Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders

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SALE, D. G., J. D. MACDOUGALL, S. E. ALWAY, AND J. R. SUTTON. *Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders.* J. Appl. Physiol. 62(5): 1786–1793, 1987.—Eight untrained women (F), 13 untrained men (M), and 11 male bodybuilders (BB) did maximal elbow flexions on an isokinetic dynamometer at velocities of 30, 120, 180, 240, and 300°/s, from which impact torque (IT), peak torque (PT), and work (W) were measured. Biceps and total flexor cross-sectional area (CSA) were measured by computerized tomographic scanning. Muscle fiber area, fiber composition, and collagen volume density were determined from single needle biopsies of biceps brachii. Biceps fiber number was estimated as the ratio of biceps CSA (corrected for connective tissue) to mean fiber area. PT and W decreased at higher velocities in M and BB but not in F; consequently, the correlation between CSA and PT and W was lower at 300°/s (r = 0.58, 0.60) than 30°/s (r = 0.80, 0.79). The ratio of PT to flexor CSA was similar in all groups at 30°/s, whereas F had greater ratios than M and BB at the remaining velocities. F had greater W/CSA ratios than M and BB at all velocities. IT increased at higher velocities in all groups; the increase was greater in F and M than in BB. In contrast to PT and W, the correlation between IT and CSA was greater at 300°/s (r = 0.67) than 30°/s (r = 0.58), and there were no differences among groups in the IT/CSA ratios. Flexor CSA correlated negatively with the ratio of IT, PT, and W to CSA. Muscle fiber composition failed to correlate with any measure of strength. M and BB had greater biceps area, fiber number, and fiber area than F. Biceps CSA correlated positively with both fiber area (r = 0.81) and fiber number (r = 0.60).

muscle cross-sectional area; muscle fiber number; torque-velocity relation

VOLUNTARY STRENGTH correlates positively with muscle cross-sectional area (11, 16, 22). The correlation is high when the subject sample includes females, males, and strength-trained males, thereby obtaining a large range in values for strength and muscle cross-sectional area (11, 22). The importance of muscle size to voluntary strength is also shown if strength is expressed per unit muscle cross-sectional area (CSA); females, males, and strength-trained males, who differ greatly in strength and muscle size, do not differ in the ratio of strength to muscle CSA (11, 22).

The correlation between muscle CSA and voluntary strength is based on measurements of isometric (11, 16) and low-to-moderate velocity concentric contraction strength (22). It is not known whether the degree of correlation is altered for strength measured at higher velocities, or whether females, males, and strength-trained males have similar high- as well as low-velocity strength/muscle CSA ratios. For example, strength training alters the strength-velocity relationship (2, 3, 6) and could affect both the correlation between muscle CSA and strength (force or torque) measured at different velocities and the strength/muscle CSA ratio determined at different velocities. Variation in muscle size may also affect the strength/muscle CSA ratio by altering the orientation of muscle fibers with the tendon's line of pull (14); the effect may be greater at higher contraction velocities. Therefore, one purpose of the present study was to determine the effect of velocity of contraction on the correlation between strength and muscle CSA and on the strength/muscle CSA ratio in subjects varying greatly in absolute strength, muscle size, and state of training.

We previously reported that male bodybuilders do not have a greater estimated muscle fiber number in biceps brachii than untrained males, despite the bodybuilders having much bigger muscles. There was a trend, however, toward a correlation between muscle CSA and estimated fiber number (13). We considered whether even larger group differences in muscle size might result in significant differences in fiber number and a significant correlation between muscle CSA and fiber number. Therefore, the second purpose of the present study was to estimate biceps fiber number in a group of untrained females and to compare their results with those obtained in untrained males and male bodybuilders.

METHODS

Subjects. Eight untrained women, 13 untrained men, and 11 male bodybuilders served as subjects. Their physical characteristics are presented in Table 1. Five bodybuilders were classified as elite on the basis of the degree of their muscle hypertrophy and their success in competition; the remaining six were classified as intermediate (13). All subjects participated with their own informed consent in accordance with the policies of the Ethics Committee of the McMaster University Medical Centre.

Voluntary strength. Voluntary strength of the elbow flexors was measured with an isokinetic dynamometer

TABLE 1. *Physical characteristics of subjects*

	Age, yr	Ht, cm	Mass, kg	Elbow Flexor Area, cm^2	Humerus Area, cm^2	Ratio of Flexor Area to Humerus Area
Females	21.0±0.6	166.2±2.0	59.8±2.0	10.8±0.6	3.69±0.19	2.94±0.13
Males	22.5±1.5	176.5±1.5*	74.4±2.0*	22.4±1.5*	4.90±0.17*	4.55±0.26*
Bodybuilders	24.8±1.6	173.5±1.4†	82.6±2.9*‡	35.2±2.5*§	5.72±0.33*	6.19±0.33*§

Values are means ± SE; N = 8 for females, 13 for males, and 11 for bodybuilders. * $P < 0.01$, † $P < 0.05$ for differences between females and male groups. ‡ $P < 0.05$, § $P < 0.01$ for differences between bodybuilders and untrained males.

(Cybex II, Ronkonkoma, NY). The test was conducted with the subject seated with the dominant upper arm supported in the horizontal plane on a padded table. The axis of the elbow joint was aligned with the axis of the dynamometer lever arm. The end of the adjustable (for length) lever arm had a handle that the subject grasped with the forearm supinated. A series of three to five maximal voluntary concentric contractions were performed in order at angular velocities of 30, 120, 180, 240, and 300°/s (300°/s is the upper velocity limit of the dynamometer). Subjects were instructed to begin contractions with the elbow fully extended and to continue the contraction through the greatest possible range of movement.

