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THE EFFECTS OF FUSIMOTOR STIMULATION DURING SMALL AMPLITUDE STRETCHING ON THE FREQUENCY–RESPONSE OF THE PRIMARY ENDING OF THE MAMMALIAN MUSCLE SPINDLE

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SUMMARY

1. Single fusimotor fibres to the de-efferented soleus of the anaesthetized cat were stimulated repetitively while recording the response of single primary afferents to small amplitude sinusoidal stretching at frequencies of 0·5–500 Hz. The response of the ending was determined by averaging its firing for many cycles to construct a 'cycle histogram'. When small enough, the stretching modulated the firing sinusoidally; as the frequency increased the requisite amplitude fell to a fraction of a micron. The amplitude of the modulation (in impulses/sec) divided by the amplitude of stretching (in mm) gave the sensitivity of the ending for the particular frequency in question.

2. The passive frequency–response curve obtained in the absence of fusimotor stimulation agreed with those obtained before. In addition, it showed a flattening for frequencies above about 100 Hz.

3. During fusimotor stimulation the low frequency end of the curve (0·5 to about 30 Hz) was displaced downwards without change of form. With dynamic stimulation the effect was small and sometimes negligible so that the sensitivity remained high and on average at 70% of the corresponding passive value. With static stimulation the effect was large so that the sensitivity became small and on average was then only 14% of the passive value. In neither case was there any systematic change in the phase of the response relative to the stimulus.

4. The high-frequency end of the frequency–response curve (above 100 Hz) was lifted upwards during stimulation of either kind of fusimotor fibre. This increase in spindle sensitivity was accompanied by a phase advance of the response in relation to the passive value.

5. At intermediate frequencies the curve during dynamic stimulation was similar to the passive one, but during static stimulation the sensitivity

increased more rapidly than normal with frequency so that over a certain range the ending was responding to the rate of change of the acceleration.

6. Fusimotor stimulation helped stabilize the responsiveness of the ending against the changes that otherwise took place on changing the mean length of the muscle. Varying the frequency of fusimotor stimulation was only systematically investigated with low frequency stretching when it had little effect.

7. The effects of static fusimotor stimulation could not be attributed to the commonly occurring modulation of afferent firing by static action. Wide variations were seen in the depth of modulation of post-stimulus histograms, relating the moment of afferent firing to the timing of the fusimotor stimuli, without being accompanied by any change in the characteristic static effects on the frequency–response curve. Dynamic stimulation hardly ever produced significant modulation of the discharge.

8. It is notable that in the functionally most relevant frequency range (below 20 Hz) fusimotor action, whether static or dynamic, provides control of overall sensitivity but without affecting spindle dynamics. This is not felt to be in contradiction with previous findings which are based on the spindle responses to stretches of appreciable amplitude.

INTRODUCTION

On using suitably small amplitudes of stretching the mammalian muscle spindle behaves approximately linearly. This permits the response of its afferents to a particular frequency of sinusoidal stretching to be expressed as a sensitivity, in impulses/sec of firing per millimetre of stretching, which is independent of the precise value of the amplitude of stretching. Previous studies have shown that the sensitivity of the primary ending increases rapidly as the frequency of stretching is increased above about 1 Hz. Matthews & Stein (1969) documented such behaviour using a wide range of frequencies in the decerebrate cat where the endings were being influenced by fusimotor activity of unknown degree. Poppele & Bowman (1970) derived an empirical 'transfer function' which provided a good fit to their results obtained with a rather narrower range of frequencies in the de-efferented spindle. Such findings are of interest in relation to the functional role of the spindle in the body, particularly with regard to any liability to spontaneous tremor (cf. Joyce & Rack, 1974; Stein, 1974), and may also help throw light upon the rather complex internal operating of the spindle. The present experiments were undertaken, with both aims in view, to compare the effects of stimulating the static and dynamic fusimotor fibres on the frequency–response curves of primary endings obtained with a wide range of frequencies of stretching

(0·5–500 Hz). Brief notes on such work have already been published both by ourselves (Goodwin & Matthews, 1971) and by Chen & Poppele (1973) working along comparable lines.

METHODS

Preparation. The experiments were performed on the soleus muscle of the anaesthetized cat (pentobarbitone sodium given I.P.). The limb was otherwise extensively denervated. Soleus was removed from any central control by section of the appropriate dorsal and ventral spinal roots. Muscle spindle afferents were isolated as functionally single units in dorsal root filaments. They were characterized as primary afferents on the basis of their conduction velocity (over 75 m/sec) and on their well-marked dynamic responses to a ramp stretch, usually 8 mm at 5 or 10 mm/sec. Functionally single fusimotor fibres to the soleus were isolated in ventral root filaments. They were initially detected by observing the effect of stimulation of fine root filaments on the response of the chosen primary ending to a ramp stretch. Likewise, this permitted their ready classification into static and dynamic fibres. Those studied produced no overt contraction (tension below 10 mN) and had conduction velocities within the gamma range. In total, thirty-three primary afferents were studied systematically in twenty-six preparations during stimulation of thirty-seven single fusimotor fibres, twenty-two of which were static fibres and fifteen dynamic fibres; in four cases the action of a static and of a dynamic fibre were compared on the same afferent. Subsidiary observations on the 'passive' behaviour alone were made on a number of other endings. Fuller descriptions of technique have been published earlier (Matthews, 1962; Crowe & Matthews, 1964*a*).

Collection and analysis of data. In the first ten preparations the response to sinusoidal stretching was determined 'off-line' using techniques similar to those employed by Matthews & Stein (1969) in their 'probability density' method. Standard pulses, each corresponding to a single afferent spike, were recorded on magnetic tape along with various signal markers; the data were subsequently processed by a large central digital computer. In the last sixteen preparations much of the computation was performed 'on-line' with a PDP 12 computer (Digital Equipment Corp.). The computer averaged the response to a number of cycles of sinusoidal stretching and displayed a 'cycle histogram' in which the number of spikes in each of a series of bins of constant duration was plotted against the phase of the cycle (see Fig. 1). With appropriate scaling this gives the average frequency of firing throughout the course of a cycle of sinusoidal stretch. The histogram was fitted by the method of least squares with a sine curve and its parameters displayed (amplitude, phase, mean displacement from zero). The computer did not store the original spike trains but these were preserved on a separate tape recorder so as to permit further analysis. In particular, this allowed the generation of post-stimulus histograms relating afferent firing to the time of stimulation of the single fusimotor fibres. The various programmes were largely written in assembly language and are detailed elsewhere (Dale & Hulliger, 1973; Hulliger, 1975). Even with such direct computer assistance the collection of data still proved too slow for us to study all that we wished. Our chief effort was devoted to obtaining full frequency–response curves, when it required some 5 hr of satisfactory recording to assess the action of a single fusimotor fibre.

The data for an individual histogram were collected over an integral number of cycles, normally occupying a recording period of about 10 sec and corresponding to the collection of some 300–1000 spikes. Most computation was done with

24 bins per cycle. Successive histograms were determined at intervals of about 1 min, thus allowing the preparation to recover from the effects of fusimotor stimulation. Sometimes the muscle was held at a constant length during data collection. But this was deemed undesirable in the usual case when lengths near the physiological maximum were being studied, since the local circulation might have been impeded. Instead, the muscle was alternately stretched to collect the data and then released, with a repeat cycle of about 1 min; the stretch was 8 mm at a velocity of about 5 mm/sec. The small-amplitude sinusoidal stretching was normally left on throughout. In the absence of fusimotor stimulation, data collection was started 3–5 sec after reaching the final length. When fusimotor stimulation was used it was started at an equivalent time after stretching and data collection begun 1–2 sec later. Comparisons of similar observations made over a period of an hour or more showed that the response of the endings normally remained constant with such a routine.

Particularly during fusimotor stimulation there tended to be a small progressive decline in the mean frequency of firing of the ending during the 10 sec required for data collection. The computation simply averaged the response over the whole period. It seems unlikely that small changes in mean frequency would be accompanied by any appreciable change in receptor sensitivity. This view was supported by control observations in which computations were performed on successive shorter periods of discharge in which the mean frequency differed slightly. However, a progressive fall in mean frequency might be suggested to manifest itself as part of the sinusoidal response. This seems unlikely, but in any case must have been too small to matter. For example, on stretching at 1 Hz a drop in mean firing of 20 impulses/sec over 10 sec (which would have been unusually large) could not have added more than about 1 impulse/sec to the amplitude of modulation of the sinusoidal response of the ending (see Fig. 1). Experimentally, any such effect should still be manifest when the amplitude of stretching had been reduced to zero because the end of the cycle histogram would be lower than its beginning. This effect was looked for routinely without being seen.

It bears emphasis that the present 'probability density' procedure for determining the average frequency of firing during sinusoidal stretching (i.e. simply counting the number of spikes in each of a number of bins) is quite distinct from that of using each spike to determine the 'instantaneous frequency' and then averaging the frequencies applicable to each bin. At low frequencies (say below 2 Hz) both methods give the same result. However, as the frequency of stretching approaches the frequency of firing of the ending mathematical corrections must be applied to measurements of instantaneous frequency (Poppele & Bowman, 1970). In contrast, the present method can be applied without modification at all frequencies. When the sinusoidal frequency is above that of the afferent firing the stretching manifests its action by slightly altering the timing of the spikes so that on average more occur on the excitatory phase of the stretching and fewer during the releasing phase, but with an insignificant effect on the instantaneous frequency of firing. More formal discussion of these matters may be found elsewhere (Matthews & Stein, 1969; Poppele &. Bowman, 1970; McKean, Poppele, Rosenthal & Terzuolo, 1970).

