary, to compensate for the stretching of their tendons. Ker, Alexander & Bennett (1988) argued that a thinner tendon will require longer muscle fibres (capable of shortening more) and so increased muscle mass. They suggested that the combined mass of muscle plus tendon could be minimised by choosing an optimum area ratio (the ratio of the physiological cross-sectional area of the muscle to the cross-sectional area of the tendon). Their theory suggests an optimum area ratio of 34, implying that when a muscle exerts 0·3 MPa (a typical isometric stress for vertebrate striated muscle) the stress in an optimum tendon would be about 10 MPa. This is very much less than the breaking stress of tendon in tension, which is about 100 MPa.

Ker *et al.* (1988) measured area ratios for many of the limb muscles of a wide variety of mammals and calculated the stresses that would act in the tendons when the muscles exerted 0·3 MPa. Most of these stresses lay between 5 and 25 MPa, with a mode at about 13 MPa (close to the theoretical optimum), but a few tendons were subject to much higher stresses; for example, 67 MPa for the human tendo calcaneus. These highly stressed tendons are believed to be important as strain energy stores in running. If they were thicker they would store less strain energy, for given force, and so be less effective in that role.

The material studied by Ker *et al.* (1988) included human leg muscles and their tendons, but no arm muscles. Many of the muscles of the forearm have long tendons,

* Reprint requests to Professor Alexander.

but these cannot serve as strain energy stores in running. We may expect them to have area ratios of about 34, corresponding to tendon stresses (in maximal isometric contractions) of about 10 MPa.

In this paper we report measurements of area ratios for the muscles of the forearm. Dissecting room cadavers generally have their muscles wasted by a period of inactivity (due to age or illness) before death. The physiological cross-sectional areas of their muscles are obviously less than in healthy, active people and we cannot be confident that there have been proportionate changes in their tendons. To avoid the danger that this would bias our results we thought it essential to make our measurements on an arm that was known to have been healthy and in active use shortly before amputation. Regrettably, we were able to obtain only one such arm.

It can be calculated from Fig. 3D of Brown, Rack & Ross (1982) (using also anatomical data from Rack & Ross, 1984) that flexor pollicis longus can impose stresses up to about 15 MPa on its tendon, a little more than the theoretical optimum. Amis, Dowson & Wright (1979) and Brand, Beach & Thompson (1981) measured physiological cross-sectional areas of arm muscles from cadavers, but did not report tendon dimensions.

MATERIALS AND METHODS

The measurements were made on the arm of a man aged about 20 years, that was amputated midway along the humerus after an accident in which he fell under a railway train. The second metacarpal was fractured but there were no other injuries to the hand or forearm. The elbow–fingertip distance was 468 mm, which is 0·5 standard deviations below the mean (480 mm) for British men aged 19–25 years (Pheasant, 1986). The arm looked healthy and muscular. It was not embalmed but had been stored deeply frozen.

The muscles and tendons were dissected out in turn. The specimen was kept moist by covering it with damp tissues in the intervals between the removal of successive muscles. A measured length cut from each tendon was weighed and its cross-sectional area calculated from its length and mass, assuming a density of 1120 kg/m^3 (Ker, 1981). The belly of each muscle was weighed and then cut in the plane of its fascicles. The lengths of the fascicles were measured from tendon of origin to tendon of insertion in several parts of the muscle. The physiological cross-sectional area of a muscle is $(m/\rho l)\cos\alpha$ where m is the mass of the muscle, ρ its density, l the mean fascicle length and α the angle of pennation (see, for example, Yamaguchi *et al.* 1990, equation A5). If the angle of pennation is small, its cosine is close to 1·00 and the physiological cross-sectional area is approximately $(m/\rho l)$. This approximation was used because the angles of pennation of all forearm and hand muscles for which data are available are less than 15° (Yamaguchi *et al.* 1990), so that $\cos\alpha$ lies between 0·97 and 1·00. The density of muscle was assumed to be 1060 kg/m^3 (Mendéz & Keys, 1960).

RESULTS

Table 1 shows the dimensions of muscles and of their tendons. It includes only those muscles with reasonably long tendons, for which we were able to determine tendon cross-sectional areas. Masses and fascicle lengths were also determined for a further 19 muscles, for which we did not obtain tendon areas. Some use is made of these additional data in the Discussion section below, but they are not presented in detail because the area ratios, which are the principal subject of this paper, could not be calculated. They will be made available on request.