The undamped torque signal from the Cybex transducer was displayed on one channel of an oscillograph recorder (Hewlett-Packard 7402A, San Diego, CA). The second channel of the recorder displayed the torque-time integral of each contraction (Fig. 1). Three measurements were made: *1)* impact torque (IT), the initial torque overshoot produced when the accelerating limb and dynamometer lever arm engage the resistance mechanism of the dynamometer (a separate evaluation of the Cybex torque transducer indicated that the torque overshoot was not a transducer artifact) (17); *2)* peak torque (PT), the greatest torque developed during the contraction after IT; and *3)* work (W), the torque-time integral multiplied by the angular velocity (in rad/s) at which the contraction was done. IT increased at higher velocities and on some occasions the oscillations after IT made it difficult to determine PT (Fig. 2). Our success in overcoming the difficulty is indicated by the high correlation found between PT and W (Table 2).

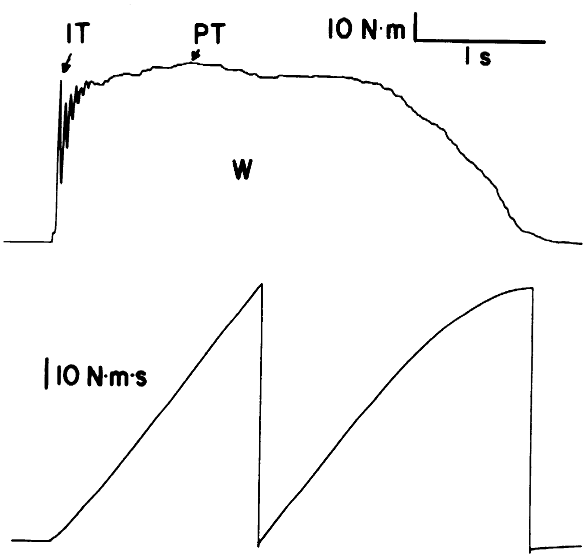

FIG. 1. Recording of elbow flexion at 30°/s in a male subject. Torque recording (*top*) shows impact torque (IT) and peak torque (PT). Work (W, area under torque-time recording) was calculated as product of torque-time integral, taken from second channel (*bottom*) and angular velocity (in rad/s). Torque-time integral channel saturated and reset every 100 N·m·s. IT and PT were expressed in newton meters and W in joules.

Muscle and bone area. Cross-sectional area of biceps was determined from computerized tomography scans as described previously (13). From the scan selected for measurement of biceps area, total flexor cross-sectional area (biceps plus brachialis) and humerus cross-sectional area were also measured.

Muscle fiber characteristics. Muscle fiber characteristics of biceps brachii were determined from single needle biopsy samples by methods described in detail previously (13). Measurements included percent fiber type (types I and II from a minimum of 550 fibers per biopsy), fiber area (types I and II and mean fiber area for a minimum of 200 fibers of each type per biopsy), and percent collagen and other noncontractile tissue. Biceps fiber number was estimated by dividing the mean fiber area into the biceps cross-sectional area (corrected for connective tissue).

Statistics. Descriptive statistics included means ± SE. The results of the strength measurements were analyzed by a two-way analysis of variance (group, velocity, and interaction). The results of the remaining measurements were analyzed by one-way analysis of variance. Differences among group means were tested by the Tukey method. Pearson product correlation coefficients (r) were computed between pairs of variables. The probability level accepted for statistical significance was $P < 0.05$.

RESULTS

Voluntary strength (Fig. 3). Male bodybuilders (BB) had greater IT, PT, and W at all velocities than untrained males (M) and untrained females (F). M had greater IT, PT, and W at all velocities than F except for PT and W at 240°/s. There was a significant ($P < 0.001$) interaction between group and velocity in PT and W; PT and W decreased at higher velocities in M and BB but not in F. IT increased at higher velocities ($P < 0.001$) in all groups, although M and F showed a greater increase than BB (group × velocity interaction, $P < 0.05$).

IT increased at higher velocities in all groups, whereas PT decreased (M and BB) or did not change (F); therefore, the ratio of IT to PT increased ($P < 0.001$) at higher velocities (Fig. 4). At 30 and 120°/s, the IT/PT ratios were similar in the three groups, whereas at higher velocities the IT/PT ratios were greater in M and BB

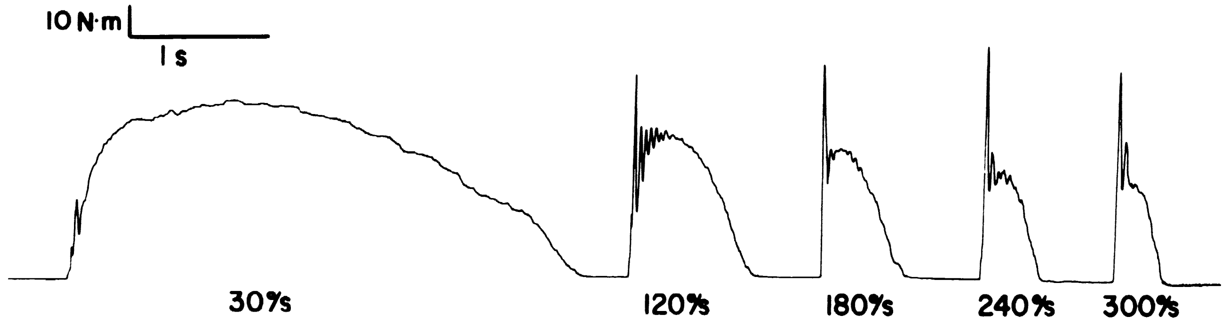

FIG. 2. Contractions done at test velocities by a male subject. Impact torque (IT) increased at higher velocities, whereas peak torque (PT) and work decreased. Oscillations after IT occasionally made determination of PT difficult at highest velocities.

