

Elastic properties of muscles measured at the elbow in man: I. normal controls

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SUMMARY Passive elastic stiffness of muscle acting at the elbow was assessed in 19 normal subjects by measuring displacements produced by a torque motor acting at the joint. Stiffness ranged from 0.40 to 1.8 Nm/radian and was strongly correlated ($r = 0.85$) with upper arm volume, allowing us to define a "normal" range for stiffness when corrected for arm volume. In addition, the angle of the elbow with the arm fully relaxed and no external torque applied ("neutral" angle) was found to be $107^\circ \pm 10^\circ$. Thus, we have quantified resting stiffness or "tone" in the arm and provided normal data for comparison with patients with pathophysiological conditions such as rigidity or spasticity.

Although one usually considers muscle *activity* as underlying movement, recent studies of the control of limb movements have recognised the importance of *passive* elastic and viscous properties of muscles for their effects on limb positioning,¹⁻³ postural stability,⁴ ballistic movements,⁵ and in the evaluation of patients with pathologically increased muscle "tone".⁶ Lakie and colleagues⁴ found an increased stiffness at resting, as compared to moving, joints of humans which they and Wiegner⁷ have shown to be due at least in part to the short range stiffness properties of passive muscle. Electromyograms (EMG) recorded from the antagonist muscle during ballistic movements of a given size vary as a function of the ending position of those movements, reflecting a varying contribution of passive muscle properties to limb deceleration.⁵

Clinical "tone" as assessed during physical examination is used as a diagnostic sign and as a means of following the progress of treatment of disorders which involve spasticity or rigidity. A clinician's evaluation of enhanced tone on a scale of mild to severe may be consistent in a given patient, but it is not an ideal system for following changes over time, or when making quantitative comparisons between examiners. Thus a number of attempts to quantify tone have

been described in the literature (see Watts *et al*⁸), in each case with the aim of evaluating a particular class of patients. With spasticity or with Parkinsonian patients who have assumed a more flexed posture, it is not obvious whether increased tone is due to heightened reflexes alone or whether inactivity-related muscle contractures also play a role.⁹ Such contractures can affect the working length of a muscle, altering the resting limb position and passive torque-angle relation at the joint(s) at which the muscle acts. Therefore we have measured the resting elbow angle and the compliance at the elbow in a series of normal subjects, with the dual purposes of finding a convenient, quantitative measure of compliance as well as defining "normal" compliance and elbow angle for later comparison with patient groups having heightened tone or rigidity.

Methods

Subjects were seated in a chair with the right upper arm supported comfortably on a table at shoulder height. The forearm, wrist, and semi-pronated hand were strapped to the lever arm of a printed motor (Axem MC19S) mounted below the table. Each subject was positioned so that the axis of rotation of the elbow joint was co-axial with the motor shaft. Lever arm position was measured with a magnetoresistive potentiometer (Midori CP-2U-33) on the motor shaft. Motor torque was set under computer control; torque in the lever arm was measured with strain gauges mounted on the lever arm. Friction torque in the motor was specified as 0.1 Nm, and this value was observed in practice; the damping constant of the

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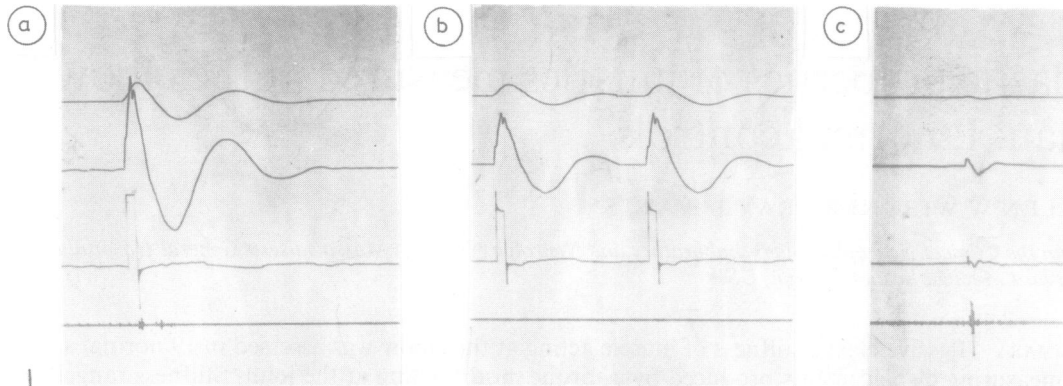