Table 1. *Dimension of muscles in the forearm and of their tendons of insertion. This table includes only the muscles with reasonably long tendons, the cross-sectional areas of which were measured. (P)CSA means (physiological) cross-sectional area. The area ratio is (muscle PCSA)/(tendon CSA).*

	Mass (g)	Fascicle length (mm)	Muscle PCSA (cm^2)	Tendon CSA (cm^2)	Area ratio
Muscles of the wrist					
Flexor carpi ulnaris	49·7	56	8·42	0·248	34
Flexor carpi radialis	35·0	49	6·81	0·122	56
Extensor carpi ulnaris	38·2	56	6·44	0·169	38
Extensor carpi radialis longus	47·4	90	5·00	0·129	39
Extensor carpi radialis brevis	40·5	49	7·81	0·195	40
Extrinsic flexors of the digits					
Flexor pollicis longus	26·5	60	4·17	0·113	37
Flexor digitorum superficialis II	24·3	58+*		0·109	
Flexor digitorum superficialis III	42·2	88	4·53	0·151	30
Flexor digitorum superficialis IV	22·6	89	2·40	0·104	23
Flexor digitorum superficialis V	19·3	58+32*	2·04	0·044	46
Flexor digitorum profundus II	37·2	75	4·68	0·131	36
Flexor digitorum profundus III	47·1	88	5·05	0·130	39
Flexor digitorum profundus IV+V	73·4	100	6·92	0·230	30
Extrinsic extensors of the digits					
Extensor pollicis longus	11·5	55	1·98	0·120	17
Extensor pollicis brevis	8·0	53	1·43	0·028	51
Extensor indicis	9·3	49	1·78	0·059	30
Extensor digitorum II	7·6	65	1·10	0·044	25
Extensor digitorum III	14·7	70	1·98	0·080	25
Extensor digitorum IV	11·7	73	1·52	0·057	27
Extensor digitorum V	10·0	73	1·30	0·038	34
Extensor digiti minimi	11·3	59	1·81	0·045	40
Others					
Abductor pollicis longus	23·8	50	4·49	0·133	34
Mean ± standard deviation					35±9

* This muscle has two bellies in series (see Brand *et al.* 1981). We unfortunately failed to measure the fascicle length of the second belly of flexor digitorum superficialis II.

The area ratios shown in Table 1 are 35±9 (mean and standard deviation). The mean is almost identical with the optimum (34) calculated from the theory of Ker *et al.* (1988). There is little difference between the area ratios for the muscles of the wrist (41±8), the extrinsic flexors of the hand (34±7) and the extrinsic extensors (31±11).

DISCUSSION

The total mass of muscle in the forearm was 765 g and in the hand 92 g. In contrast, Amis *et al.* (1979) found only 483 g muscle in the forearm of a cadaver of 'stout muscular build'. Large differences of mass have been found between homologous muscles of different cadavers (Friederich & Brand, 1990, on leg muscles) but it seems likely that our values for a healthy arm are more typical of healthy adults than are the values that Amis *et al.* (1979) obtained from their cadaver.

Brand *et al.* (1981) did not publish muscle masses but we estimate below, from their physiological cross-sectional areas, that the muscles of their cadavers had masses nearly 20% less than homologous muscles of our specimen. They gave the mass of each forearm or hand muscle only as a fraction of the total. We have calculated mass fractions similarly from our data, and find that in most cases they are very similar. The ratio

$$\frac{\text{mass fraction determined by us}}{\text{mass fraction determined by Brand } et\ al. \text{ (1981)}}$$

for the 41 muscles common to the two data sets is $0{\cdot}99 \pm 0{\cdot}23$ (mean and standard deviation). The mean is very close to 1·00 but the standard deviation reflects differences between the data sets for individual muscles.

Brand *et al.* (1981) published standard deviations as well as means for the mass fractions of the muscles of their 15 cadavers. We find from their data that the coefficients of variation (standard deviation divided by mean) of their values for the mass fractions of the muscles had a mean value of 0·26. This is close to the coefficient of variation of the ratio of our mass fractions to theirs ($0{\cdot}23/0{\cdot}99 = 0{\cdot}23$, see above). This shows that the differences in distribution of mass fractions, between the two data sets, are not more than might have been expected.