TABLE 2. *Correlations among impact torque, peak torque, and work*

	Velocity, deg/s				
	30	120	180	240	300
Impact torque vs. peak torque	0.70	0.75	0.89	0.83	0.86
Peak torque vs. work	0.96	0.98	0.97	0.89	0.92
Impact torque vs. work	0.72	0.75	0.88	0.83	0.82

$N = 32$. All correlations significant at $P < 0.001$.

than in F (group × velocity interaction, $P < 0.001$).

There was a high correlation between PT and W at all velocities (Table 2). The correlations between IT and PT and between IT and W were lower.

Elbow flexor cross-sectional area (Table 1). The BB and M possessed about three and two times, respectively, the elbow flexor CSA of F; BB had 1.6 times the flexor CSA of M.

Relationship between strength and flexor CSA. Strength measured as torque is a function of muscular force (related to CSA) and muscle moment arm length. The latter was not measured directly but was considered to be proportional to body height (22). Therefore, IT, PT, and W were correlated with the product of CSA and body height (CSA × BH) with the latter expressed in meters. Significant positive correlations were found between CSA × BH and IT, PT, and W at all velocities (Table 3). For PT and W, the correlation coefficients were smaller in order from the lowest to highest velocities, whereas for IT, the opposite pattern was obtained. The highest correlation found was for PT at 30°/s (Fig. 5).

Strength/muscle CSA ratio (Fig. 6). There were no significant differences among the groups in the ratio of IT to CSA × BH. F had greater PT/CSA × BH ratios than M and BB at all velocities except 30°/s. F had greater W/CSA × BH ratios than M and BB at all velocities. M and BB did not differ significantly in the PT and W ratios.

Relationship between muscle CSA and strength/muscle CSA ratio (Table 4). Significant negative correlations were found between CSA and the ratios of IT, PT, and W to CSA × BH, with the exception of IT at 180 and 240°/s. The correlations tended to be more negative at higher velocities. The most negative correlation was for

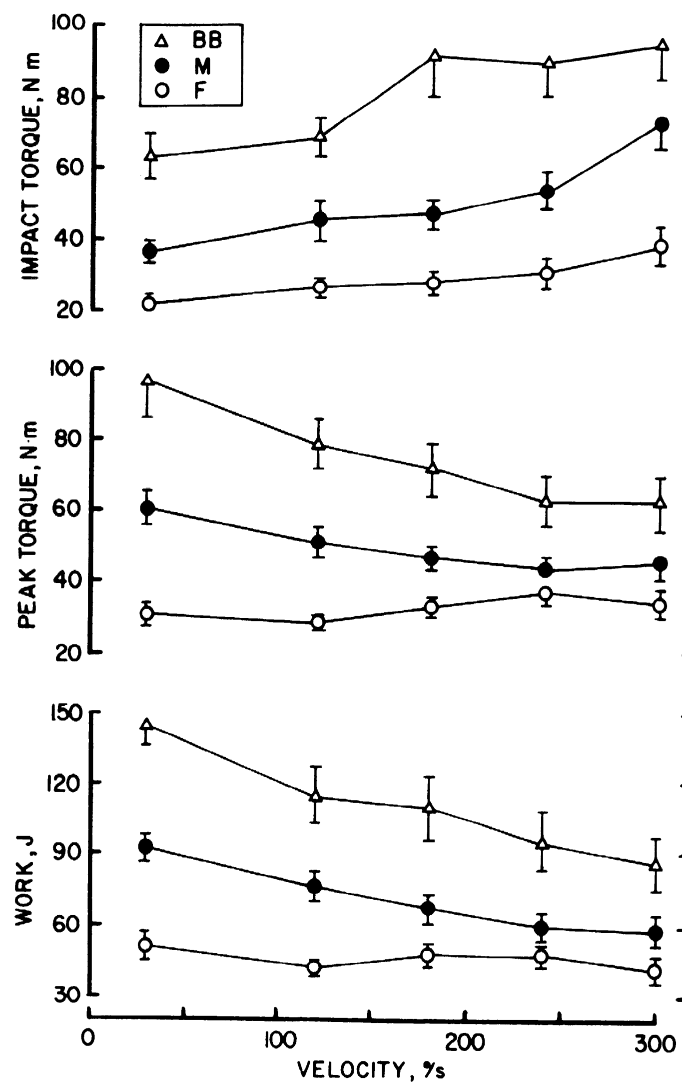

FIG. 3. Elbow flexion impact torque (*top*), peak torque (*middle*), and work (*bottom*) in untrained females (F), untrained males (M), and male bodybuilders (BB). Values are means ± SE. All differences between groups were significant ($P < 0.05$) except that M did not differ from F in peak torque and work at 240°/s.

PT at 240°/s (Fig. 7).

Biceps brachii. M and BB had greater fiber numbers, mean fiber area, and muscle CSA than F (Fig. 8, Table 5). There was a positive correlation between CSA and both mean fiber area and fiber number (Fig. 9). Biceps

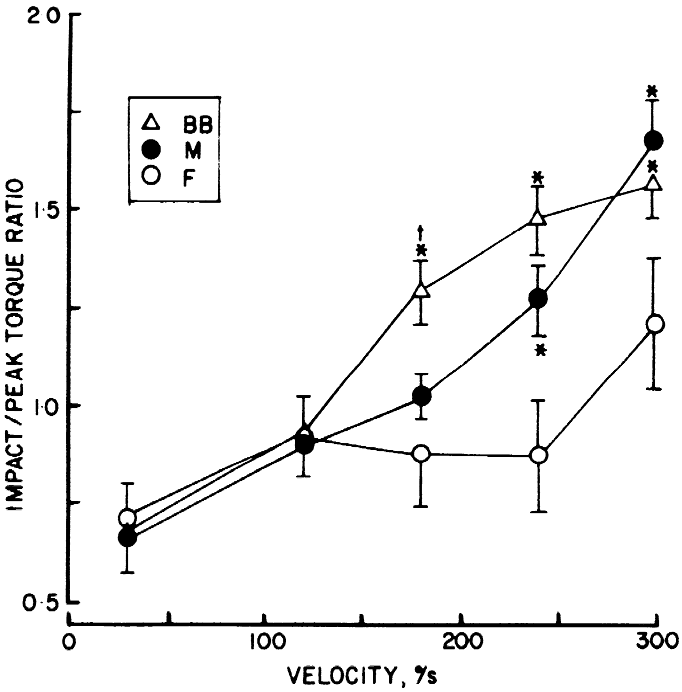

FIG. 4. Ratio of impact torque to peak torque in females (F), males (M), and male bodybuilders (BB). Values are means ± SE. * $P < 0.01$ for differences between F and M groups. † $P < 0.05$ for differences between M and BB groups.