The muscle stretcher and its residual noise. The muscle was stretched sinusoidally by an electromagnet controlled by feed-back to form a positional servomechanism (Matthews, 1962; Matthews & Stein, 1969). The amplitude of stretching (half its peak-to-peak value) was varied from nearly 1 mm down to 0·05 μm and the frequency from 0·5 to 500 Hz (occasionally down to 0·2 Hz). The requisite amplitudes decreased sharply with increasing frequency because of the increasing sensitivity

of the endings. At the higher frequencies the inescapable mechanical 'noise' of the stretcher became comparable with the size of the stimulus. In the first group of experiments (ten with off-line computation) the stretcher was the self-same one that was used before (Matthews & Stein, 1969) and had a noise level of about 0·25 μm amplitude for its peaks. In the later experiments (sixteen with on-line computation) a newer stretcher was used, designed and built by Mr W. Laycock. Its principle advantage was that it contained a 'home-built' variable inductance length transducer which operated with a carrier frequency of 1·5 MHz instead of one operating at 6 kHz, thereby improving the assessment of high frequency noise. The noise level of the new stretcher was reduced to about 0·1 μm amplitude for noise peaks in the range 10 Hz to 1 kHz. In the range 10–0·1 Hz, the noise was still below 0·5 μm.

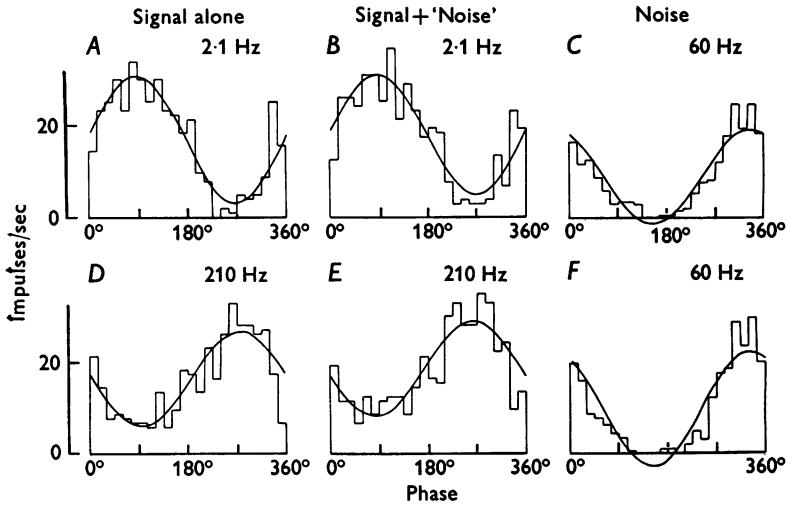

Fig. 1. Cycle histograms with their fitted curves showing the occurrence of linear superposition of the afferent response to two separate stretching sine waves, the one being considered as the 'signal' and the other as 'noise'. This argues that the slight residual mechanical 'stretcher noise' was without effect on the afferent response to a signal. 'Signal' either 32 μm at 2·1 Hz (above) or 0·5 μm at 210 Hz (below). 'Noise' 0·25 μm at 60 Hz (*not* U.K. mains frequency). The 'signal' histograms (*A*, *B*, *D*, *E*) relate the afferent firing to the signal cycle. The 'noise' histograms (*C*, *F*) are based on the same period of discharge as the middle two 'signal' histograms (*B*, *E*) but instead relate the afferent firing to the 'noise' cycle; the values for their ordinate are twice those indicated to the far left. The parameters of the curves fitted to equivalent pairs of responses do not differ significantly. Nor do the 'noise' histograms differ from those obtained in the absence of a 'signal' (not illustrated). Each histogram based upon slightly over 400 spikes collected in about 25 sec.

Averaging, of course, prevents noise obscuring the signal, but the question remains whether the noise could be distorting the response of the ending. For example, if the noise level were to have been 20–30 μm, then its peaks, considered as isolated rapid stretches, would have been sufficient to excite the discharge of

an afferent impulse. The degree to which this occurred might vary during the course of a slow stretch (say 1 Hz) thus producing a spurious indication of the extent to which the ending was being influenced by the 1 Hz stretching *per se*. It is held, however, that the present noise level was low enough for such artifacts to have been absent. Although the noise was large enough to be comparable to the amplitude of the high-frequency signals, yet it was still small enough to fall within the linear range of response of the endings (see results). A linear system responds to two independent inputs by simple summation so that the noisiness of the stretcher should merely have increased the noisiness of the cycle histograms without otherwise changing them. Support for this view is provided by the results shown in Fig. 1 which were obtained by simple mixing of a 'wanted' stretching signal of either 2 or 210 Hz with 'unwanted noise' consisting of another sinusoidal movement at 60 Hz; all these movements fell within the linear range. In both cases the wanted signal could be extracted without bias from the noise, although the 'noise' was strongly modulating the response of ending. The occurrence of such simple mixing in the spindle output can equally be expected with 'white' noise, provided it falls within the linear range of response.

The applied stretching was normally monitored continuously by the length transducer incorporated in the stretcher. The transducer was calibrated by microscopic observation for movements down to 10 μm amplitude; on the basis of its construction it was presumed to continue to behave linearly for smaller movements. Movements below 0·1 μm amplitude could not be measured accurately but were assumed to be linearly related to the magnitude of the input command to the stretcher. The correct performance of such small movements is jeopardized by the occurrence of static friction in any of the bearing surfaces and some occurred in the teflon bearing which maintained the alignment of the rod which transmitted the stretch to the muscle. However, the range of action of the friction was shifted away from zero movement by mounting the Teflon bearing upon a flexible Tufnol spider; this, by virtue of its elasticity, allowed movements of many micra even though the bearing was 'seized'. Thus the smallest movements occurred as desired. The difficulties arose as the stretching became large enough to cause movement at the teflon bearing. The amplitude of the movement remained as desired, and in any case was monitored. But a small additional phase lag developed between the movement and its command signal (over and above that normally found at any particular frequency). The value of this lag was effectively zero (below 2°) for movements of below 10 μm and of above 100 μm, but became measurable for certain intermediate amplitudes, varying somewhat with frequency, and might be accompanied by slight harmonic distortion. The largest lag for 1 Hz stretching, to which we have paid particular attention, was only 6°. The effect probably led us to slightly underestimate the mean value of the phase advance at 1 Hz (cf. Fig. 9); any such error will have been appreciably less than 6°. For frequencies of 5–30 Hz the uncontrolled lag could reach 10°. At higher frequencies the effect became immaterial since the amplitudes of movement employed were then below those at which it manifested itself. In view of the numerous other errors involved we have not corrected for these small effects.

The question also arises whether the movements that were generated were faithfully transmitted to the muscle. The myograph, through which the movements were conveyed, had a stiffness in our later experiments of 4 μm/N with a resonant frequency around 1·5 kHz and so should have transmitted the full movement even with the higher frequencies. It may have introduced phase changes for the higher frequencies (over 100 Hz); but these should have been the same in the presence and absence of fusimotor stimulation.

Corrections to phase. Any 'raw' measurement of phase from the cycle histograms required correction for various lags before it could be applied to the spindle. First, the movement of the stretcher lagged on its command by an amount increasing with the frequency. Albeit with a caveat for the effect of amplitude (see above), this was readily corrected by calibrating the movement with the length transducer. Secondly, the wave of movement will have been transmitted along the muscle with a finite velocity. Allowing a velocity of 40 m/sec (Brown, Engberg & Matthews, 1967) and a 'typical' distance of 2 cm this will have added a lag of 0·5 msec. Thirdly, the afferent impulses were recorded some 20 cm away from their point of initiation in the spindle. The time for conduction from the popliteal fossas was known, on the basis of electrical stimulation, and was around 2 msec. The value for each ending was increased by 30 % to allow for the remaining part of the conduction pathway, as suggested by control observations in which the latency to a brief tap was recorded. Together, the last two factors make for a delay of about 3 msec and the particular value concerned was used for correction in any particular case, as in discussing Fig. 4. But the error in these corrections could readily have reached 1 msec, corresponding to a phase of 7° at 20 Hz and 36° at 100 Hz. Thus we have paid little attention to the absolute values of the phase for the higher frequencies of stretching. But since the corrections apply equally, changes in phase induced by fusimotor stimulation would seem meaningful, since our absolute measurements of time were good to a fraction of a msec. It may also be noted that phase measurements can be made to within a few degrees in spite of using a bin width of 15° in the cycle histogram, as is readily shown by experiment.

RESULTS

Validation of linear range. The present type of analysis rests on the presumption that it is proper to treat the response of the spindle to suitably small stretches as 'linear' so that doubling the input doubles the output without altering its phase or changing the mean rate of firing of the ending. Earlier work has justified this view under various conditions and suggested that stretches producing modulations of firing of up to 30–50 % of the mean level can generally be relied upon to fall within the linear range (Matthews & Stein, 1969; Poppele & Bowman, 1970). However, the matter has been relatively little studied with higher frequencies of stretching and has not been reported upon during fusimotor stimulation. Fig. 2 illustrates responses under such conditions. For stretching at 1 Hz the passive responses (*A*, ●) show a satisfying linearity and constancy of phase over a wide range. The same is true at a much higher frequency, both in the presence and absence of fusimotor stimulation (*B*). However, although some endings show a convincing straight line relation for 1 Hz stretching during static fusimotor stimulation (*A*, ×) this is not always so. The responses of the ending chiefly portrayed in Fig. 2 (*A*, ○) are then fitted by the interrupted straight line only up to a depth of modulation of 8 impulses/sec which corresponds to an amplitude of movement of about 150 μm; even over this range the fit is not particularly good. However, although strict linearity may reasonably

be denied in such a case there can be no doubt that the ending was about ten times less responsive to the stretching during the static stimulation than in the passive state. The slope of the linear approximation still provides a useful guide to the extent of this reduction. Responses showing linearity comparable to that of the various relations of Fig. 2 have been observed for a wide range of frequencies of stretching, and during dynamic as well as static stimulation. They were deemed acceptable on pragmatic grounds and without prejudice as to whether the linear relation regularly