Fig 1 Responses of the relaxed arm to imposed torque pulses. Traces are, from top, elbow angle ($cal = 35^\circ$); angular velocity ($cal = 2 \text{ rad/s}$); torque ($cal = 5 \text{ Nm}$); and brachioradialis EMG measured with Copeland-Davies electrodes ($cal = 250 \mu V$), time $cal = 0.5 \text{ s}$. Note stretch reflex EMG response with torque pulse of 7 Nm (left) which is absent at 4 Nm (centre). A stretch reflex can also be elicited by tapping the biceps tendon (right).

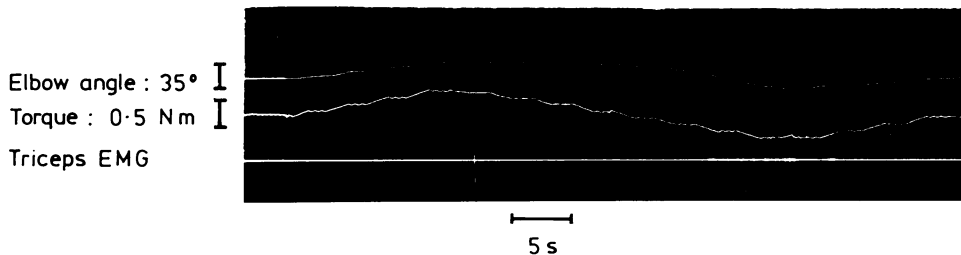


Fig 2 A single trial showing extension and flexion at the elbow. Small ripples seen in the torque trace were part of the input pattern to the torque motor. The EMG record is silent except for a random noise spike.

motor was specified at 0.0008 Nm s/rad and was ignored.

A series of preliminary experiments was performed to examine the relationship between limb velocity and reflex contraction of muscles in the relaxed limb. Torque pulses were applied to the relaxed arm while in its neutral position (the position to which it would return when manually deflected by the experimenter and allowed to move freely until it stopped). Torque pulses ranged from 1 to 7 Nm in amplitude and were of 100 ms duration, with rise and fall times of 10 ms. Resulting trajectories of the limb were repeatable and consisted of a linear increase in angular velocity during the duration of the pulse, as would be expected of a mass subjected to constant torque, followed by a damped oscillatory displacement pattern (fig 1). Maximum velocity was proportional to torque pulse amplitude in a given subject. To assess muscle activity we monitored the EMG of each of the muscles acting at the elbow (three heads of triceps, two heads of biceps, brachialis, brachioradialis, anconeus) in at least one of three subjects. EMG was recorded using

surface, Copeland-Davies, or intramuscular wire electrodes, the latter used on the deep brachialis. Arm position, velocity, and EMG were recorded on a TECA Instagraph which records on light-sensitive paper (Kodak type 1895). The magnitude of reflex responses, as measured by EMG, was a function of the magnitude of the applied torque (and hence the resulting velocity of the limb) and of the subject's state of relaxation. As a subject learned to relax more completely, reflex responses became less frequent. Occasionally a startle response produced a large reflex contraction. Reflex responses were not seen when peak velocities at the elbow joint were less than $100^\circ/\text{s}$; this corresponded to a torque pulse amplitude of approximately 4 Nm.

In the formal series of experiments, a computer (Digital Equipment Corporation 11/23) provided a torque pattern to the motor so that the elbow was first extended and then flexed during a single trial lasting one minute (fig 2). This torque pattern consisted of a series of four positive (extending) levels of torque (levels 1-4) and four negative (flexing) levels of torque

(levels 5–8), with the difference between levels selected by the experimenter so that the total range of movement was approximately 60° . Small oscillations in torque were superimposed at each torque level to minimise effects of “sticktion” in the apparatus and thixotropic effects in the passive limb.⁴ To insure that reflex activity would not confound the results of our regular experiments, the rate of change of torque was selected to be less than 0.11 Nm/s , which produced velocities of less than $20^\circ/\text{s}$. This gave us a safety factor of five below the minimum velocity values at which reflex responses were seen in the preliminary experiments.