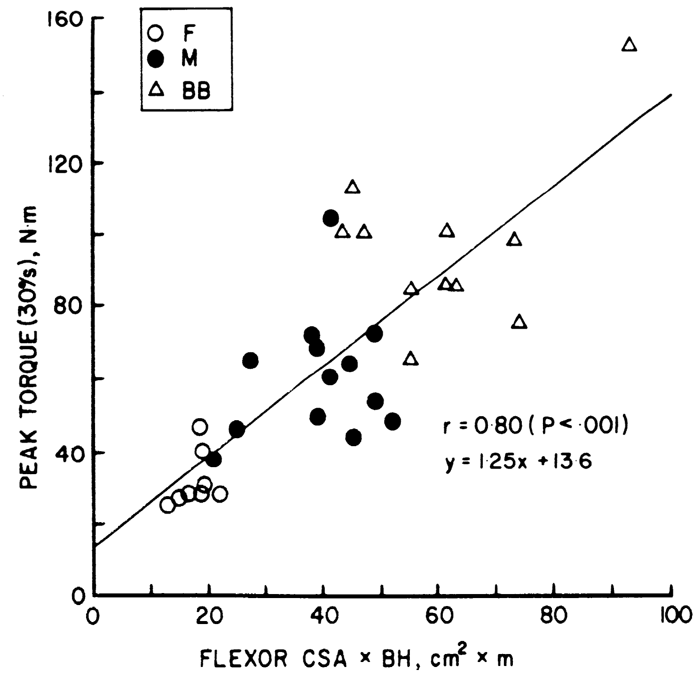

FIG. 5. Correlation between elbow flexion peak torque at 30°/s and product of flexor cross-sectional area (CSA) and body height (BH). Individual values for females (F), males (M), and bodybuilders (BB) are shown ($N = 32$).

TABLE 3. *Correlation between product of flexor cross-sectional area and body height and absolute values of impact torque, peak torque, and work*

	Velocity, deg/s				
	30	120	180	240	300
Impact torque	0.58	0.65	0.75	0.71	0.67
Peak torque	0.80	0.78	0.77	0.58	0.58
Work	0.79	0.78	0.70	0.65	0.60

$N = 32$. All correlations significant at $P < 0.001$.

CSA correlated highly ($r = 0.98$, $P < 0.001$) with total (biceps plus brachialis) flexor CSA.

The three groups had similar percent type II fibers and percent type II fiber area, although the bodybuilders had a higher II/I area ratio than the females (Table 5). There was no correlation between percent type II fibers, percent type II fiber area, or II/I area ratio and IT, PT, and W expressed absolutely or in relation to CSA × BH.

The relative amount (percent) of collagen and other noncontractile tissue was greater in the F than in M and BB, whereas the converse was true for the absolute amount of this tissue. M and BB were similar in these two measures (Table 5). There was a significant negative correlation ($r = -0.63$, $P < 0.001$) between mean fiber area and the relative amount (percent) of connective tissue within the muscle.

DISCUSSION

The present study confirmed previous reports of *1)* a high correlation between elbow flexor CSA and isometric (11) and low-velocity concentric (22) strength, *2)* similar ratios of low-velocity concentric (22) and isometric (11) strength to muscle CSA in groups differing greatly in muscle size and strength, and *3)* no correlation between muscle fiber composition and the ratio of strength to muscle CSA (15, 22). At the higher velocities (120–300°/s) we tested, however, the correlations between strength (PT and W) and muscle CSA × BH were lower, and F had greater ratios of strength to muscle CSA than M and BB. These two findings were caused by the decrease in PT and W at higher velocities in M and BB but not in F; the smaller differences among groups (i.e., smaller variance) at higher velocities lowered the correlations (5).

PT and W normally decline at higher velocities on an isokinetic dynamometer (e.g., 7, 20, 24) even when, as in the present study, the highest velocity tested (300°/s) is only ~35% of maximum velocity of unresisted elbow flexion (4, 18). Thus F's lack of decline in PT and W was unusual, although in a previous study elbow flexion PT declined only ~4% between the velocities of 30 and 180°/s in a group of mostly females (8). Also, we have recently repeated the test protocol on separate groups of untrained men and women and male bodybuilders. The results (unpublished observations) indicated a small decline in torque at higher velocities in women; however, the decline was much less than in the male groups.

