THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

SYMTHESIZED EMG WAVES AND THEIR IMPLICATIONS

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May, 1966

IP-739

ACKNOWLEDGEMENTS

The interest taken in this study and encouragement given by Dr. John V. Basmajian, Head of Anatomy, Queen's University, Kingston, Ontario, is deeply appreciated. Dr. James A. Bennett, Electrical Engineering, also at Queen's, while a graduate student at Michigan, indispensably assisted the study by handling all of the computer work. Dr. Jo C. Moore, Anatomy Department, University of Michigan, carried out some of the tedious preliminary synthesizing of waves, and otherwise gave valuable consultative aid at various stages of the work.

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INTRODUCTION

When twin surface electrodes are placed over the belly of a muscle and the muscle is tensed, an EMG wave of muscle action potential can be picked up amplified and recorded. The wave is a summation of anywhere from a few, to a great many signals (emf impulses) arising from the random firing of motor units. If the tension is increased, the EMG wave changes, tending to become greater in amplitude.

It is very simple, and no doubt appealing, to think that if a certain muscle tension gives a certain electrical effect at the surface, then, doubling that tension should double the surface effect by making the wave's amplitude twice as great. As we shall see, the phenomena are actually so much more complex than that, that such "reasoning" is not only not helpful - it is useless and misleading.

Can a graded series of increasing tensions and the corresponding series of EMG waves be correlated, so that some characteristic of the wave will serve as an indirect measure of the muscle tension? The attempt to predict such a correlation presents its difficulties. At a lower tension, the wave represents an unknown number of unknown components; at a higher tension, a larger number of still-unknown components. This at once says that there is no way of looking at the wave, to find out "what happened". If the components are unknown, how can we make sound predictions about the wave?

Moreover, there appears to be no hope of ever untangling the problem, working from direct physiological research alone. A complete understanding of just one case would require that for a given tension, not only would the EMG wave be recorded - but also, every component of it due to every motor unit involved, would simultaneously be recorded. This is impossible today; and it bids fair to remain impossible, except for the very simplest cases.

For gaining insight in these matters, the opposite approach, and the one attempted in this paper, is to begin with known components, summate them somehow, and see what kind of wave is built up. If we knew (as we do not) all about all of the individual motor unit emf components in an actual case, as to shape, amplitude, number, and distribution, we could synthesize a wave that would precisely duplicate the actual measured wave. A series of these studies, representing graded increasing tensions, would tell us a great deal. The ideal, complete study just described cannot be made, for lack of sufficient information about components. However, synthesis on a simplified basis, made by adopting simple components, can be accomplished. That is the approach used herein.

The Impulse Adopted, and the Period

A single fiber of a single motor unit is prone to give a biphasic impulse. The several or many fibers in the unit may somewhat overlap their impulses, due to different lengthwise locations of the motor endplates, and different times of nerve stimulus arrivals. Thus the motor unit impulse may be more complex than a simple, symmetrical biphasic wave such as is shown in Figure 1a. Also, motor units nearer to the electrodes will give larger impulses than those farther away.

Even so, this study had to be kept to a simple, basic level. With one exception taken up later, all synthesized waves herein were made up of identical components: copies of the Figure 1a impulse. Moreover, this is not a physiologically-derived impulse: instead, it is an arbitrary symmetrical curve, assumed to be sufficiently representative of the real thing. The ordinates are given in the appendix.

If nothing informative comes out of such a simplified study, nothing could come from a more realistic and complicated study; but if the simplified study is informative, encouragement is given for expanding this line of attack.

The adopted impulse was drawn to an arbitrary scale. Its time length, on the horizontal axis, is herein called the period.

What Kind of Wave Can Be Anticipated?

If a lot of these impulses, randomly distributed, are summated, what would we anticipate as to the character of the resultant wave? And if then, the number of impulses is doubled, how would this wave compare with the first? These questions were put to a number of experts working in electronics, communications, and statistics. No helpful answers came. This is a problem that still defies analysis, even though able men are interested in it and working at it.