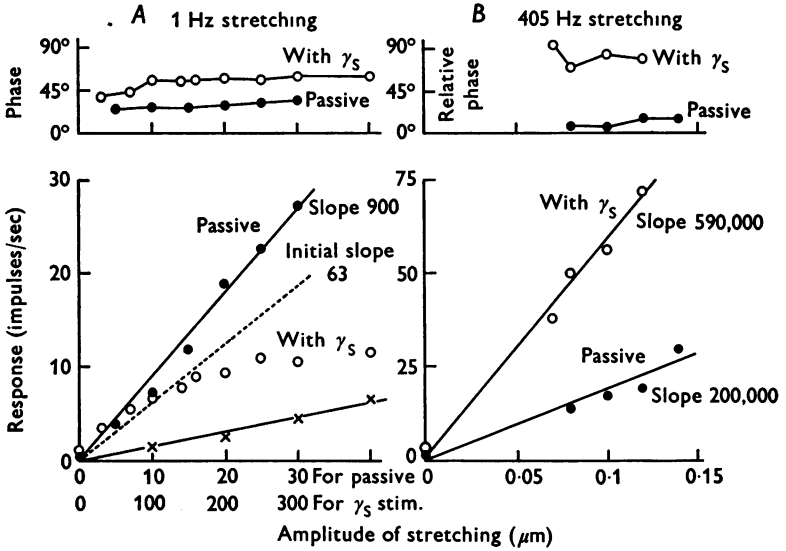

Fig. 2. The occurrence of an approximately 'linear range' of response for small amplitudes of stretching. *A*, response of one primary ending to 1 Hz stretching when passive (●) and during stimulation of a static fusimotor fibre at 87/sec (○). *B*, responses of same ending on stretching at 405 Hz. *A* also includes the response of another primary ending (×) during stimulation of a static fibre at 125/sec to illustrate linearity over a wider range. The 'response' is defined as the amplitude of the sine curve fitted to the relevant cycle histogram. The values of slope or 'sensitivity' are given in impulses sec^{-1} mm^{-1}. In *A*, the values for phase are relative to the stretching. In *B*, the values are relative to an arbitrary zero chosen so as to give the passive responses a small positive value. In all cases the fusimotor stimulation increased the afferent firing by about 70 impulses/sec.

provided the best fit to the data or whether it sometimes simply yielded a working approximation to a 'true' relationship between input and output, applicable over a wider range.

Measurements of sensitivity at a given frequency were normally based upon a straight line from the origin through at least 3 points as in Fig. 2

accompanied by observations on the relative constancy of the phase of the response. An additional criterion employed in the testing of linearity was the calculation of an error term giving the mean square deviation of the points of the observed cycle histogram from the sinusoidal curve of best fit. After remaining approximately constant, the error would normally increase as the amplitude exceeded the linear range (assessed by other criteria), arguing that the data could no longer be well fitted by a single sine and that harmonic distortion was occurring. This, however, was not invariable, and sometimes the response stopped increasing linearly with amplitude although it was still well fitted by a single sine (cf. Matthews & Stein, 1969, Fig. 3). Also, as may be noted in Fig. 2*A* (○), a partial saturation of the amplitude response might occur without gross change of phase. Modulations of up to 30% of the pre-existing firing usually proved to be safely linear on all criteria at all frequencies, and often much deeper modulations proved acceptable as noted in more detail below.

Extent of linear range. At 1 Hz the linear range for passive endings extended up to about 50 μm. Expressed as a modulation of discharge this corresponded to about 60% of a mean rate of firing of 20–40 impulses/sec. During static fusimotor stimulation the linear range at 1 Hz was commonly only 10–30% of a rather higher mean frequency (often around 100/sec) but now corresponding to a movement of 100–500 μm because of the decreased sensitivity of the ending; the absolute value of modulation, in impulses/sec, was sometimes even reduced. At 1 Hz, dynamic fusimotor stimulation tended slightly to reduce the linear range irrespective of whether it was expressed as the absolute or the % modulation of firing.

At high frequencies the linear range, expressed as an amplitude of stretching, was commonly only a fraction of a micron as in Fig. 2*B*. With fusimotor stimulation of either kind the range tended to be smaller, in line with any action tending to increase sensitivity. On the other hand, expressed as a modulation of firing it might reach values of 200% of the pre-existing rate of discharge on allowing the fitted sine to project into regions of negative frequency (cf. Fig. 1*C*, *F*: the computation then ignored the range of empty bins in the cycle histogram). It should be noted, however, that at high frequencies such extreme modulations did not entail any appreciable alteration in the interval between successive spikes, but simply represented a large difference in the probability with which spikes could occur at different phases of the cycle. In contrast, with low frequency stretching large modulations entailed large cyclic changes in the instantaneous frequency of firing of the ending, and linear modulations over 100% were hardly ever seen.

Sometimes the linear relation between stretch and response terminated abruptly with an angle where the points started to fall below the line given by direct extrapolation. This behaviour was common for passive endings during low frequency stretching, but was rare otherwise. It could well be due to mechanical factors analogous to the sudden yielding of the short range series elastic resistance of striated muscle (Hill, 1968) allowing the applied stretch to be taken up by the poles of the spindle rather than transferred to the sensorially innervated region. In accordance with this, it was noted that the point of angular departure could be altered by the preceding history of stretch and release (cf. Brown, Goodwin &

Matthews, 1969). For high frequencies, however, mechanical factors seem unlikely to contribute to the deviation from linearity observed for movements well below 1 μm in total extent. Neural factors were presumably responsible as they may well also have been on some occasions with low frequency stretching.

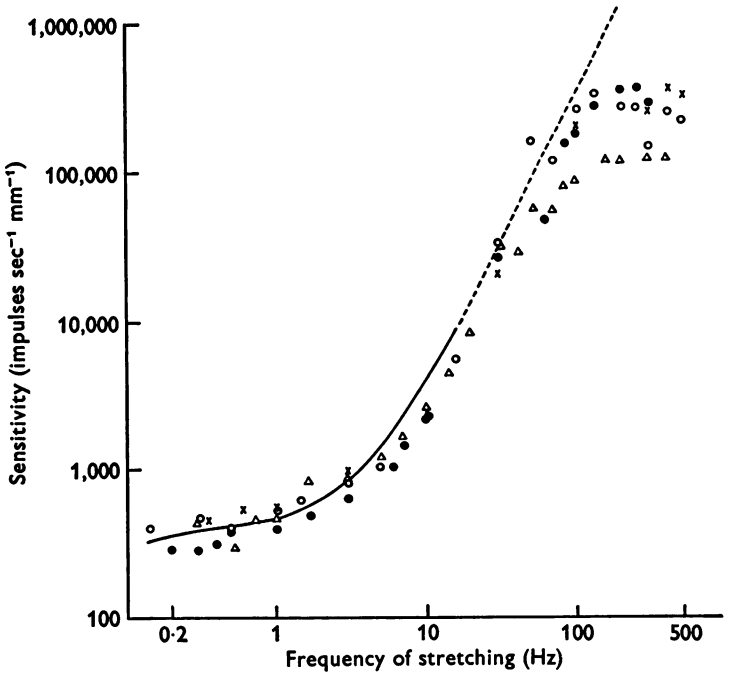

Fig. 3. Frequency–response curves for four separate primary endings in the absence of fusimotor stimulation (passive curves). Each set of symbols represents observations on an individual ending. The endings were studied in different preparations and were selected so as to have similar sensitivities to 1 Hz stretching, but their responses were not otherwise 'normalized' for illustration. The line is derived from Poppele & Bowman's transfer function (see text).

Passive frequency–response curves

Form. Fig. 3 shows superimposed typical frequency–response curves for four different primary endings studied in the absence of fusimotor stimulation (passive curves). The 'sensitivity' is simply the slope of the linear approximation relating the amplitude of the response (in impulses/sec) to the amplitude of the stretching (in mm). As with all passive endings we have studied, the disposition of the points may be described in the following general terms: For frequencies below 1–2 Hz the sensitivity becomes nearly constant with frequency, but above this it rises sharply so that it is some thousandfold larger by 100 Hz. Above 100–

200 Hz the sensitivity again becomes approximately constant and may even show signs of starting to decrease.

The continuous line in Fig. 3 is that given by the empirical transfer function used by Poppele & Bowman (1970) to fit their similar data which lay in the range 0·05–20 Hz. (i.e. $Ks\,(s+0{\cdot}44)\,(s+11{\cdot}3)\,(s+44/(s+0{\cdot}04)\,(s+0{\cdot}816)$, where s is the Laplace complex variable and K is a constant). Within their range it also provides a reasonable fit to the present data. The dotted line shows the extrapolation of the function to frequencies outside the range for which it was derived. It can be seen to continue to provide a tolerable fit for frequencies up to about 100 Hz. This curve emphasizes that for frequencies of about 5–100 Hz the sensitivity of the ending was increasing as the square of the frequency (slope of 100 per decade). In other words, over this range of frequencies the sensory ending may be said to be responding to the acceleration component of the stretching rather than to its length or velocity components. It should be stated, however, that our present measurements of gain and especially of phase were appreciably better fitted on slightly modifying the parameters of their transfer function (the zeros of 11·3 and 44 should be increased by about 50%); but this difference from their findings on tenuissimus spindles has not seemed worth pursuing since the various parameters are currently without physical significance (Rosenthal, McKean, Roberts & Terzuolo, 1970, chose to meet a similar difference for triceps surae spindles by introducing two extra terms into the function as well as by a fivefold increase in the zero at 44).

The flattening of the experimental curve for frequencies above 100 Hz cannot be accommodated without introducing entirely new terms into any transfer function derived on the basis of the low frequency end of the curve. The flattening causes no surprise, however, since there are a variety of reasons why the sensitivity of an ending must at some point cease to increase with frequency. It would be of interest to describe the flattening with further terms in the transfer function, since this might perhaps help specify the responsible mechanisms. But this has not been presently attempted. Such curve fitting depends crucially upon measurements of phase as well as of gain, and we felt that at high frequencies we could not apply proper corrections to our measurements of phase to compensate the various lags involved in recording impulses from spinal roots while stretching a muscle some 20 cm away.