Muscle fiber composition of one of the elbow flexors (biceps) did not cause the "flat" PT- or W-velocity relation in F because F did not differ from M and BB in %II fibers or %II area in this muscle. Nor was there a correlation between muscle fiber composition and the ratios of PT and W to CSA × BH at any velocity. We cannot exclude the possible influence of muscle fiber composition in the other elbow flexors. The flat relation in F was probably not related to maximum unresisted

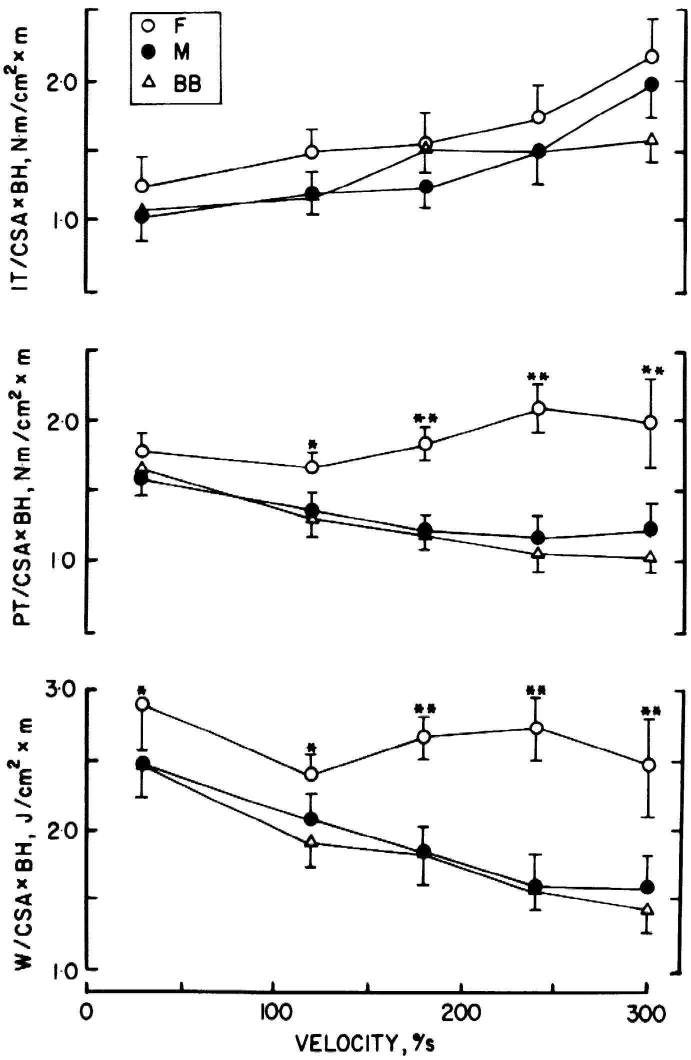

FIG. 6. Ratios of impact torque (IT, *top*), peak torque (PT, *middle*) and work (W, *bottom*) to product of flexor cross-sectional area and body height (CSA × BH). Values are means ± SE for untrained females (F), untrained males (M), and male bodybuilders (BB). * $P < 0.05$, ** $P < 0.01$ for differences between F and male groups (M & BB).

TABLE 4. *Correlation between flexor cross-sectional area and IT, PT, and W expressed in relation to the product of flexor area and height*

	Velocity, deg/s				
	30	120	180	240	300
Impact torque	−0.41	−0.40	−0.18	−0.34	−0.49
Peak torque	−0.37	−0.50	−0.61	−0.67	−0.55
Work	−0.45	−0.49	−0.52	−0.58	−0.55

IT, impact torque; PT, peak torque; W, work. $N = 32$. $r = 0.35$ for $P < 0.05$.

elbow flexion velocity because females have a maximum velocity similar to (18) or less than (4) males.

The relatively greater PT and W at higher velocities in F may be partly due to a sex difference in the shape of the isometric strength curve of elbow flexion; the optimal joint angle for voluntary torque is 90° in females and 120° in males (180° = full extension) (19). The smaller optimal angle in females would be an advantage because in doing contractions at higher velocities on an

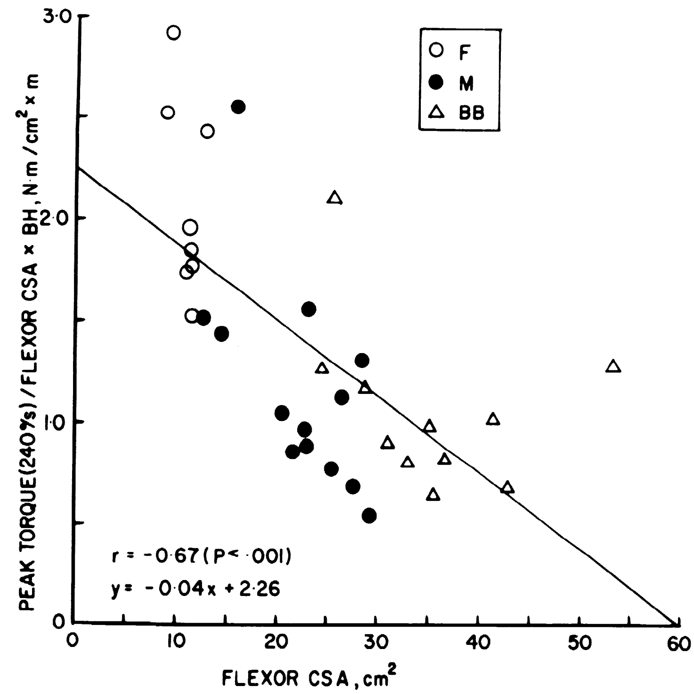

FIG. 7. Correlation between elbow flexor cross-sectional area (CSA) and ratio of peak torque at 240°/s to product of CSA and body height (BH). Individual values for untrained females (F), untrained males (M), and male bodybuilders (BB) are shown ($N = 32$).

isokinetic dynamometer, a greater range of movement (toward smaller joint angles) is traversed before the resistance mechanism is engaged and peak torque is developed. Females also show less relative decline in torque at joint angles smaller than the optimal angle (19). This would be an advantage because at higher isokinetic velocities the torque-time integral or work is more dependent on torque developed at small joint angles (it would also be an advantage at low velocities and may account for the greater W/CSA × BH ratio in F even at 30°/s). The relatively greater decline in torque at smaller joint angles in males (19) may result from their larger muscles that "bulge" during shortening. The bulging may cause many muscle fibers to be aligned more obliquely to the tendons' line of pull; the more oblique the alignment of fibers, the smaller the net force parallel to the tendons' line of pull (14). The negative correlation we found between flexor CSA and the ratios of PT and W to CSA × BH, with a trend to higher negative correlations at higher velocities, is consistent with this proposed explanation.