Among those approached, a goodly number made an almost automatic guess at one answer to the first question: there would be a large degree of cancellation. On further thought, this guess was usually withdrawn. Further guessing was withdrawn, too. This is unfamiliar territory.

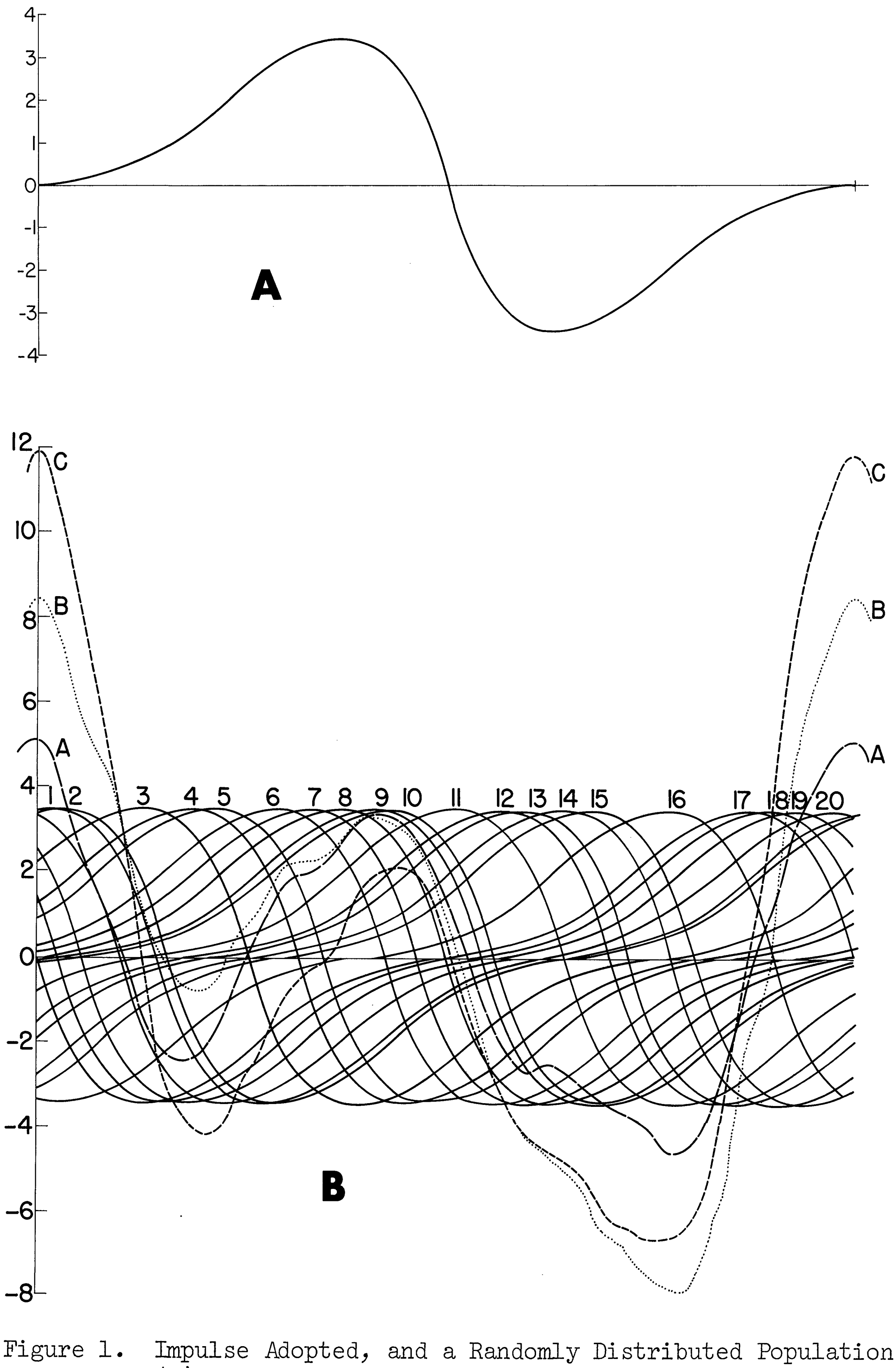

Figure 1. Impulse Adopted, and a Randomly Distributed Population.
(a) The Adopted Impulse. Its Time Length is Called a Period.
(b) A Randomly Distributed Population of Q = 20 Impulses per Period. Wave A is the Summation. For Waves B and C, See Text.