The friction torque in the apparatus (0.1 Nm), while small, was not negligible compared to applied torques. Therefore, experiments were repeated both in the presence of friction torque and when friction torque was cancelled electronically within the torque servosystem. A fixed extra current could be supplied to the motor, based on the direction of motion, of a magnitude so that the resulting extra motor torque would just cancel friction torque.

Subjects were instructed to relax, close their eyes, and neither help nor hinder the movement of their arm. The torque servosystem was set for either regular or frictionless operation, and the block of trials which was performed first alternated from subject to subject. Triceps EMG was monitored with surface electrodes during all experiments and audible feedback provided to the subject to facilitate relaxation prior to and throughout the experiment. In general, once a subject succeeded in totally relaxing his arm, no EMG was elicited during the study. However, certain subjects demonstrated a persistent shortening reaction¹⁰ in the triceps during elbow extension. That is, the muscle being shortened underwent a period of contraction, which often persisted as long as the muscle remained in its shortened state. Subjects who showed such shortening reactions, made voluntary movements, or fell asleep, were removed from the study.

Torque and position were sampled and stored in the computer at a rate of 50 Hz . Only data acquired during the latter part of the dwell at each torque level were used, in order to allow position to stabilise after each change in torque. Position data at each level (baseline, 1–3, 5–7) obtained during flexion and extension were averaged to take into account the effects of limb hysteresis (fig 3). Data at levels 4 and 8, the maximum extension and flexion excursions of the limb, were ignored. Ten trials were recorded from each subject; position and measured torque were averaged at each level. A linear regression was then performed on the points obtained at the remaining levels in order to obtain a measure of limb compliance in degrees/Nm. Stiffness was calculated by inverting

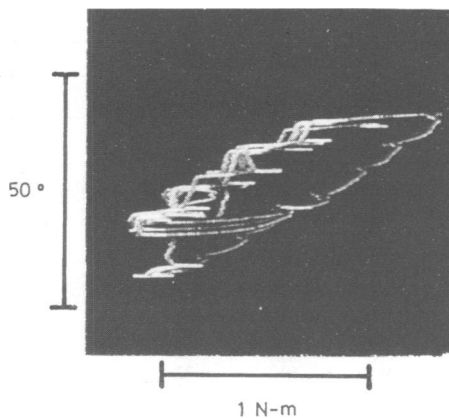


Fig 3 A plot of elbow angle versus measured torque during a block of ten trials. The area within the circles, traversed in a counterclockwise manner, represents work done in moving the resting limb and apparatus.

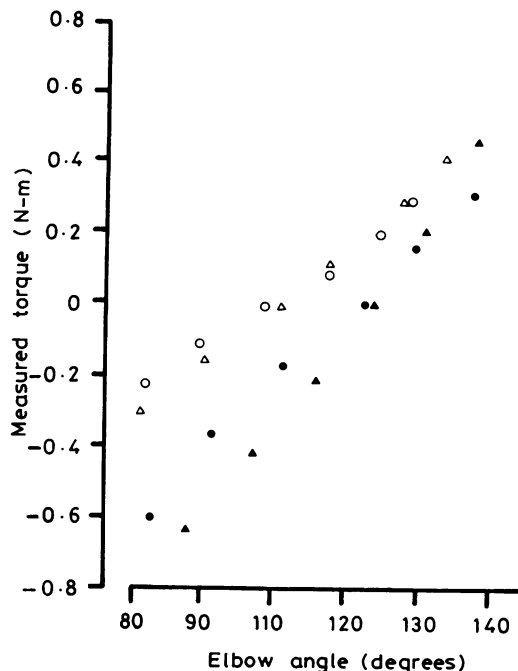


Fig 4 Reproducibility of measured torque versus elbow angle data was assessed in subjects 1 (open markers) and 3 (closed markers) by testing them on two different days. Note the essentially linear relation obtained from each test. The slope of the linear regression of angle on torque is the limb's compliance. The average correlation coefficient from these 4 regressions was 0.995 , which is equal to the mean for all subjects tested.