Carrier dependence. Poppele & Bowman (1970) described a form of behaviour for the secondary ending of the spindle which they termed 'carrier dependence', but which they then believed was not shown by the primary ending. Subsequently, by implication, Poppele & Chen (1972) accepted its existence for the primary ending but to a restricted

degree. Our observations are in accordance with their later view and require brief mention since the effect provides a potential source of difficulty in determining the frequency–response curve over a wide range of frequencies. By 'carrier dependence' is meant a specific enhancement of the sensitivity of an ending, when the frequency of stretching approximates to the spontaneous rate of firing of the ending or 'carrier' of its signal; there are also major effects on the phase of the response. Poppele & Bowman argued convincingly that the effect depended not upon the transducing properties of the endings, but upon somewhat accidental interactions occurring at the pace-maker (their encoder) between two separate forms of cyclic activity, namely the sinusoidally modulated receptor potential and the rhythmic discharge of impulses. It is therefore only of secondary interest when studying the frequency–response curve since the intent is then to display the properties of the receptor *per se*. Its action may be seen for one point in Fig. 3, namely the open circle lying above the dotted curve at a frequency of stretching of 50 Hz, which was also almost precisely the mean frequency of firing of the ending.

For the primary ending the effect is relatively small in relation to the gross changes in sensitivity produced by varying the frequency and it disappears when the frequency of stretching differs from the carrier by more than about 15%. In addition, it becomes less prominent with increase in the variability of discharge of an ending (cf. Matthews & Stein, 1969; Stein & French, 1970), and so was less important to us during fusimotor stimulation. In general, we have avoided stretching at the carrier frequency of any particular ending; or, at the least, having recognized the occurrence of carrier dependence have given such points relatively little weight as in Fig. 3. Observations on phase, however, come under greater suspicion and for a wider range of frequencies since the phase of the response changes by 180° on passing through the carrier, as we ourselves have seen. Thus in the illustrations that follow no great significance should be attached to individual points that depart from the general run.

When the frequency of stretching is increased so as to be comparable to the higher harmonics of the carrier it becomes more difficult to decide whether carrier effects could have been influencing the response; on occasion we have seen the effect persist for the passive ending as peaks in sensitivity at integer multiples of the carrier. A further difficulty arises from the progressive fall in the carrier frequency that is liable to occur during a prolonged period of fusimotor stimulation, since this is effectively magnified for the higher frequencies of stretching. For example, a change of 10 impulses/sec in the carrier itself becomes a swing of 50 impulses/sec in the value of its fifth harmonic so that the carrier effects generated by this harmonic will influence the responses to frequencies spread over a range of 50 Hz. Thus the response at a given high frequency which is not an exact multiple of the mean value of the carrier may none the less contain undetected elements of

carrier enhancement. The over-all effect is probably to give a slight lift to the high-frequency end of the curve. Looking on the favourable side, however, the strength of carrier action should have been reduced for high frequencies because of an enhancement, in relative terms, of the noisiness of the carrier. As frequencies corresponding to each successive harmonic of the carrier are considered a given variability in the spike interval histogram comes to correspond to a progressively larger fraction of a cycle thus progressively diminishing carrier effects, since these arise from the interaction of two separate cyclic processes (namely the stimulus and impulse generation) occurring in regular synchrony. It may be concluded that although some quantitative details may be suspect there is little possibility that carrier effects can be held responsible for the two main features of the curve at middle to high frequencies, namely the rise in sensitivity until around 100 Hz and then the subsequent flattening of the curve.

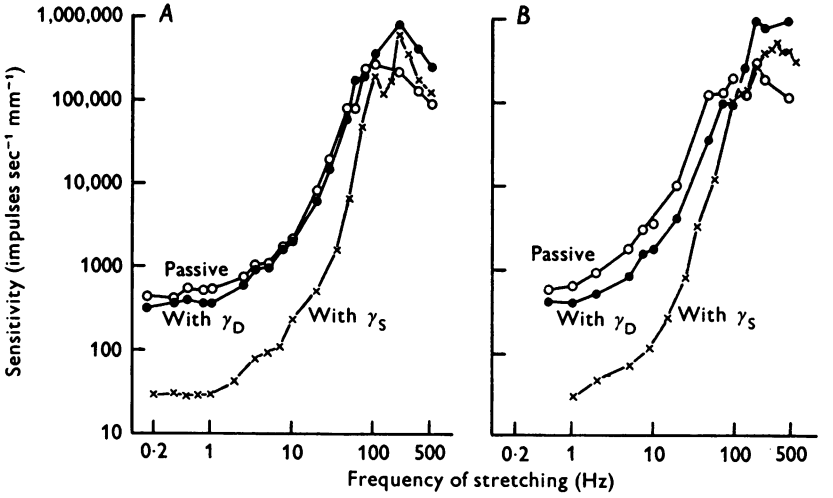

Fig. 4. Frequency–response curves obtained in the presence and absence of fusimotor stimulation. *A*, all three curves obtained on same ending. *B*, passive and 'dynamic' curve obtained on one ending; 'static' curve from another preparation with a passive curve generally similar to that illustrated. The curves in *B* confirm that the main features of those in *A* do not arise fortuitously either from a weakness of the excitatory action of the dynamic fibre in increasing the mean rate of firing (see below), or from a particular degree of phased temporal action of the static fibre (see Fig. 10). In *A*, the frequency of stimulation was 87/sec in both cases; in *B* the values were 57/sec and 120/sec for the dynamic and the static fibre respectively. This led to increases in afferent firing of 20 and 38 impulses/sec with the dynamic fibres of *A* and *B* respectively, and to 53 and 55/sec with the static fibres.

Effects of fusimotor stimulation

Fig. 4 illustrates the typical effects of fusimotor stimulation on the frequency–response curve. The passive curves (○) are of the form already described. The two curves obtained during dynamic stimulation (●) are

displaced slightly below the values for passive sensitivity in their lower reaches and slightly raised above them at high frequencies, but they are chiefly notable for their similarity to the passive curves. This was in spite of the fact that both fusimotor fibres had well marked dynamic actions when tested in the conventional manner with ramp stretches of several mm amplitude, instead of with the present stretches limited to a few hundredths of a mm.

The curves obtained during static fusimotor stimulation ($\times$) indicate a tenfold reduction of sensitivity in comparison with the passive at low frequencies, and a slight increase in sensitivity at high frequencies. In consequence of these opposite shifts at the two ends of the spectrum, the sensitivity in between increased much more rapidly with frequency than did that of the passive ending. For frequencies of about 20–100 Hz the slope during static activation approximated to 10^3/decade, that is to say that the ending was then responding to the rate of change of the acceleration. In line with this, the absolute value of the phase of the afferent response commonly reached a value of about 180° in advance of the stretching at frequencies around 40 Hz, after discounting potential carrier effects. For example, the ending of Fig. 4*A* had an advance of 194° at 50 Hz and that of Fig. 4*B* had an advance of 164° at 35 Hz (carrier, *ca.* 100/sec in both cases).

It should be noted that, although a system responding simply to acceleration can give a phase advance of 180° and one responding to rate of change of acceleration one of 270°, these figures can only be achieved when the requisite response predominates over a very wide range of frequencies. In the present case 180° is too high a figure for a system responding to acceleration alone because of the reduction that would result from the flattening of the frequency–response curve below 1 Hz and above 100–200 Hz.

These effects of fusimotor stimulation may be further specified by plotting the difference between the responses shown by the ending when it was activated and when it was passive, as illustrated in Fig. 5. This also encourages attention to be directed towards the phase of the response since most of the factors making for inaccuracy in its determination would then seem to be eliminated; carrier errors, however, remain. The logarithmic curves of relative sensitivity may be looked upon as portraying the change in the gain of the spindle induced by fusimotor action, and thus perhaps as the frequency–response curves appertaining to an additional 'filter' element introduced by some intrafusal change. At high frequencies both types of fusimotor action introduce a 'phase advance' associated with a progressive increase in gain with frequency. In Fig. 5, as was usual, in moving along the curve the increase in gain with frequency is greater for the static action; this is an alternative expression of the

finding that static action drastically reduced the sensitivity at low frequencies while raising it above the passive value at high frequencies to about the same extent as did dynamic action. However, because of the high frequencies involved, these findings would appear to be irrelevant for considering motor control in the whole animal. At the functionally significant frequencies below 20–30 Hz fusimotor action produced small and inconstant phase changes which are remarkable for their closeness to zero rather than for their deviations therefrom, some of which may

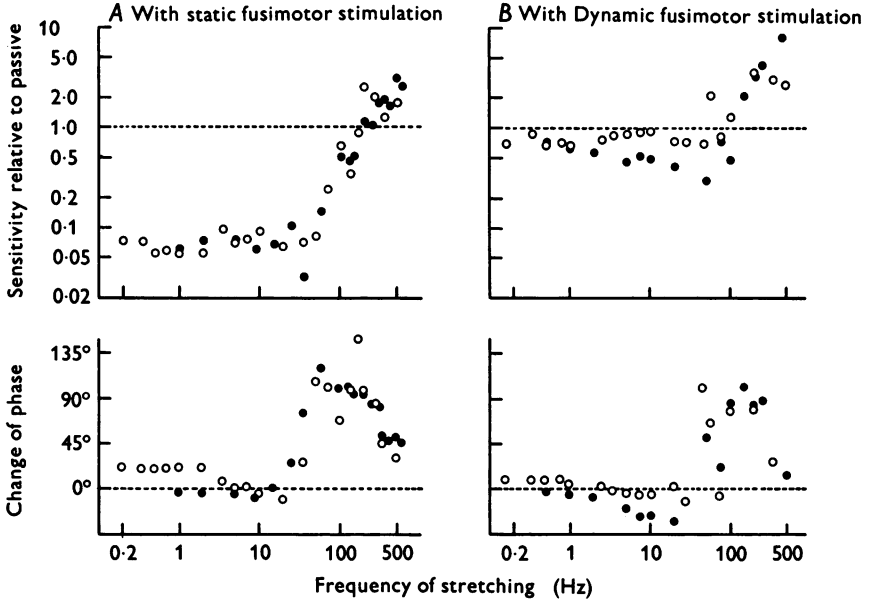

Fig. 5. The *change* induced by fusimotor stimulation in the sensitivity and phase of the spindle response to sinusoidal stretching of a range of frequencies. The upper graph is a logarithmic plot of the ratio of the sensitivity of the activated spindle divided by the corresponding value for the passive spindle. The lower graph is a linear plot of the difference between the phases in the two cases, with phase advance of the active response over the passive response being plotted upwards. Same experiments as Fig. 4 (○, endings of Fig. 4*A*; ●, endings of Fig. 4*B*).

have depended upon experimental error (see also Figs. 6 and 7). As described later the mean effect on phase at 1 Hz was negligible (Fig. 9). Thus, in the range of particular functional significance fusimotor action would appear to control the gain of the receptor while having little action on its dynamics, as judged by the phase. Dynamic fusimotor action reduces sensitivity by some 20–50 % to levels that are still high compared to those seen during static action when sensitivity is reduced by an order of magnitude.