As to cancellation, this would certainly dominate if, instead of random spacing of the impulses, equal (uniform) spacing is used. A study of this, for the Figure 1a impulse, was carried out, using 20 impulses per period. The small residue wave left in the summation had a maximum amplitude of only 0.23, as compared with the impulse maximum of 3.42.

Random distributions will of course give cancellation effects at some places, and pile-up effects at others. This helps one to appreciate the fact that there just is no way of predicting the wave characteristics. To make any progress, a population of component impulses must be added up to get a wave; likewise for larger populations to get more waves. Only then can inter-comparisons be made, and possibly, relationships be found between some wave characteristic, and the population of impulses that produced it.

Preliminary Trials; the Population; a Showcase Example

"Population", having the symbol Q herein, means the number of impulses per period. A template was made to fit the impulse shape, making it easier to draw many overlapping impulses. A few trial cases of differing populations were carried out the hard way (graphics-plus-arithmetic) to get the summation waves. They seemed to show promise.

A "showcase example", Figure 1b, was then made up, also the hard way. It has a randomly distributed population of $Q = 20$. A roulette wheel type of scheme (tossing a round disk up and catching the edge) dictated the random locations of the impulses. Curve A is the summation wave. Impulse No. 15 was then deliberately selected for removal - to have the largest effect on the peak. Curve B resulted, giving a higher peak for 19 impulses than we had for 20. For further emphasis, the missing impulse was deliberately put back in to coincide with No. 20, giving Curve C with a still higher peak. (This synchronizing of two impulses will be brought up again later.)

For Curves A, B, and C, in that order, the peaks are 5.0, 8.4, and 11.9. In the same order, the RMS (root mean square) values are 2.8, 4.7, and 5.2. One lesson to learn here is that, since random distribution of impulses may sometimes yield any of these effects, a wave train as short as one of these periods cannot be expected, for $Q = 20$, to yield anything like a standard, reliable summation wave. Neither will a far larger population - as will be seen when computer-derived waves are taken up.

The large amount of work involved in creating Figure 1b clearly showed that any real progress from there on would have to bring the computer into the picture.

Computer Data; Plotting the Wave

The adopted impulse, Figure 1a, was readied for the IBM 7090 computer by reading 101 ordinates, evenly spaced (see appendix). The computer was ordered to use the ordinates, to randomize and sum up a population of $Q = 20$ impulses, and to do it for 20 periods. Some 2000 numbers came out, as ordinates of the summation wave. Since the first period was a get-ready period and incomplete, it was discarded, leaving 19 usable periods.

To save a great deal of work, only every tenth number from the computer was read and plotted in Figure 2a. This is why the wave, which otherwise would have smoothly rounded peaks, was drawn with broken lines. The compromise makes no essential difference in the findings to be described later. The dash lines, Figure 2a, show the amplitude of the impulses.