Other factors may have acted either to enhance higher or depress lower velocity performance in F. At 30°/s, fatigue during single contractions may have affected (depressed) torque production more in F because a greater range of movement (90° lasting 3 s) had to be traversed before the optimal joint angle was reached (cf. M: 60°, 2 s). On the other hand, fatigue would not have influenced the brief (~1 s) contractions at 120°/s, yet in F, PT and W were depressed relative to higher velocities. A second possible factor is inhibition. A flattening of the low-velocity region of the torque-velocity relation is present in some movements tested on isokinetic dynamometers (20, 24). A tension-related inhibition has been

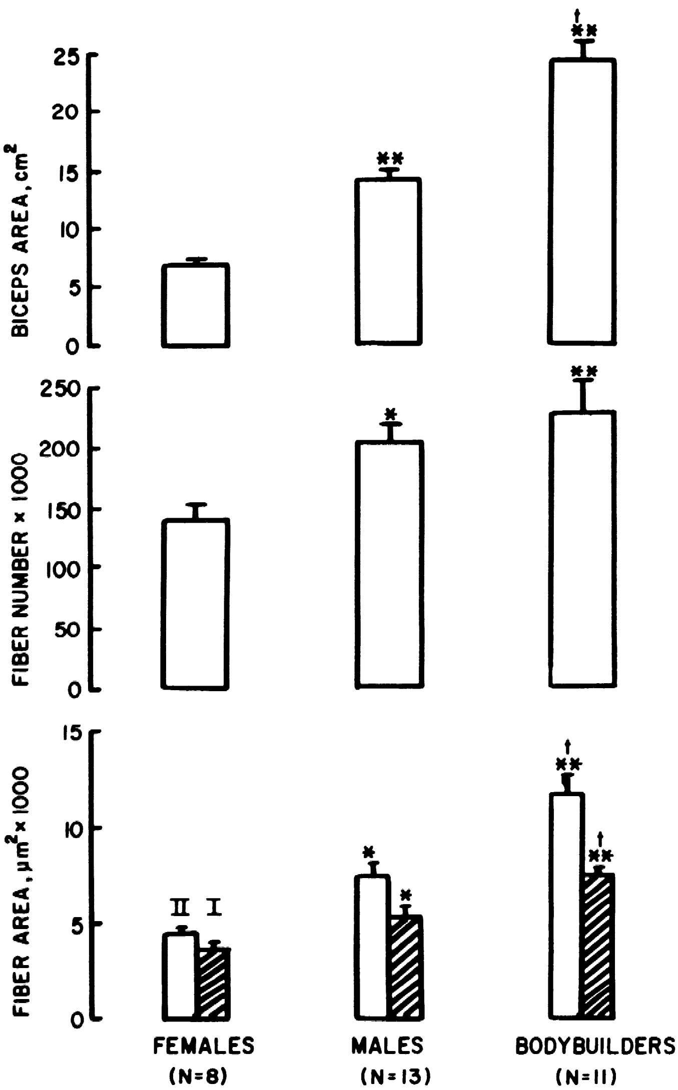

FIG. 8. Biceps cross-sectional area, biceps fiber number, and type I and II fiber area in untrained females and males and male bodybuilders. Values are means ± SE. * $P < 0.05$, ** $P < 0.01$ for differences between females and two male groups, † $P < 0.01$ for differences between two male groups.

suggested as the cause of the flattening (20). If females were more susceptible than males to this inhibition, greater inhibition would cause more flattening in the low-velocity region. Greater inhibition in F was unlikely, however, because recent observations (unpublished) in our laboratory indicate that females can achieve the same degree of motor unit activation as males during maximal voluntary isometric elbow flexion. Also, the extent of motor unit activation in two other muscle groups is similar in males and females (1). Thus the flat torque-velocity relation found in F at velocities ranging from ~4 to 35% of maximum velocity cannot be explained at present.

IT is caused by the impact of the accelerating limb and dynamometer lever arm against the resistance mechanism of the isokinetic dynamometer (7, 9, 21, 25). The size of IT is proportional to the momentum of the limb and lever arm at impact. IT would then be expected to increase at higher velocities and, unlike PT and W, it did in the present study. The IT results differed from the PT and W results in four other ways: *1*) there was no difference between F and M in the IT-velocity relation; *2*) M differed from BB in the IT-velocity relation; *3*) F, M, and BB did not differ in the IT/CSA × BH ratio; and 4) the correlation between IT and CSA × BH tended to increase at higher velocities. In addition, the IT/PT ratio did not differ among F, M, and BB at 30 and 120°/s but M and BB had higher ratios than F at 180, 240, and 300°/s. These data and the lower correlations between IT and PT or W than between PT and W indicate that the factors affecting IT performances are different from those affecting PT and W performance.

The size of IT is determined largely by the ability to develop torque at the beginning of the movement (joint angle = 180°), thereby overcoming the inertia and weight of the limb and dynamometer lever arm and producing a large acceleration. In this situation, the sex difference in the elbow flexion strength curve (19) discussed previously would work in favor of M and BB because males are closer than females to their optimal joint angle at large joint angles, and torque does not decline as much in males at angles greater than the optimal angle (19). Also, it would be easier for the stronger M and BB to accelerate the mass of the dynamometer lever arm. It is therefore important when making measurements of strength on isokinetic dynamometers, to distinguish between IT and the PT produced after the constant velocity state is attained.