The precise form of the curves required to fit the data of Fig. 5 is of interest in relation to the type of 'filter' element required to model the effect of intrafusal action. The mathematically simplest appropriate 'phase advance' element has a transfer function of $(1+T_1 s)$ and would give a gain curve which is flat until the frequency approaches the critical 'corner frequency' and which thereafter rises at 6 db/octave. Its phase is zero at low frequencies, $+45°$ at the 'corner' and then rises asymptotically to 90°. However, in the experiments as a whole the fusimotor-induced phase advance tended to fall back towards zero for frequencies of 300–500 Hz, as in Fig. 5. Also, the gain often failed to increase appreciably within this range. Thus it seems more probable that the gain curve has the form of a sigmoid, such as would be given by a phase advance element with a transfer function of $(1+T_1 s)/(1+T_2 s)$ which would also give a reduction in phase advance at high frequencies. Moreover, this form of response arises more readily from simple physical systems than does the mathematically simpler continuously rising gain curve. It may be noted that in either case the requisite low frequency corner fell within the range 40–100 Hz for both kinds of fusimotor fibre: on average, the value was appreciably lower for the static action. However, estimates of any high frequency corner showed no difference for the two types of fusimotor action.

Effect of altering mean length. The endings were normally studied with the muscle stretched to within a few millimetres of its maximum physiological length. At shorter lengths the passive sensitivity tended to diminish progressively for all frequencies of stretching, as illustrated in Fig. 6 for stretching at 1 Hz. The soleus usually becomes slack within 9 mm of physiological full extension. During fusimotor stimulation, however, the effect of length on sensitivity tended to be diminished, though as in Fig. 6 the action of dynamic fibres was regularly the less pronounced. Both in the presence and absence of fusimotor stimulation any effect of changing the length on the phase of the response was small (within 20°). Thus fusimotor stimulation may be said to help stabilize the sensitivity of the ending against changes of length at an absolute value which is held low during static fusimotor stimulation and relatively high during dynamic fusimotor stimulation, but which has a constant phase. On dynamic stimulation this stabilizing action sometimes (3/5 cases) had the effect, as in Fig. 7*B*, that fusimotor stimulation increased the sensitivity at short lengths while decreasing it at the high lengths which are those at which we have chosen normally to study their action. Using high frequencies of stretching both static and dynamic fusimotor stimulation typically increase the sensitivity at all lengths of the muscle. At frequencies of 10–20 Hz, however, the effects of length on sensitivity would seem much the same as at 1 Hz.

Fig. 6 has a further interest. Taken in conjunction with measurements of the mean frequency of firing against length it shows that the sensitivity of an ending to low-frequency stretching cannot depend uniquely upon its frequency of firing. Both stretch and fusimotor activity increase the mean rate, but the former increases sensitivity whereas the latter

diminishes it. Thus on bringing the frequency to a given level by the two methods very different values of sensitivity result. The ending of Fig. 6*A* fired at nearly the same rate when fully stretched and passive (0 mm, 43/sec) as when fully relaxed and activated (−8 mm, 55/sec), yet its sensitivity under the two conditions differed more than tenfold (570 and 36 impulses sec^{-1} mm^{-1} respectively). Further, during fusimotor

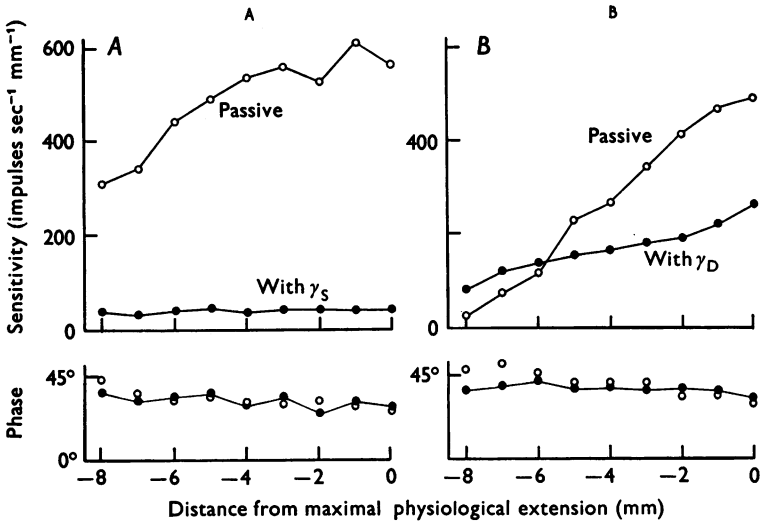

Fig. 6. Effects of varying the length of the muscle on the sensitivity to low-frequency stretching (1 Hz) applied in the presence (●) and absence (○) of fusimotor stimulation. *A*, static fusimotor stimulation at 123/sec. *B*, dynamic stimulation at 120/sec in a different preparation. (When passive, both endings showed an approximately linear increase in mean rate of firing with the extension with a slope of about 2·3 impulses sec^{-1} mm^{-1} and a frequency of firing at the final length of about 40 impulses/sec. During fusimotor stimulation the slope in *A* increased to 5·6 impulses sec^{-1} mm^{-1} with a final value of 120, whereas in *B* the frequency of firing was between 45 and 50/sec at all lengths.)

stimulation large changes may occur in mean frequency at successive mean lengths with little change in sensitivity; the negligible change in sensitivity with length of the activated ending of Fig. 6*A* was accompanied by an increase in firing of 61 impulses/sec. All this precludes the suggestion that the fusimotor-induced changes in low frequency sensitivity depend upon varying the bias of either a single transducer region or of a single pacemaker of the ending.

Frequency of fusimotor stimulation. The frequency–response curves were normally determined with frequencies of fusimotor stimulation of 50–120/sec, the choice in any particular experiment being made somewhat

arbitrarily. However, the differing effects of static and dynamic fibres on the response to low-frequency stretching did not depend upon any particular choice of the frequency. Rather, as the frequency of stimulation was increased the sensitivity tended to an approximately constant level in spite of continued increase in the strength of fusimotor action, as shown by further increase in the mean frequency of discharge of the ending. This generalization is largely based on the effects of varying the

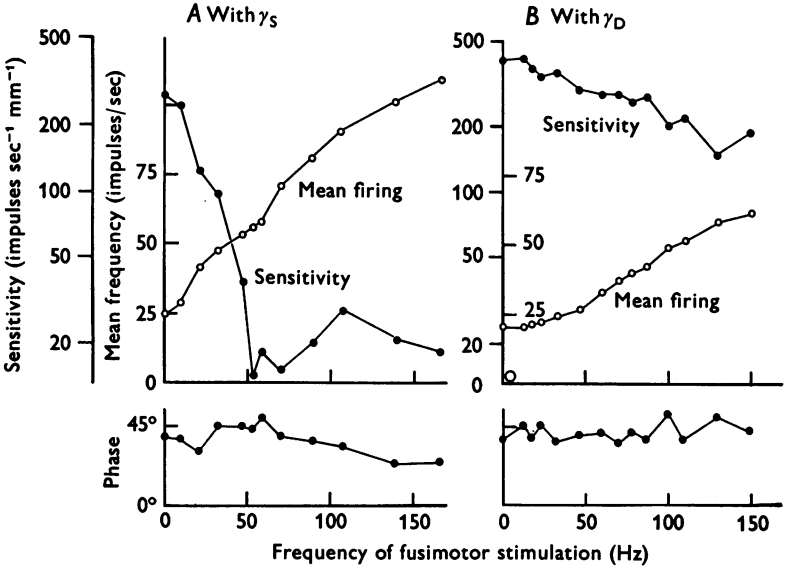

Fig. 7. The effect on spindle sensitivity (●) to low frequency stretching (1 Hz) of increasing the frequency of fusimotor stimulation. The characteristic actions of each kind of fusimotor fibre do not depend crucially either upon the frequency of stimulation or upon the value of the consequent increase in afferent firing (○). *A* and *B* from different preparations.

frequency of stimulation of 10 static fibres and 8 dynamic fibres up to about 200/sec while stretching at 1 Hz, but scattered observations were also made at various other frequencies of stretching. The effect of static stimulation was the more regular and a typical example is illustrated in Fig. 7*A*. After reaching a frequency of stimulation of 50/sec the sensitivity of the ending consistently remained below 12% of its original value; the scatter of the points represents very small absolute changes in sensitivity and achieves prominence through the logarithmic scaling. The only complication in interpreting such observations arises for those points at which the frequency of afferent firing happens to be the same as the frequency of γ stimulation, for this favours any tendency to 1:1 driving with consequent distortion of the response (see later); but as shown in

due course in Fig. 11 this cannot be held responsible for the uniform low sensitivity of the ending of Fig. 7*A* during static stimulation. The effects of dynamic fusimotor stimulation were more variable. Fig. 7*B* illustrated the largest reduction observed from the passive sensitivity. Moreover, in this case the sensitivity progressively crept downwards with increasing frequency although remaining high throughout. On other occasions, there was either an initial fall to a steady level as on static fusimotor stimulation, or else the sensitivity barely changed from its passive level and any systematic change was obscured by variability. Fig. 7 also shows for both kinds of fusimotor fibre that there is little deviation of the phase from the passive value on varying the frequency of stimulation.