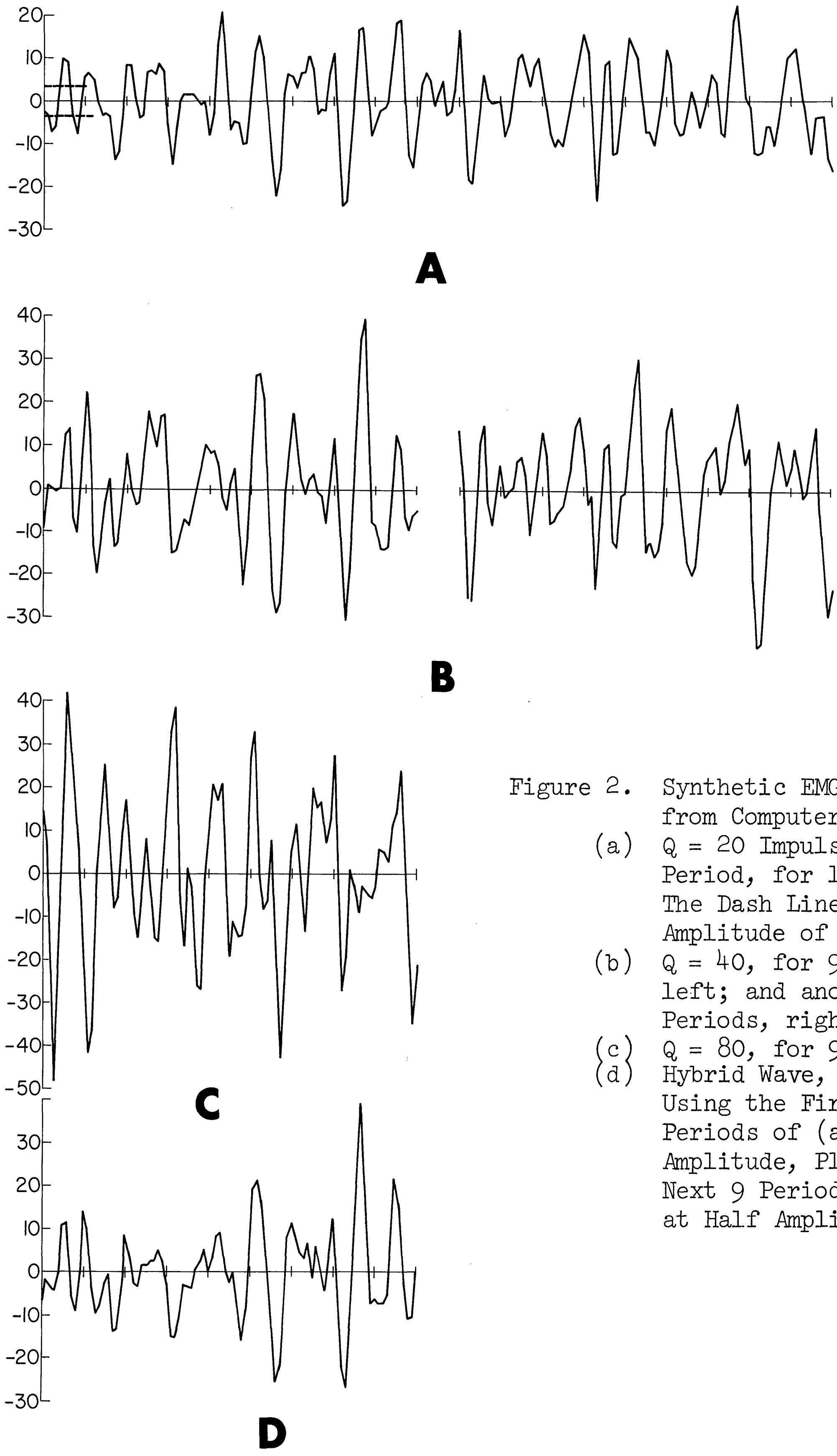

Figure 2. Synthetic EMG Waves from Computer

(a) Q = 20 Impulses per Period, for 19 Periods. The Dash Lines Show the Amplitude of the Impulses.

(b) Q = 40, for 9 Periods, left; and another 9 Periods, right.

(c) Q = 80, for 9 Periods.

(d) Hybrid Wave, Made by Using the First 9 Periods of (a) at Full Amplitude, Plus the Next 9 Periods of (a) at Half Amplitude.

Higher Populations, and Comparison by Inspection

The available computer time was used up in the Q = 20 run. However, a Q = 40 wave could be obtained, Figure 2b left, by adding the first 9 periods of Figure 2a to the next 9 periods. This was done by long-hand methods. This derives a 40-wave in precisely the same random way that a computer might happen to produce it directly. Also, another 40-wave, Figure 2b right, was obtained by adding the 20-wave's first 9 periods to the last 9 periods. By the same kind of manipulation of the 40-waves, the 80-wave, Figure 2c, was produced.

Three observations can at once be made, from visual inspection alone. First, the greater the population, the greater the amplitude. Second, the average frequency, indicated by number of axis crossings in 9 periods, remains essentially unchanged by population increase. Third, the general characteristic or appearance of the wave (except for amplitude) seems to be unchanged by population increase. Inspection can lead to such an opinion about the general similarity of the waves, but opinion is not proof. Some function of the wave, such as the RMS (root mean square) requires investigation.