The muscle fascicle lengths measured by us were $1{\cdot}19 \pm 0{\cdot}25$ (mean and standard deviation) times the values given for the same muscles by Brand *et al.* (1981). The generally greater lengths measured by us cannot be explained by any differences of joint position that there may have been between the specimens, which would have made some muscles longer and others shorter. Our specimen may have been larger than theirs, or we may have stretched the muscles slightly during dissection. It is more difficult to measure fascicle lengths in fresh specimens such as we used, than in embalmed ones. (We left our specimen unembalmed, to avoid altering muscle masses.)

The physiological cross-sectional areas of the muscles of our forearm and hand totalled 135 cm^2. Brand *et al.* (1981) report the mean total physiological cross-sectional area for the same muscles, for five arms 'with no undue wasting or postmortem change'. They give a value of 141 cm^2, but this would have been 136 cm^2 (almost identical with our value) if they had used the same value for muscle density as we did in their calculations. If muscles of our specimen had the same physiological cross-sectional area as theirs but had fascicles about 20% longer (see above), they must have had about 20% more mass.

The overall mean area ratio of 35 (Table 1) corresponds to a tendon stress of 10·5 MPa, if the muscle exerts 0·3 MPa. The strain in a tendon subjected to this stress would be about 1·3% (Ker *et al.* 1988). The extensors and superficial flexors of the digits have tendons of origin as well as of insertion, so the effective lengths of their tendons can be calculated by subtracting muscle fascicle length from the overall length of muscle plus tendon (Ker *et al.* 1988). The ratio of the fascicle lengths of these muscles to their effective tendon lengths had a mean value of 0·22, so 6% shortening of the fascicles would be needed to compensate for the 1·3% strain in the tendons that was estimated above. The longest of these tendons had effective lengths of about 350 mm, so 1·3% stretching would amount to 5 mm.

SUMMARY

The muscles and tendons in the forearm and hand of a young man, amputated after an accident, have been weighed and measured. The physiological cross-sectional areas of those muscles that had long tendons were 35 ± 9 (mean and standard deviation) times the cross-sectional areas of the tendons. The mean is very close to the optimum

calculated from the theory of Ker, Alexander & Bennett (1988). It implies that the tendons experience stresses of about 11 MPa and strains of about 1·3%, when the muscles exert their maximum isometric forces. Very much larger forces would be needed to break the tendons.

REFERENCES

AMIS, A. A., DOWSON, D. & WRIGHT, V. (1979). Muscle strengths and musculo-skeletal geometry of the upper limb. *Engineering in Medicine* **8**, 41–48.

BRAND, P. W., BEACH, R. B. & THOMPSON, D. E. (1981). Relative tension and potential excursion of muscles in the forearm and hand. *Journal of Hand Surgery* **6**, 209–219.

BROWN, T. I. H., RACK, P. M. H. & ROSS, H. F. (1982). Forces generated at the thumb interphalangeal joint during imposed sinusoidal movements. *Journal of Physiology* **332**, 69–85.

FRIEDERICH, J. A. & BRAND, R. A. (1990). Muscle fibre architecture in the human lower limb. *Journal of Biomechanics* **23**, 91–95.

KER, R. F. (1981). Dynamic tensile properties of the plantaris tendon of sheep (*Ovis aries*). *Journal of Experimental Biology* **93**, 283–302.

KER, R. F., ALEXANDER, R. McN. & BENNETT, M. B. (1988). Why are mammalian tendons so thick? *Journal of Zoology* **216**, 309–324.

KER, R. F., BENNETT, M. B., BIBBY, S. R., KESTER, R. C. & ALEXANDER, R. McN. (1987). The spring in the arch of the human foot. *Nature* **325**, 147–149.

MENDÉZ, J. & KEYS, A. (1960). Density and composition of mammalian muscle. *Metabolism* **9**, 184–188.

PHEASANT, S. (1986). *Bodyspace: Anthropometry, Ergonomics and Design*. London: Taylor & Francis.

RACK, P. M. H. & ROSS, H. F. (1984). The tendon of flexor pollicis longus: its effects on the muscular control of force and position at the human thumb. *Journal of Physiology* **351**, 99–110.

YAMAGUCHI, G. C., SAWA, A. G. U., MORAN, D. W., FESSLER, M. J. & WINTERS, J. M. (1990). A survey of human musculotendon actuator parameters. In *Multiple Muscle Systems: Biomechanics and Movement Organization* (ed. J. M. WINTERS & S. L.-Y. WOO), pp. 717–773. New York: Springer.