With sufficiently high frequencies of stretching static and dynamic fibres act similarly and slightly increase the sensitivity. Unsurprisingly, this action did not appear to depend upon any particular choice of the frequency of stimulation, although we made only sporadic tests of the matter. In two cases that were studied more systematically than the rest, there was a suggestion that increasing the frequency of static fusimotor stimulation continued to increase the value of the sensitivity to stretching at 350–400 Hz for frequencies of stimulation beyond those which might have been expected to produce a constant sensitivity to low frequency stretching.

Fusimotor actions on a range of endings

Sensitivity. Fig. 8 emphasizes the salient actions of the two kinds of fusimotor fibres by plotting the value of the sensitivity during fusimotor stimulation of every ending studied. The absolute values seemed the most appropriate since these are more constant with change of muscle length and are thus more physiologically relevant than are the values relative to those of the endings when passive (cf. Fig. 6). With low frequency stretching, as exemplified by responses to 1 Hz stretching, static fusimotor action can be seen to have typically set the sensitivity of the ending to a low value (mean 73 ± 18 S.E. impulses sec^{-1} mm^{-1}) while dynamic fusimotor action left the sensitivity at a fivefold higher value (mean 355 ± 27 impulses sec^{-1} mm^{-1}) though slightly reduced from the mean passive value (465 ± 28 impulses sec^{-1} mm^{-1}). Averaging the changes produced individually for each fusimotor fibre the statics produced a reduction of sensitivity to 14% (± 3% S.E.) and the dynamics a reduction to 69% (± 3%) of the original value. For the static effects as a whole the value of sensitivity does not vary with the excitatory action of the fusimotor fibres in increasing the mean rate of discharge, which is in line with the effect of increasing the frequency of stimulation of a

given fusimotor fibre (cf. Fig. 7). For the dynamic effects, in contrast with the action of some individual fibres, the sensitivity increases on average with increasing strength of fusimotor action. This invalidates any suggestion that the preservation of a high sensitivity during dynamic action might be merely due to a weakness of excitation. Equally, it can be seen that static and dynamic fibres with equal actions in raising mean

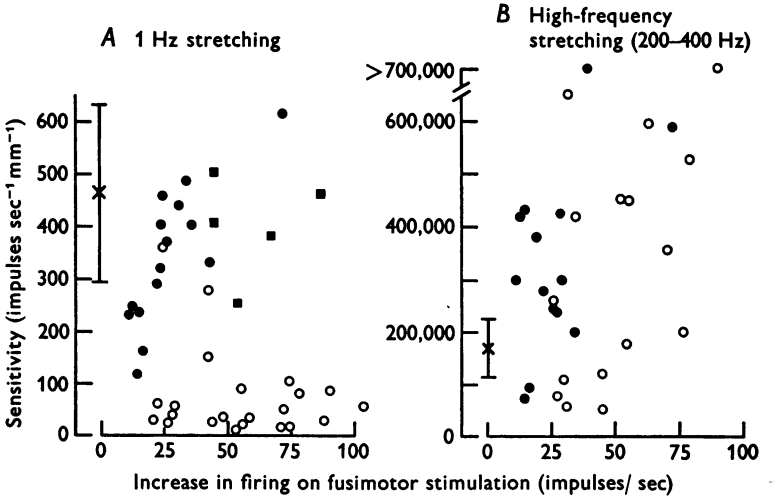

Fig. 8. Scatter diagrams for the whole population studied, relating the absolute sensitivity of an ending during fusimotor stimulation to the direct excitatory action of the stimulation in increasing the mean rate of afferent firing. ●, ■, dynamic fusimotor stimulation; ○, static stimulation (both classified on their action on the afferent responsiveness to a large ramp and hold stretch.) *A*, on stretching at 1 Hz. *B*, on stretching at high frequency (average of all observations made between 200 and 400 Hz). The points at 0 on the abscissa give the mean and standard deviation for the same endings when passive. The frequency of fusimotor stimulation varied between 50 and 150/sec for the different preparations; where more than one frequency was used for a given ending then only the value associated with the highest frequency has been plotted. (Values marked ■ were derived from the work of Crowe & Matthews, 1964, by approximate manual analysis of frequency displays like those shown in their Fig. 7; this provided additional dynamic points associated with an appreciable increase in afferent firing, but did not contribute to the passive values or to the phases in Fig. 9.)

firing typically lead to quite different values of sensitivity. However, measurement of sensitivity alone would not have allowed unequivocal classification of every fibre as a static or dynamic one; the sensitivity remained inappropriately high for two static fibres and rather low for two dynamic fibres, which also had rather a weak excitatory action. Since these divergencies from the general pattern only drew attention

to themselves retrospectively, it was too late to inquire whether the anomalies were characteristic and persistent features of these particular fusimotor fibres, or whether they depended in part upon particular conditions of study such as the length of the muscle or frequency of fusimotor stimulation.

Fig. 8*B* shows the effects of fusimotor stimulation on the sensitivity to high frequency stretching averaged over the frequency range 200–400 Hz; systematic observations were not taken at a single frequency as at 1 Hz nor were all endings studied in this range. There is no longer any occasion to distinguish between static and dynamic action, since both lead to similarly high values of sensitivity. The mean passive value of 116,000 ($\pm$ 19,000 S.E.) was increased to 342,000 ($\pm$ 52,000) during dynamic fusimotor stimulation and to 371,000 ($\pm$ 84,000) during static fusimotor stimulation. In three cases only was a reduction of sensitivity from the passive seen on fusimotor stimulation. The slightly greater mean value on the static stimulation may perhaps be related to a greater static excitatory action, since for the population as a whole there was a tendency for sensitivity at high frequencies to increase with increased mean rates of firing.

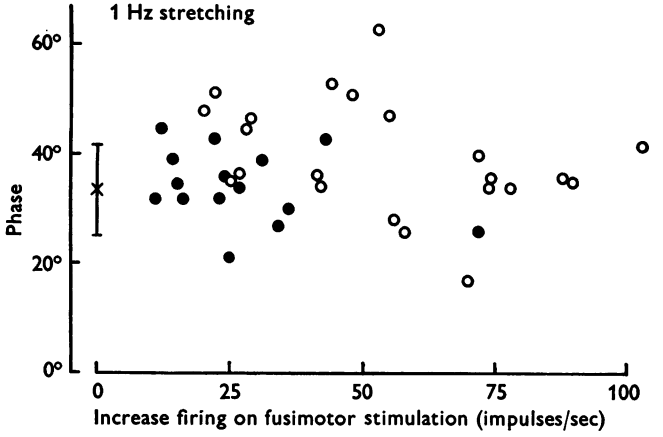

Fig. 9. Scatter diagram of the absolute values of the phase advances of the response observed during fusimotor stimulation on stretching at 1 Hz. ●, dynamic stimulation; ○, static stimulation. Data derived from same responses as Fig. 8*A*. The points at 0 on the abscissa give the mean and standard deviation for the same endings when passive.

Phase. Fig. 9 shows that fusimotor stimulation produced no appreciable effect on the phase of the response to low frequency stretching. Calculated point by point static action produced a mean increase of the phase advance of 2·7° ($\pm$ 2·2, S.E.) and dynamic action an increase of 0·9° ($\pm$ 1·1);

neither value is statistically different from zero. (The mean values of the various points of Fig. 9 do show small differences, arising from the considerable variability and the relative smallness of the samples. The mean passive phase advance was $36{\cdot}5 \pm 2{\cdot}0°$; the mean during static stimulation was $39{\cdot}2 \pm 2{\cdot}2°$ and during dynamic stimulation was $34{\cdot}3 \pm 1{\cdot}7°$; it follows from all the above, as was found, that the means of the passive values appropriate to the static and dynamic fusimotor points differed slightly.) With high frequency stretching, both types of fusimotor action were associated with a phase advance of the response over and above the unknown value for the passive ending. During dynamic fusimotor stimulation the value was 37° (± 5) and during static stimulation was 81° (± 10). On engineering principles, the larger value for the static action may be presumed to be associated with the greater slope of the frequency–response curve in nearby regions (cf. Fig. 4).

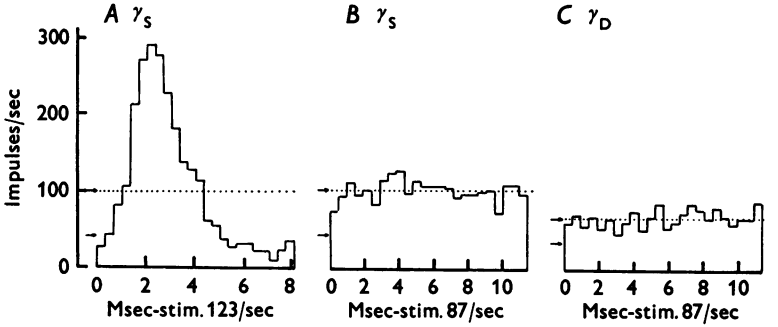

Fig. 10. Examples of post-stimulus histograms relating the timing of the afferent firing to the timing of the fusimotor stimuli. For each, the upper arrow shows the mean rate of firing during the stimulation, and the lower arrow the value in its absence. The related frequency–response curves have already been illustrated in Fig. 4 as follows: *A* above corresponds to the static of Fig. 4*B*; *B* corresponds to that of Fig. 4*A*; *C* corresponds to the dynamic of Fig. 4*A*; similar frequencies of stimulation used in both Figures. (The present histograms are analytically similar to the 'cycle histograms' except that the reference timing marks are now derived from the stimuli. Each histogram is based upon about 1000 spikes collected over 10 sec in the absence of sinusoidal stretching.)

Systematic comparison of the responses to frequencies of stretching of 30–200 Hz was not attempted. This is a region where carrier effects were sometimes severe and where the active curves were overtaking the passive curves, and would thus have required more detailed attention than could be spared in the time available. However, relative to the passive the findings at 1 Hz apply equally for frequencies up to about 30 Hz, since as illustrated in Fig. 5 the difference between the active

and the passive responses is approximately constant over this range; such behaviour was observed for all endings for which it was sought, including the majority of those in Figs. 8 and 9.