The sex difference we found in the elbow flexion torque-velocity relation using an isokinetic system differs from the findings of de Koning et al. (4), who used an isotonic system. They found the familiar concave relation between load (force) and velocity, and there were no differences in the force-velocity relation among untrained males and females and trained males. The males had a greater unresisted maximal elbow flexion velocity. Subjects in this study (4) had to flex the elbow as rapidly

TABLE 5. *Characteristics of biceps brachii*

	Mean Fiber Area, μm^2	Type II Fibers, %	II/I Area Ratio	Type II Fiber Area, %	Collagen and Other Noncontractile Tissue	
					%	cm^2
Females	4,112±232	61.3±1.6	1.23±0.06	65.6±2.2	19.7±1.9	1.36±0.14
Males	6,248±359*	61.5±1.8	1.38±0.08	68.3±1.5	14.4±0.7*	2.05±0.18
Bodybuilders	9,899±851†‡	58.1±3.5	1.55±0.08‡	67.4±3.3	12.0±1.2‡	2.91±0.38‡

Values are means ± SE; $N = 8$ for females, 13 for males, and 11 for bodybuilders. * $P < 0.05$, ‡ $P < 0.01$ for differences between females and 2 male groups. † $P < 0.05$ for differences between bodybuilders and untrained males. Collagen and other noncontractile tissue (cm^2) were calculated from relative value (%) and biceps cross-sectional area.

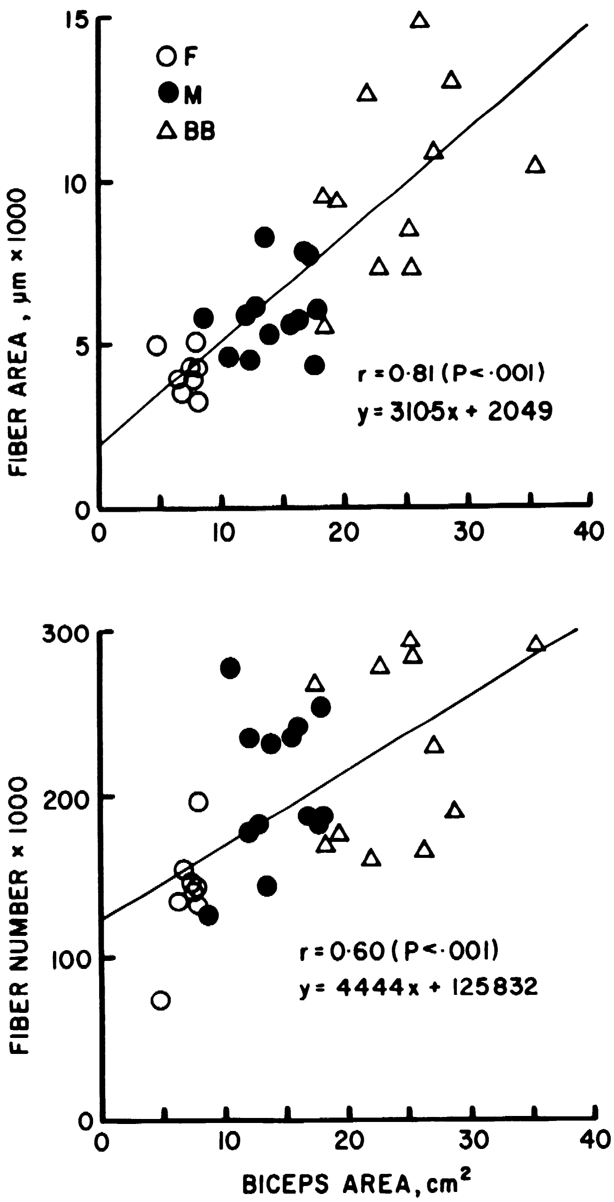

FIG. 9. Correlation between biceps cross-sectional area and mean fiber area (*top*) and fiber number (*bottom*). Individual values for untrained females (F), males (M), and male bodybuilders (BB) are shown ($N = 32$).

as possible against different constant-force spring loads. The movement started at an elbow joint angle of 120° (180° = full extension) and velocity was measured at 80° (4). The factors affecting performance on this isotonic system may differ from those affecting PT and W performance on the isokinetic system we used, thus producing the different results in the two studies. On the other hand, our IT-velocity results agreed with the force-velocity results of de Koning et al., in showing no difference between untrained males and females. The factors we proposed as determining IT performance may also determine performance on the isotonic system; namely, the ability to generate large torque at relatively large joint angles and overcome the inertia and weight of the limb and lever arm.

Our results also differ from those of Nygaard et al. (18) who used a custom-made isokinetic system rather than the more common Cybex system that we used. Their subjects flexed the elbow joint as hard as possible beginning at full extension (180°); force was measured at 100°. Velocities ranged from ~115 to 400°/s. Males and females had a similar concave force-velocity relation, and there was a significant correlation between muscle fiber composition and the relative decline in force at higher velocities (18). We cannot explain why these results differed from ours; different apparatus and procedures probably caused the differences. Our experimental conditions (isokinetic loading, limited velocity range) apparently masked the classic force-velocity relation that would be found in isolated human muscle regardless of sex.

In the present study, biceps fiber number was estimated as the ratio of muscle CSA to mean muscle fiber area. BB (62%) and M (46%) had significantly more muscle fibers than F. Furthermore, there was a positive correlation between muscle CSA and fiber number. Males also have a greater fiber number than females in tibialis anterior (10). In contrast, males do not have more muscle fibers than females in vastus lateralis (23) and triceps brachii (22). In our study and that done on tibilialis anterior (10), estimates of muscle fiber number included a correction for connective tissue and other noncontractile tissue. This correction was important in our study because F had a greater relative amount of this tissue than M and BB; without the correction, the fiber number in F would have been overestimated. Our results in biceps are most directly comparable to those of Schantz et al. (22) who also studied an upper limb muscle (triceps brachii). They found 18% more fibers in males ($n = 8$) than females ($n = 6$) but the difference was not significant. Had they used the correction for noncontractile tissue, the difference would have been larger and perhaps significant. We used the correction, had slightly larger samples (8 F, 13 M), and had a larger group differences in muscle size (107 vs. 64%). The different methods and subject samples may explain why we found a sex difference in fiber number, whereas Shantz et al. (22) did not.