TABLE: Data summary, 19 subjects

Subject	Sex	Age (yr)	Regular Compliance (°/Nm)	Frictionless Compliance (°/Nm)	Stiffness (Nm/rad)	Upper Arm Volume (cm ³)	Neutral Elbow angle (degrees)
1	M	35	81	74	0.77	1950	101
2	M	24	51	63	0.91	2090	120
3	M	29	46	52	1.10	2470	114
4	M	48	55	50	1.15	2390	94
5	F	28	140	121	0.48	1360	108
6	M	32	52	65	0.88	1620	107
7	M	36	35	39	1.47	2380	114
8	F	38	76	74	0.77	2040	130
9	F	62	73	73	0.78	1570	119
10	F	22	171	144	0.40	1380	111
11	M	20	30	36	1.59	2740	100
12	M	30	52	44	1.30	2380	93
13	F	22	54	67	0.85	1410	87
14	M	59	32	32	1.79	3130	111
15	M	78	82	86	0.66	2360	106
16	M	70	54	48	1.19	1880	102
17	F	22	72	107	0.53	1200	111
18	F	23	138	145	0.40	1450	101
19	F	51	50	46	1.24	2340	108
Mean			71	72	0.96	2010	107
±SD			±39	±34	±0.40	±540	±10

compliance and multiplying by $360/2\pi$. At this point friction was either restored or cancelled and a second block of trials performed.

Upper arm volume was estimated by recording the circumference of the arm at three points equidistant between the shoulder and elbow, and by measuring the length of the arm from the acromion to the elbow. After averaging the circumferences we modelled the upper arm as a cylinder and calculated its volume.

Results

Nineteen subjects, 11 males and eight females, successfully completed the study (table). They ranged in age from 20 to 78 years with a median of 32. Compliance curves from repeated trials on two subjects are shown in fig 4. Subject 1 (open markers) and subject 3 (closed markers) were each tested twice, each test on a separate day. Figure 4 demonstrates both the linearity of the relation between torque and elbow angle over a range of $\pm 30^\circ$ from the neutral angle, and the reproducibility of the test from day to day. The slopes of the lines fitted to this data, and similar data from other subjects, are shown in the columns labeled "regular compliance" and "frictionless compliance" in the table, the latter from the blocks of trials in which friction was electronically cancelled. Regular compliance ranged from 30 to $171^\circ/\text{Nm}$ and frictionless compliance from 32 to $145^\circ/\text{Nm}$; there was no consistent difference between the two measures and frictionless compliance will be used hereafter. The *smallest* correlation coefficient among all of the linear regressions

used to determine compliance was 0.986. Compliance was significantly correlated ($r = -0.76$, $p < 0.01$) to upper arm volume (fig 5A), which reflects the mass of the muscles acting at the elbow. Neither compliance nor upper arm volume was correlated with age. Neutral position of the forearm (the resting elbow angle in absence of applied torque) ranged from 87° to 130° with a mean \pm SD of $107 \pm 10^\circ$.

The apparently hyperbolic relation between compliance (C) and upper arm volume (V) suggested the following equation relating the variables:

$$C(V - V_0) = K \quad (1)$$

where V_0 is an asymptote corresponding to a volume within the arm consisting of non-elastic structures. Equation 1 can be linearised by expressing compliance as its inverse, stiffness (S) in Nm/radian (1 radian = 57.3°):

$$(1/S)(V - V_0) = K \quad (2)$$

$$\text{or, } S = (1/K)V - V_0/K \quad (3)$$

The compliance data in the table were converted to their stiffness equivalents and a linear regression line fitted to the data. The result was:

$$S = -0.32 + 0.00064 V \quad (4)$$

with a correlation coefficient of 0.85 and standard error of estimate (SEE) = 0.22. From Equations 3 and 4 one can calculate $V_0 = 500 \text{ cm}^3$. Figure 5B shows the fitted linear regression line and 95% confidence limits for predicted stiffness at a given arm volume.¹¹

