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CHANGES IN THE LENGTH OF THE HUMAN BICEPS BRACHII MUSCLE DURING ELBOW MOVEMENTS

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SUMMARY

1. Needles inserted into the biceps move with the muscle as the elbow flexes or extends. Pairs of needles were used to indicate changes in length of the muscle fibres.

2. During low-frequency flexion–extension movements the biceps lengthened as the joint extended.

3. When, however, joint movements at $> 2{\cdot}2$ Hz were maintained by external electrical stimulation of triceps and the long head of biceps, or of biceps alone, the biceps lengthened and shortened in antiphase to the joint movement. The elastic properties of the biceps tendons then combined with the mass of the forearm as a spring–mass system whose natural frequency was about 2·2 Hz.

4. No such phase reversal appeared during voluntary elbow movements at frequencies up to 5 Hz. It was concluded that the combined tendons of biceps, brachialis and brachioradialis made a much less compliant muscle-to-bone coupling.

5. The results are discussed in relation to possible tremor mechanisms.

INTRODUCTION

Many muscles are attached to bone by compliant tendons; nevertheless, it is often assumed that the movements of the bones give a reliable indication of the movements of muscle fibres and muscle spindles. Many analyses of stretch reflex behaviour use this assumption (e.g. Stein & Oguztoreli, 1978; Rack, 1981). In particular, movements of the elbow joint have been used to predict length changes in biceps spindles during voluntary movement, during tremor (Prochazka & Trend, 1985), and during percutaneous muscle stimulation (Jacks, Prochazka & Trend, 1986).

Previous papers have shown that muscle fibres and spindles within flexor pollicis longus may move in ways that differ from the movements of the thumb (Rack & Ross, 1984; Rack, 1985). In this paper we describe experiments in which movements of the biceps muscle were recorded while the elbow made repeated flexion–extension movements. There were some circumstances in which the muscle fibres of the long head of biceps moved in an opposite direction to the tendinous attachments.

Some of these results have already been briefly reported (Fellows & Rack, 1986).

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METHODS

Experiments were carried out on the right arms of two subjects (the two authors). The subject sat in a dental chair with his right shoulder firmly supported. The forearm was bandaged to a light aluminium support (moment of inertia 16 g m^2) which was pivoted at the elbow joint; the radio-ulnar joint was supinated. In some experiments the forearm and upper arm were horizontal; the elbow could then rest in any position without muscular effort. In other experiments the arm sloped downward from the shoulder; the elbow then fell into extension when the flexor muscles relaxed. In some experiments the subject repeatedly flexed and extended the elbow by voluntary effort; in others the muscles were electrically stimulated. A board beneath the upper arm supported the biceps, and prevented it from sagging downward as it relaxed.

Stimulation. The stimulation of biceps and triceps was through electrodes taped to the skin over the muscles. In each case, this local electrode served as a cathode, the anode being a larger plate behind the shoulder. The biceps and triceps electrodes were placed in the positions at which a small stimulating pulse gave the largest elbow movement; in practice this occurred with the biceps electrode approximately midway between elbow and shoulder joints, but overlying parts of the muscle which arose from the long tendon.

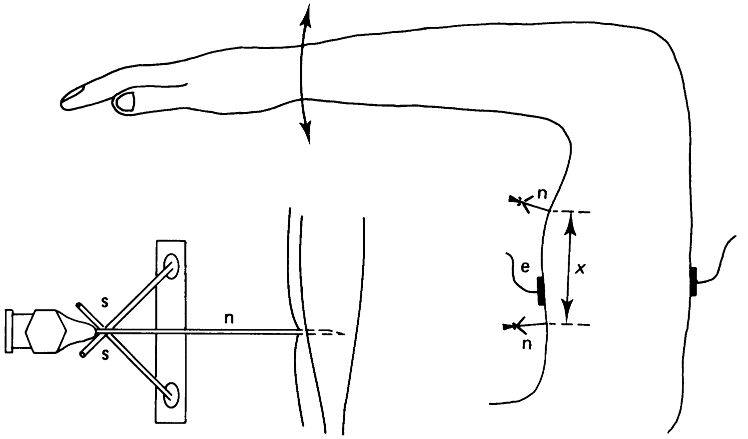

Fig. 1. The right arm was fixed to an aluminium support (not shown), the elbow joint being free to flex and extend. Two needles (n) were inserted into the biceps; their butts were fixed to a pair of crossed straws (s) which allowed a swivelling movement. Stimulating electrodes (e) were fixed to the skin over biceps and (sometimes) over triceps.