Phased modulation of afferent firing by fusimotor stimulation

Under some conditions some static fusimotor fibres elicit 1:1 'driving' of the primary ending so that each fusimotor impulse is directly followed by an afferent impulse (Kuffler, Hunt & Quilliam, 1951; Crowe & Matthews, 1964*b*). This effect is usually attributed to pulsed mechanical stimulation of the ending by residual twitching of the relevant intrafusal muscle fibres. The majority of static fibres show weaker manifestations of the same underlying tendency in the frequencygram (superimposed records of afferent instantaneous frequency locked to the fusimotor stimulus) when evidence of the stimulus rhythm commonly persists for frequencies of above 100 Hz, giving the frequencygram the appearance of an incompletely fused tetanic muscular contraction (Bessou, Laporte & Pagès, 1968). Dynamic fusimotor fibres, however, never elicit driving and give smooth frequencygrams for frequencies of stimulation above about 40/sec. *A priori*, by its domination of the ending, frank driving might be expected to interfere with or to abolish the response to a simultaneously applied small sinusoidal stretch, and this has been noted experimentally (Emonet-Dénand, Jami & Laporte, 1975; Chen & Poppele, 1973).

In the present experiments, static fusimotor fibres that elicited driving were avoided; the effect is readily recognizable at the time. However, the frequencies of static fusimotor stimulation employed (over 40/sec) commonly produced a degree of modulation in the afferent firing. A well marked example is illustrated in Fig. 10*A* by a post-stimulus histogram which relates the moment of afferent firing to the timing of the fusimotor stimuli; we examined such histograms routinely in the last half of the present experiments. Fig. 10*C* shows the typical absence of modulation on dynamic fusimotor stimulation, as would be expected from earlier frequencygrams. It may therefore be asked whether the modulation produced by the static stimulation was of itself the prime cause of the reduction of gain produced by static action on the low frequency end of the frequency–response curve. This, however, seems to be excluded since wide variation occurred in the degree of modulation of the post-stimulus histograms elicited by different static fibres without being associated with the magnitude of effect on low frequency-sensitivity. A particular example is provided by Fig. 10*B* which shows the effect of a static fibre which led to no detectable afferent modulation, yet which had an action on the frequency–response curve which was

indistinguishable from that associated with the deep modulation of Fig. 10*A*; in fact, the relevant frequency–response curves have already been illustrated in Fig. 4.

The records of Fig. 10 characterized the actions of the various fusimotor fibres in the absence of stretching. Fig. 11 shows a fusimotor-induced modulation of discharge occurring simultaneously with a sinusoidally induced modulation. The situation seems akin to that seen during the mixing of two separate frequencies of sinusoidal stretching (cf. Fig. 1), when each elicits its normal response with little or no interference from

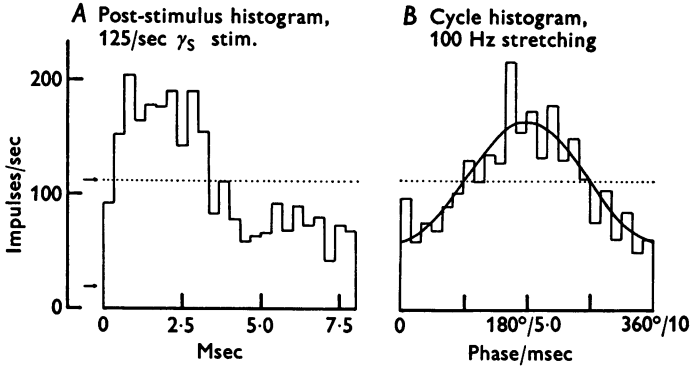

Fig. 11. Simultaneous modulation of afferent firing by static fusimotor stimulation and by sinusoidal stretching. Both histograms were obtained from the same period of discharge but using different reference timing marks. The muscle was being stretched at 100 Hz, 0·2 μm amplitude during stimulation of a static fusimotor fibre at 125/sec. (Same ending as Fig. 7*A*.) The post-stimulus histogram did not differ significantly from that obtained on applying the same stimulation in the absence of stretching.

the other. Of course, the effect of fusimotor stimulation could not be tested for linearity; but the response to stretching within the linear range (cf. Fig. 2) did not interfere with the normal form of the post-stimulus histogram. On the evidence of Fig. 10 the essential static fusimotor action is related to the steady excitation of the afferent terminals, presumably arising from their steady deformation, rather than to any residual intrafusal tremor arising from lack of smoothness of the contraction. The smallness of the tremor is shown by comparison of the post-stimulus histogram with the cycle histogram as in Fig. 11; in this case the tremor was equivalent to a stretch of 0·4 μm total extent. By analogy, static fusimotor action may be likened to a ramp stretch of 10 mm combined with sinusoidal stretching of 0·2 μm at 100 Hz; the former determines the mean rate, while the latter is largely responsible for controlling the precise moment of firing. The next question is whether

the tremor itself ever contributes to the characteristic static actions on the frequency–response curve. When very pronounced, it may reasonably be held partly responsible for the reduction in sensitivity for low frequencies (cf. Chen & Poppele, 1973); but equally, it would then be expected to reduce sensitivity for high frequencies instead of increasing it as observed. On a few occasions band-limited 'white' noise (10 Hz–1kHz) of several μm amplitude was mixed with the sinusoidal stretching and found to reduce the sensitivity for high frequencies. The same was found when the 'noise' consisted of a single sine of an amplitude falling well beyond the linear range. Thus the characteristic elevation of the upper end of the frequency–response curve induced by static action would appear attributable solely to the steady component of intrafusal contraction and thus a simpler phenomenon than the action on low-frequency sensitivity. Of course, from the point of view of central function it is probably immaterial how far the reduction for low frequencies in each particular case is due to steady action and how far to phased intrafusal action, since any phased afferent modulation caused by intrafusal tremor would seem beyond the ken of the synaptic mechanisms involved in reading the afferent signal (cf. Matthews, 1975).

DISCUSSION

The present findings amplify and extend earlier work showing a high sensitivity of primary endings to small amplitude movement (Matthews & Stein, 1969). With low frequency sinusoidal stretching, dynamic fusimotor stimulation leaves the sensitivity high and comparable to that of the passive ending, while static fusimotor stimulation produces nearly a tenfold reduction. Such effects have long been apparent from displays of instantaneous frequency (cf. Crowe & Matthews, 1964*b*). The essential new feature for low frequency stretching is the finding that fusimotor action, whether static or dynamic, does not produce any systematic change in the phase of the response; this was also reported by Chen & Poppele (1973) for the action of static fusimotor fibres on both primary and secondary endings. With high frequency stretching, the comparable increase in sensitivity produced by both types of fusimotor action parallels their comparable effects in sensitizing the primary ending to being 'driven' by large amplitudes of vibration to discharge a spike on every cycle (Crowe & Matthews, 1964*b*; Brown *et al.* 1967). Indeed, the occurrence of such 1:1 driving with movements of a few micra may encourage acceptance of our present, somewhat abstract, procedures as measuring something meaningful when they show that the fine patterning of afferent firing can be modulated by movements of a tenth of a micron.

Functional implications. The physiological significance of the present findings for motor control is likely to be restricted to frequencies of stretching below 20–30 Hz. In this range, for small displacements, fusimotor action specifically controls the gain (sensitivity) of the feed-back from muscle spindles without affecting its dynamics, as shown by the constancy of phase and the similarity in form of the low-frequency end of the various frequency–response curves. In other words, for such stretching fusimotor action does not change the balance between the length, velocity and acceleration sensitivities of the ending: in particular, it cannot be said that dynamic fibres act selectively to increase velocity sensitivity and static fibres to decrease it, for their action should then have been accompanied by the appropriate phase changes (increase for dynamic action and decrease for static). Fusimotor action may also help stabilize the gain of the feed-back against the otherwise considerable effects of changing the mean length of the muscle. These findings should not be neglected on the grounds that the linear range, viewed as a movement, might be felt to be rather small to be of functional significance. Because of the high values of sensitivity, small movements at low frequency lead to large changes in spindle firing (cf. Matthews & Stein, 1969), except during static fusimotor stimulation when the movement itself becomes appreciable. Furthermore, powerful stretch reflex activity may be seen in man for just those amplitudes of tremor which are comparable, as far as the spindle is concerned, to those we have used here (Joyce & Rack, 1974).

These conclusions complement earlier views on the regulatory role of the muscle spindle. In particular, they do not affect the validity or otherwise of the idea of the servo-assistance of movement by the muscle spindle (cf. Matthews, 1972). In so far as static fusimotor action provides part of the 'command' for large movements then it is not inappropriate that it should be accompanied by a reduction of spindle sensitivity; for instance, the primary ending is then less likely to be saturated by small misalignments since static action increases the linear range viewed as a length. Dynamic fusimotor action has long been seen not as a 'command' but as a regulator of spindle responsiveness that assists the stretch reflex maintain a set position in the face of disturbance, particularly during posture. The present findings emphasize its efficacy for fine regulation while finally eliminating the initial tentative suggestion that the prime function of the dynamic fibres is the control of the damping of the stretch reflex (Jansen & Matthews, 1962), which view likewise failed to gain support from systematic work with stretches of large amplitude (Crowe & Matthews, 1964*a*, *b*; control of 'damping' entails regulation of velocity sensitivity independently of other parameters of

the primary afferent response). Also, it is interesting that near threshold any sensory contribution from muscle spindles to kinaesthesia is provided uncomplicated by a variation of the velocity sensitivity of the receptor.