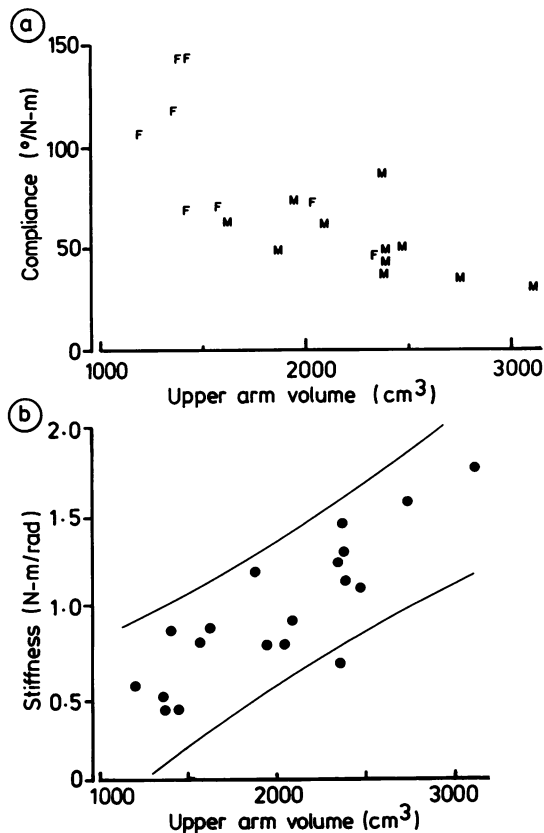


Fig 5 (a) Relation between compliance at the elbow and upper arm volume in the absence of muscle activity. Correlation was significant ($r = -0.76$, $p < 0.01$) with male subjects (M) having lower compliance values and larger arm volumes than female subjects (F). (b) Inverting compliance to stiffness linearises the above relation. The regression line fitted to all 19 subjects is given in text Eqn. 4. The curved lines represent 95% confidence limits for normal data.

Discussion

Quantitatively, compliances obtained in the present study agree with those of Fel'dman¹ (1 measurement, 45°/Nm) and Hayes and Hatze² (three measurements, 41, 41, and 57°/Nm, converted to compliance). Compliance is found to have a large range of values in normal subjects, probably because it is a function not only of the properties of muscle, but also of the mass (or more precisely, cross-sectional area) of muscles acting at the elbow. Thus one expects compliance to be correlated with upper arm volume, as indeed it is.

Our use of upper arm volume to estimate muscle area obviously did not take into account the volume occupied by bone and adipose tissue. V_0 , the non-

elastic volume, was found to be 500 cm³, which is equivalent to a cylinder 4.4 cm in diameter within the upper arm (somewhat larger than the volume of the humerus). More accurate estimates of muscle mass could be obtained using a triceps skinfold technique¹² to estimate adipose tissue content, or, ultimately, by using a computed tomography (CT) scan at the biceps level. CT scanning would have added substantially to the cost of the study and subjected the subjects to a small dose of radiation, without assurance of a significantly improved correlation.

The linearity of the angle versus torque relation found here is a consequence of our analysis over a limited angular range, approximately $\pm 30^\circ$ from the neutral position. The exponential length-force relation of muscle and the hard limits imposed by joint structures cause the angle-torque relation to become non-linear for large excursions, as can be seen in the data of Hayes and Hatze.² By limiting our study to the middle of the range, we characterise compliance with a single number and minimise other complexities such as shortening reactions which are more common at full extension or flexion.

Shortening reactions or responses, that is EMG activity in a muscle being passively shortened, have been observed for a long time¹⁰ but not widely reported. They may act to prevent buckling of muscle fibres and consequent loss of sensitivity of muscle spindle primary endings as a muscle is passively shortened to its slack length. Norton and Sahrman¹³ found biceps or brachioradialis shortening responses in a majority of normal subjects. In the present study, shortening responses in the triceps were observed in a number of subjects; most subjects could eliminate the response by concentrating on total relaxation of the limb. Occasional shortening responses were handled by repeating trials in which they occurred. Three subjects were removed from the study because of intractable shortening responses. To the extent that any shortening responses went undetected, they would tend to increase the apparent compliance at the elbow.

Neutral elbow angle has been reported to be $122 \pm 24^\circ$ by the National Aeronautics and Space Administration¹⁴ for persons under weightless conditions, while here on earth, Pertuzon and Lestienne¹⁵ found an equilibrium position of 75° from full extension (105° angle at elbow). Interestingly, this equilibrium point has also been found to be the point of minimum viscous stiffness.²

Thus, we have defined a simple method for quantifying resting "tone", or stiffness, at the elbow in normal subjects, as well as defining the neutral angle of the relaxed limb. Measurements of upper arm volume were used to reduce the variance of the data and allowed us to set up reasonably narrow limits for

“normal” tone. We can compare these normal values for tone with those obtained from patients with rigidity⁸ or spasticity in order to determine to what extent this increased tone is a consequence of altered muscle properties as opposed to enhanced reflexes.

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