When the arm was horizontal, groups of stimulating pulses (0·1 ms) were supplied alternately to biceps and triceps (Fig. 2), their amplitudes being adjusted to give flexion–extension movements of about 5 deg (peak to peak). When the arm sloped downward, only biceps was stimulated, and gravity supplied the extending force (as in the experiment of Fig. 3).

Measurements of movement. Sterile intramuscular needles (diameter 0·55 mm, length 50 mm) were inserted into biceps to a depth of 10–20 mm, at positions determined by palpation (Fig. 1). One went into the lower end of the muscle where it narrows to its tendon of insertion, the other into the upper part of the muscle, close to the long tendon of origin.

The proximal end of each needle was mounted on a structure which was made from a pair of crossed straws fixed together with cyano-acrylate glue (Fig. 1). The needle butt was fixed in the crutch of this structure; the shaft of the needle could then swivel as its tip moved with the biceps, but the butts were prevented from moving along the limb.

Movements of the forearm and of the needles were recorded by a 16 mm cine-camera (53 frames s^{-1}) mounted 1 m from the limb. The cine-photographs were later projected and measured frame by frame. In some experiments movements of the elbow were also detected by an 'asyn' angular position transducer at the axis of the joint; the signal from this was recorded on magnetic tape, along with stimulus markers. A commutator attached to the cine-camera provided a signal each time the shutter opened; this signal was also recorded on the tape and enabled us to relate each frame of the cine-photograph to the tape-recorded signals.

With the upper arm forward, and the elbow joint semi-flexed, the skin was freely mobile over the surface of biceps. As the elbow joint flexed, there was appreciable movement of the biceps, as indicated by movements of the points at which the needles pierced the skin. The needles then swivelled on their mountings, but the mountings remained equidistant (as confirmed by the cine-photographs). There was no significant bowing of the needles, and it was concluded that the skin did not seriously impede their movement.

Movements of the visible parts of each needle were therefore assumed to indicate movements of the corresponding parts of the underlying muscle. In particular, changes in the distance between the points at which the needles pierced the skin (x in Fig. 1) were taken to indicate lengthening or shortening of the muscle.