Possible intrafusal mechanisms

On limited evidence, previous workers have attributed the form of the passive frequency–response curve to the behaviour of the underlying sensory transducer mechanisms rather than to any visco-elastic properties of the intrafusal fibres (Poppele & Bowman, 1970; Kirkwood, 1972; Matthews, 1972). The present experiments provide no fresh evidence either way. They have shown a flattening of the curve at high frequencies, hitherto undescribed for cat spindles, which could likewise be attributed to transducer properties. An alternative is that the flattening and subsequent fall is an effect of the finite value of the membrane time constant, which as the frequency is increased must progressively prevent the membrane depolarization following the cyclical membrane conductance change which may be presumed to underly transducer action. Such loss of sensitivity to high frequency events would be particularly severe if a certain amount of electrotonic transmission was required between the site of generation of the receptor potential and its action upon a neural pace-maker. The flattening begins at a frequency of about 100 Hz, corresponding to a time constant of 1·6 msec, which would appear to be of the right order. For the frog spindle, apparently similar flattening occurs at about 10 Hz (Kirkwood, 1972), thus possibly betokening different mechanisms.

Fusimotor activated spindle

The complexity of the situation precludes unique interpretation of the present effects of fusimotor stimulation, but certain issues require clarification since previous views appear unduly simple (cf. Matthews, 1964, 1972). Whatever the mechanisms underlying the response of the passive spindle, it may be anticipated that fusimotor stimulation produces some of the present effects by mechanical action, by altering the properties of the contractile poles of the spindle and thereby modifying the extent to which any deformation applied to the spindle as a whole is transmitted to the sensory terminals. Alterations, with activity, in the properties of this muscular filter cannot be ignored whatever the contributions of other mechanisms to the selectivity of fusimotor action, such as the preferential activation of terminals with different transducing properties which then dominate the overall response of the ending.

Static action and cross-bridge detachment. By analogy with the 'resting' frog sartorius muscle (Hill, 1968), the stiffness of the poles of the passive spindle may be attributed to the existence of a number of stable

cross-bridges between the actin and myosin filaments within the sarcomere (cf. Matthews, 1972). Static fusimotor action may be presumed to lead to contraction of nuclear chain fibres along most of their length. The consequent continual detachment and re-attachment of the cross-bridges will reduce the polar stiffness for low frequencies of stretching, thus permitting freer polar movement and reducing the amount of deformation transmitted to the sensory terminals. This would explain both the reduction in sensitivity and the expansion of the linear range when expressed as a movement. The absence of phase change at 1 Hz with static action would appear to be due to the rapidity of the re-arrangement of the cross-bridges. Microscopic observation suggests that the nuclear bag fibres would normally be slack during static fusimotor stimulation (Boyd & Ward, 1975); even when they are not, 'pacemaker switching' probably ensures that the afferent terminals upon them make little contribution to the overall afferent response (Crowe & Matthews, 1964; Lennerstrand, 1968; Matthews, 1972).

However, as the frequency of stretching is increased there must come a point at which the bridges fail to turn over fast enough to allow free movement between the actin and myosin filaments. A few cross-bridges should then begin to be strained, as in the passive muscle, because they remain attached for an appreciable fraction of the stretch cycle. Thereafter the polar stiffness should increase with frequency as the proportion of cross-bridges that are so attached steadily increases, giving a progressive rise in spindle sensitivity with a phase advance. On this interpretation, the difference between the active and the passive responses should be related to the kinetics of intrafusal cross-bridge attachment and detachment. As with the force–velocity curve, muscle 'viscosity' during sinusoidal stretching can be readily mimicked quantitatively along such lines (Hullinger, 1975).

Extent of sarcomere movement and cross-bridge 'swinging'. Recent studies on frog-muscle show that while it is contracting small sudden movements of within 3–4 nm/$\frac{1}{2}$ sarcomere lead to very little change in tension after the settling of an initial transient lasting 1–2 msec (Huxley 1974). This is attributed to the movement being taken up by a 'swinging' of the heads of the cross-bridges, rather than to any stretching of the bridges themselves or of other components of the series elastic resistance; attachment and detachment of the bridges occurred much more slowly, and for these small stretches produced a negligible effect. The initial transient (increase in tension on stretching and decrease on release) shows an approximately exponential decay which is attributed to limitation in the rate of swing of the heads leading them to behave collectively like a viscoelastic element.

In the present work, by virtue of restricting observation to the linear range, many of the movements have also been of extreme smallness. Assuming that stretch of soleus leads to a uniform deformation along its length then 50 μm amplitude stretching, which is the limit of the passive linear range at 1 Hz, corresponds to a total movement of 2·5 nm/$\frac{1}{2}$ sarcomere. By 50 Hz, the linear range for the passive spindle was always below 2 μm corresponding to 0·1 nm/$\frac{1}{2}$ sarcomere (1 Å), and even with static action was about 10 μm corresponding to 0·5 nm/$\frac{1}{2}$ sarcomere.

Thus large segments of the present frequency–response curves have been obtained with movements falling entirely within the range of swing of the active cross-bridges. It follows that the visco-elastic behaviour attributable to the swinging heads provides an additional mechanism for the increase in spindle sensitivity, relative to the passive, seen at high frequency during fusimotor stimulation. Again, at some frequency of stretching, swinging must begin to be relatively less free leading to a progressive increase in the stiffness of the contractile poles of the muscle filter. To cover all aspects of the matter, it must also be supposed that the free swinging at low frequencies is restricted to 'activated' cross-bridges and not shown by any stable bridges in passive muscle. In the frog, the time constant of this visco-elastic swinging is about 1·5 msec corresponding to a 'corner' frequency of about 100 Hz; its range of action is thus potentially of current interest, provided that the value is comparable in the mammal. On the present evidence it seems impossible to decide upon the relative importance of these two potential mechanisms, namely cross-bridge formation and cross-bridge swinging, in determining the high frequency responses during static fusimotor stimulation; indeed, they may even act co-operatively.

Possible interactions. If the swinging of the bridges were sufficiently free for frequencies below the critical 'corner' set by their visco-elasticity then the resistance to movement would be provided by parallel elastic elements rather than by the cross-bridges. In this case any effect of the kinetics of cross-bridge attachment would be obscured because, while the amplitude of stretching remained sufficiently small, the cross-bridges would not be providing the effective resistance; it would then be immaterial how many remained attached throughout the course of the cycle.

However, at low frequencies during static stimulation the linear range would appear to be outside the limits of swing of the cross-bridges (i.e. up to 500 μm or 25 nm/$\frac{1}{2}$ sarcomere movement). Here gross movement of the cross-bridges provides the only satisfactory mechanical explanation for the low sensitivity, because when attached the bridges are relatively stiff outside their range of swing. None the less, there is no necessity for the kinetics of detachment to manifest themselves in the frequency–response curve at the requisite higher frequency. By the time the frequency in question is reached the amplitude of movement is probably sufficiently reduced to fall within the range of cross-bridge swing, so that the failure of the bridges to release themselves in the course of the cycle is again

immaterial. The necessary reduction of the linear range by this point would be caused by the great dynamic sensitivity of the sensory transducer bringing into play neural limitations on the permissible extent of afferent modulation. Thus there can be no certainty that the finite but unknown speed of cross-bridge attachment has influenced the present curves. But, equally, there is no certainty that the damping of the cross-bridge swinging contributed, since in the mammal at 37° C the expected effect might be shifted to frequencies above those we have studied.

Dynamic action. The lesser potency of dynamic action in reducing sensitivity at low frequency seems likely to be related to the fact that it produces a localized intrafusal contraction rather than a propagated one; whatever the detailed cross-bridge mechanism, the shorter the actively contractile region the less movement it would be expected to absorb. It should next be noted that during dynamic action, then at all frequencies, the movements studied fall within the range of cross-bridge swinging. Thus the finding that at high frequencies dynamic and static action appear similar, with an overlapping frequency range occupied by the increase of gain and phase relative to the passive (cf. Fig. 5), does not admit of unique interpretation. On one hand, it might be taken to show that the essential underlying kinetics of cross-bridge attachment and detachment are similar in all kinds of intrafusal fibre. This would go against the standard view that nuclear bag fibres contract more 'slowly' than nuclear chain fibres, since this would lead one to expect that dynamic action would be associated with a phase advance and rising gain at lower frequencies than static action, as bag fibres are preferentially activated by dynamic fibre stimulation (cf. Matthews, 1972). On the other hand, the similarity may mean no more than that the kinetics of cross-bridge swinging are the same in the two cases and that effects related to slow force–velocity properties of bag fibres failed to manifest themselves at lower frequencies. It seems unlikely, however, that nuclear bag contraction could be so slow as to push the expected effects down to frequencies below those we have studied (i.e. below 0·2 Hz). The simplest view is that our frequency–response curves have little or no bearing on the 'normal' contractile properties of the relevant intrafusal muscle fibres; but it would be premature to see this as a necessary conclusion.

Characterization of fusimotor actions. All this raises the recurrent question as to whether the contrasting actions of static and dynamic fusimotor fibres on the response of the primary ending to large stretches could be mediated by one and the same intrafusal muscle fibre, depending upon whether it is activated locally or throughout its length. Such an explanation would probably suffice for our various frequency–response curves, although these were produced by fusimotor fibres which gave clear-cut static and dynamic effects when tested in the usual way. However, because of their restriction to small amplitudes of movement

the present experiments can do nothing to alter the balance of previous evidence (Hunt, 1974; Matthews, 1972). With ramp stretching of several millimetres extent the intrafusal fibres must be extended far beyond the limits that can be accommodated without gross structural re-arrangement of cross-bridges along at least part of their length. Furthermore, it seems possible that there may be regions of nuclear-bag fibre which are too weakly activated to allow appreciable active shortening and so fail to influence the small-amplitude responses, yet which have an increased number of relatively stable cross-bridges linking the myofilaments which will affect the responses to large stretches. The paradox that dynamic fibres increase dynamic sensitivity as expressed in the dynamic index (Crowe & Matthews, 1964*a*), while producing no change in spindle dynamics under the present conditions, would appear to arise from the very different amplitude of stretching in the two cases. It may be concluded that the present results give no reason to question the validity of drawing a distinction between static and dynamic fusimotor action. Neither does there seem any reason to change the terminology, although the words static and dynamic are potentially confusing for the actions of fusimotor fibres within the small amplitude range.

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