We believe that the greater fiber number in males than females is due to genetic endowment rather than to different activity patterns because we have found that male bodybuilders do not have significantly more fibers than untrained men, despite many years of intense training (13). On the other hand, the greater mean fiber area in males than females may reflect different activity patterns.

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REFERENCES

1. BELANGER, A. Y., AND A. J. MCCOMAS. Extent of motor unit activation during effort. *J. Appl. Physiol.* 53: 419–424, 1981.
2. CAIOZZO, V. J., J. J. PERRINE, AND V. R. EDGERTON. Training-

induced alterations of the in vivo force-velocity relationship of human muscle. *J. Appl. Physiol.* 51: 750–754, 1981.

3. COYLE, E. F., D. C. FEIRING, T. C. ROTKIS, R. W. COTE III, F. B. ROBY, W. LEE, AND J. H. WILMORE. Specificity of power improvements through slow and fast isokinetic training. *J. Appl. Physiol.* 51: 1437–1442, 1981.
4. DE KONING, F. L., R. A. BINKHORST, J. A. VOS, AND M. A. VAN'T HOF. The force-velocity relationship of arm flexion in untrained males and females and arm-trained athletes. *Eur. J. Appl. Physiol. Occup. Physiol.* 54: 89–94, 1985.
5. DU BOIS, P. H. *An Introduction to Psychological Statistics.* New York: Harper & Row, 1965.
6. DUCHATEAU, J., AND K. HAINAUT. Isometric or dynamic training: differential effects on mechanical properties of a human muscle. *J. Appl. Physiol.* 56: 296–301, 1984.
7. FROESE, E. A., AND M. E. HOUSTON. Torque-velocity characteristics and muscle fiber type in human vastus lateralis. *J. Appl. Physiol.* 59: 309–314, 1985.
8. FUGL-MEYER, A. R., K. H. MILD, AND J. HORNSTEN. Output of skeletal muscle contractions. A study of isokinetic plantar flexion in athletes. *Acta Physiol. Scand.* 115: 193–199, 1982.
9. GRANSBERG, L., AND E. KNUTSSON. Determination of dynamic muscle strength in man with acceleration controlled isokinetic movements. *Acta Physiol. Scand.* 119: 317–320, 1983.
10. HENRIKSSON-LARSON, K. Distribution, number and size of different types of fibres in whole cross-sections of female m. tibialis anterior. An enzyme histochemical study. *Acta Physiol. Scand.* 123: 229–235, 1985.
11. IKAI, M., AND T. FUKUNAGA. Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Int. Z. Angew. Physiol. Einschl. Arbeitsphysiol.* 26: 26–32, 1968.
12. KANEHISA, H., AND M. MIYASHITA. Effect of isometric and isokinetic muscle training on static strength and dynamic power. *Eur. J. Appl. Physiol. Occup. Physiol.* 50: 365–371, 1983.
13. MACDOUGALL, J. D., D. G. SALE, S. E. ALWAY, AND J. R. SUTTON. Muscle fiber number in biceps brachii in bodybuilders and control subjects. *J. Appl. Physiol.* 57: 1399–1403, 1984.
14. MAUGHAN, R. J. Relationship between muscle strength and muscle cross-sectional area. Implications for training. *Sports Med.* 1: 263–269, 1984.
15. MAUGHAN, R. J., AND M.A. NIMMO. The influence of variations in muscle fibre composition on muscle strength and cross-sectional area in untrained males. *J. Physiol. Lond.* 351: 299–311, 1984.
16. MAUGHAN, R. J., J. S. WATSON, AND J. WEIR. Strength and cross-sectional area of human skeletal muscle. *J. Physiol. Lond.* 338: 37–49, 1983.
17. MOROZ, J. S., AND D. G. SALE. Evaluation of the torque transducer of the Cybex II dynamometer (Abstract). *Med. Sci. Sports Exercise* 17: 247, 1985.
18. NYGAARD, E., M. HOUSTON, M. SUZUKI, Y. JORGENSEN, AND B. SALTIN. Morphology of the brachial biceps muscle and elbow flexion in man. *Acta Physiol. Scand.* 117: 287–292, 1983.
19. O'HAGAN, F., N. TSUNODA, AND D. SALE. Effect of joint position on evoked and voluntary elbow flexion torque in men and women. *Can. J. Appl. Sport Sci.* 10: 22P, 1985.
20. PERRINE, J. J., AND V. R. EDGERTON. Muscle force-velocity relationships under isokinetic loading. *Med. Sci. Sports* 10: 159–166, 1978.
21. SAPEGA, A. A., J. A. NICHOLAS, D. SOKOLOW, AND A. SARANTI. The nature of torque "overshoot" in Cybex isokinetic dynamometry. *Med. Sci. Sports* 14: 368–375, 1982.
22. SCHANTZ, P., E. RANDALL-FOX, W. HUTCHISON, A. TYDEN, AND P.-O. ASTRAND. Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. *Acta Physiol. Scand.* 117: 219–226, 1983.
23. SCHANTZ, P., E. RANDALL-FOX, P. NORGEN, AND A. TYDEN. The relationship between the mean muscle fibre area and the muscle cross-sectional area of the thigh in subjects with large differences in thigh girth. *Acta Physiol. Scand.* 113: 537–539, 1981.
24. WICKIEWICZ, T. L., R. R. ROY, P. L. POWELL, J. J. PERRINE, AND V. R. EDGERTON. Muscle architecture and force-velocity relationships in humans. *J. Appl. Physiol.* 57: 435–443, 1984.
25. WINTER, D. A., R. P. WELLS, AND G. W. ORR. Errors in the use of isokinetic dynamometers. *Eur. J. Appl. Physiol. Occup. Physiol.* 46: 397–408, 1981.