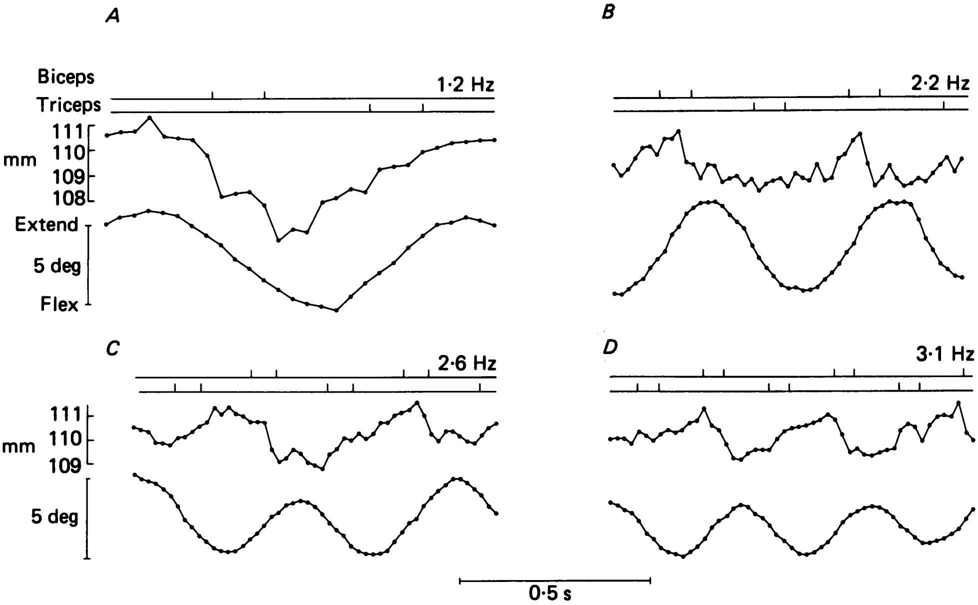

Fig. 2. The response to cyclical stimulation of biceps and triceps at four different frequencies. In each part of the Figure the upper two traces show stimulus pulses. Each cycle of stimulation consisted of a pair of pulses to biceps separated by an interval $\frac{1}{8}$ of the cycle period, and a pair to triceps which were similarly timed, but in antiphase. The lower two records are constructed from frame-by-frame measurements of cine-film, showing the elbow movement, and the distance between the needles as they penetrated the skin. Subject P.M.H.R. Inertia of forearm and attachments was 100 g m^2 (measured by the method of Evans, Fellows, Rack, Ross & Walters, 1983).

Some irregularity in the muscle length records (Figs. 2, 3 and 4) was probably a result of the twitching of muscle fibres which were close to the needle tips, but the point-to-point irregularity in Fig. 3 arose from the difficulty of measuring to precisely the same point on photographs of a brightly illuminated cylindrical needle.

RESULTS

Muscle stimulation

Fig. 2 shows movements of the elbow joint (lowest records in Fig. 2*A–D*) during intermittent stimulation (upper records) of the biceps and triceps. Movements of the joint lagged behind the stimulating pulses, as one might expect from the delays involved in muscle contraction and the inertial nature of the load. The actual phase separation between biceps stimulation and elbow flexion widened as the frequency was increased from 1·2 to 3·1 Hz (see Jacks *et al.* 1986).

In each part of Fig. 2 the middle trace shows the distance between the two needles. This distance was measured between the points at which the needles pierced the skin, but it is assumed that changes in this distance reflect changes in the muscle length. When the movement was slow (1·2 Hz in Fig. 2*A*), the muscle length changed approximately in phase with the joint movement; elbow flexion was thus accompanied by muscle shortening, and elbow extension by muscle lengthening. The joint movement did, however, lag slightly behind that of the muscle.

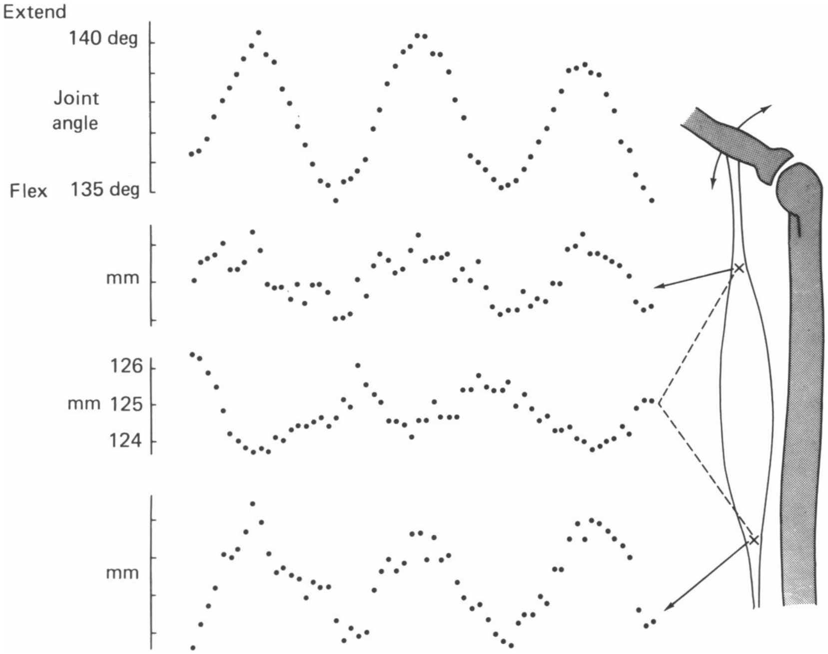

Fig. 3. Movements of the individual needles. Trains of four pulses (24 impulses s^{-1}) were supplied to biceps 2·6 times s^{-1}. The period of stimulation thus occupied $\frac{1}{3}$ of the cycle. The records show joint position, the two needle positions, and the distance between them (as in Fig. 2). Measurements from sixty-two frames of cine-film. Subject S.J.F.

With higher frequencies of stimulation (2·6 and 3·1 Hz in Fig. 2*C* and *D*) the situation was quite different; the joint movement and the muscle length were then approximately in antiphase, so that this *flexor* muscle was actually *lengthening* while the joint was *flexing*. At an intermediate frequency (2·2 Hz in Fig. 2*B*) the amplitude of muscle movement was small compared with the joint movement, and the muscle reached its shortest length while the joint was still moving towards flexion. Similar results were obtained from each subject, and it made little difference whether trains of two, three or four stimulating pulses were used.

Fig. 3 shows the individual movements of the two needles. Needle positions were again measured in successive frames of a cine-film, and on this occasion the joint moved at 2·6 Hz in response to stimulation of the biceps only (details in Figure legend). Movements of the elbow joint (uppermost graph) were accompanied by movements of the needles, both of which moved in the same direction as the joint, indicating that the bulk of the muscle moved down the limb as the joint extended. However, the proximal needle moved further than the distal one, so that the distance between them *decreased* as the joint extended, confirming that the length of the muscle fibres changed in antiphase to the joint movement. This was the regular response to intermittent stimulation at 2·5–5 Hz.

Voluntary movements

It is easy to flex and extend the elbow at frequencies up to 3·5 Hz. Voluntary movements at 5 Hz were only possible with considerable effort; the muscles were then visibly and palpably taut. At higher frequencies only very small movements were possible.

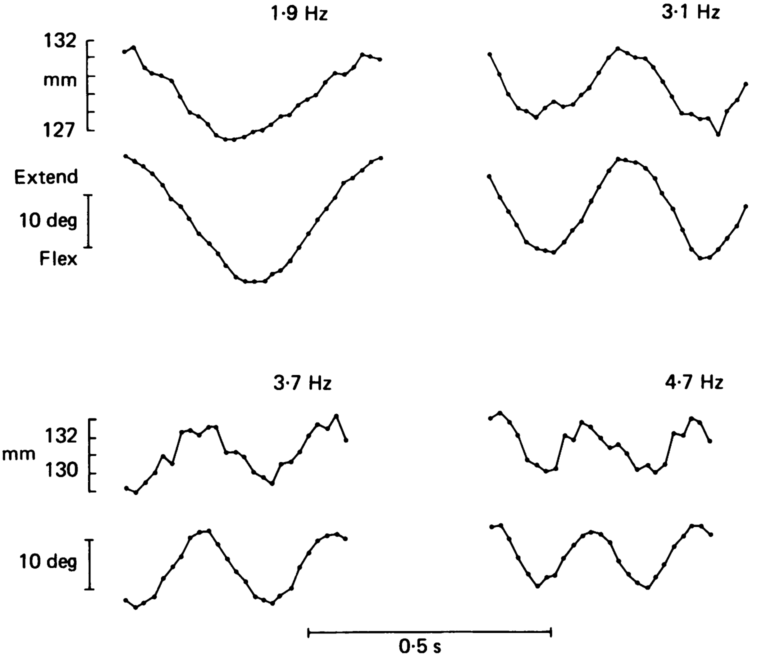

Fig. 4. Voluntary movements of the elbow at four different frequencies. The movements of the forearm and the needle are displayed in the same way as in Fig. 2. Subject S.J.F.

Voluntary movements of the elbow were accompanied by movements of the needles in biceps, indicating changes in the muscle length. However, in contrast to the results in the previous paragraphs, the muscle always lengthened as the joint extended, and this was true at all the frequencies of movement which we could maintain (Fig. 4). During voluntary movements we never saw the phase reversals which had appeared so clearly during electrical stimulation. A similar result was obtained by Prochazka & Trend (1986).

We carried out voluntary flexion–extension movements of different amplitudes, with different positions of the shoulder and radio-ulnar joints, and around various mean positions of the elbow joint; none of these alterations reproduced the phase reversals that had occurred during external stimulation, nor did the phase reverse when we generated the movements by deliberate impulsive contractions of the muscles. Inspection and palpation of the limb indicated that during voluntary movements brachialis and brachioradialis always contracted in synchrony with biceps, and that the flexing effort was thus distributed between these muscles. We attempted by conscious effort to restrict the contraction to biceps, but were unable to do so.

DISCUSSION

During stimulation experiments, the movements of the complete muscle–tendon combination clearly differed from the movements of the muscle fibres. At low frequencies most of the muscle movement was communicated to the bones, whereas at the higher frequencies it was 'lost' in the tendons of attachment. The combination of forearm and tendons was, in fact, behaving as a spring–mass system with a natural frequency of 2–2·5 Hz. As the frequency of the stimulus cycle was increased from 2 to 2·5 Hz, the phase of the joint movement reversed, but when the stimulus cycle was at this natural frequency (Fig. 2*B*) there was a resonant situation in which small movements of muscle fibres sustained a relatively large joint movement. This type of behaviour was to be expected of a system in which muscles are linked to bone by spring-like tendons; why then did we see neither phase reversal nor resonance during voluntary movements?

During voluntary movements, biceps, brachialis and brachioradialis were all active, in addition to triceps. The forces required to flex the forearm were thus distributed between the tendons of a number of muscles. Acting in parallel, these tendons would add up to make a stiffer spring than the biceps tendons alone. The natural frequency of the tendon–mass complex would thus be correspondingly higher, and it is not surprising that we failed to reach it during voluntary movements of up to 5 Hz.

We could not make fast alternating movements without stiffening the limb, with appreciable activation of muscles through the whole cycle of movement (as seen in electromyograms). The flexors and extensors were thus both partially activated during the whole cycle, and with this co-activation of antagonist muscles, the mean tensions in the tendons must have been higher than during the corresponding stimulated movements. However, tendons are non-linear springs, which stiffen when tension rises (Gratz, 1931; Rigby, Hirai, Spikes & Eyring, 1960; Diamant, Keller, Baer, Litt & Arridge, 1972; Ker, 1981; Rack & Ross, 1984); the co-activation would therefore further increase the natural frequency of the tendon–forearm combination.

Furthermore, the tendon of brachialis is a relatively short one, and indeed some of the muscle fibres attach directly to bone. Therefore, when brachialis bears a significant proportion of the load, the combined tendon stiffness would be particularly high.

The responses to electrical stimulation thus differed from voluntary movements, because the stimuli were confined to the biceps (perhaps to its long head), and the muscle relaxed more completely between the stimuli. By contrast, voluntary flexing movements involved at least three muscles; their activity was modulated less completely, and one of them has only a short tendon.

A resonant frequency of 2·25 Hz, and an inertia of 100 g m^2 (forearm and attachments) implies that the flexing force increased by approximately 20 Nm radian^{-1} over the range of joint extension. It would be interesting to compare this value with more direct estimates of elastic properties of the elbow tendons, but unfortunately we lack precise information about the behaviour of tendons under these relatively small loads, and anyway it is possible that they may have been slack through some part of the cycle. When Prochazka & Trend (1986) evoked elbow movements by muscle stimulation, they found no phase reversal in this low-frequency range. However, the muscles of their subjects were activated more continuously. The tendons would therefore have been under greater mean tensions, and they would then have had a higher elastic modulus; it is not surprising that their tendon–forearm combination showed no resonance within the frequency range of the experiment.

Joint movements and muscle-spindle activity

During our voluntary movements, when the flexing effort was shared among a number of muscles, the length of biceps muscle fibres changed in phase with joint position, and the spindles presumably 'saw' a fairly straightforward representation of the joint movement. However, during electrical stimulation, when flexing force was generated only by the biceps, the relation between the spindle-afferent discharge and the joint movement would have changed dramatically.

This relationship between spindle-afferent activity and joint movement is of considerable importance in any analysis of stretch reflex function or malfunction. The important question is: can we assume that motoneurone activity will always be widely distributed among the different muscles, or are there conditions (physiological or pathological) under which the motoneurone activity is concentrated into some part of a muscle group which acts through a relatively compliant tendon? In this latter case, the muscle spindles might sometimes move in an opposite direction to the joint, with important consequences for the stability of stretch reflexes; in particular, the muscle-spindle-afferent discharge might then reach the motoneurones with a timing that supported spontaneous tremor.

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