Variation of RMS with Population

The RMS values of the three waves were next found. For 9 periods, for example, this meant squaring 91 ordinates, adding them, and dividing by 91 to get the MS, or mean square; then taking the square root to get the RMS. (Note: to be precise, this routine, theoretically, is slightly erroneous; but the error is totally negligible for this study).

For the populations of Q = 20, 40, and 80, the RMS values, in order, are 9.17, 13.4, and 18.9.

The RMS ratio, 13.4/9.17, for doubling Q, is 1.46.

The RMS ratio, 18.9/13.4, for doubling again, is 1.41.

Could these ratios, so close to 1.414, the square root of two, be suggesting that a predictable law of variation exists? Indeed they could.

Here, we go to those, especially in electronics and communications, who work with "noise", and who need to know how two or more noises will combine. There is a theorem which, when applied to our problem, says that when to irregular emf waves, such as the two that made the 40-wave, are combined (added), the RMS of the resulting wave is the square root of the sum of the two MS (mean square) values of the original waves. This law predicts that in the two cases above, when populations were doubled, the ratios should be 1.414.

The law is not confined to cases in which one population is just twice the other. It more generally says that as the population of impulses, all alike, is steadily increased, the RMS of the summation wave varied with the square root of the population. That is,

$$\text{RMS} = K\sqrt{Q}$$

where K is a constant. If we let each of the three populations above, and their respective RMS values, determine the constant, the values of K, in order, are found to be 2.05, 2.13, and 2.11. The average of these is 2.09. The equation then becomes -

$$\text{RMS} = 2.09\sqrt{Q}$$

The curve plotted from this equation is given in Figure 3. Also plotted there are the three RMS values for Q = 20, 40, and 80. The agreement, for these purposes, is virtually exact.

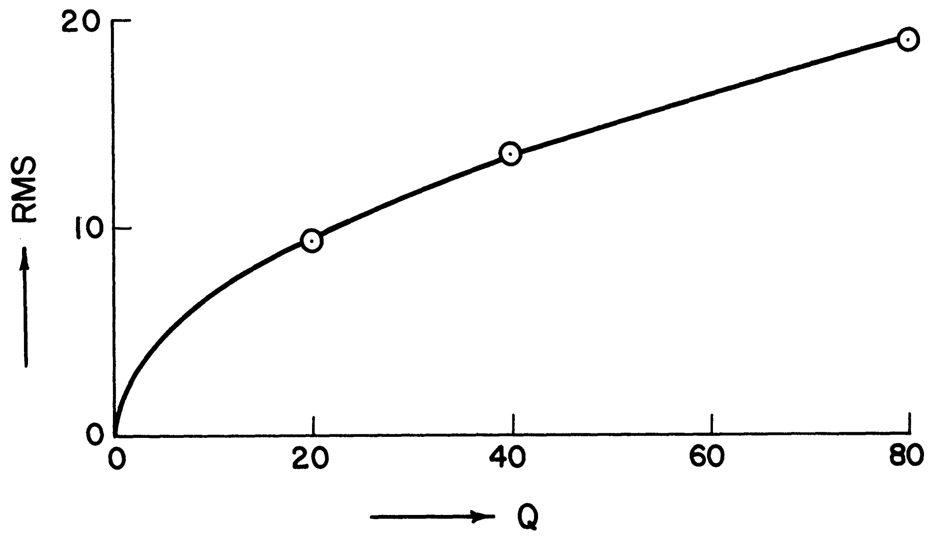

Figure 3. Variation of RMS with Population. The Curve has the Equation, RMS = 2.09 Q . The Three Points are from the Waves for Q = 20, 40, and 80.

Variation of Higher Peaks with Population

Going back to Figure 2, the four highest positive peaks in the first 9 periods of the 20-wave add up to 73, and the four highest negatives, to 78. The average is 75, rounded figure. Treating the next 9 periods likewise, we get 70 and 68, with an average of 69. The average for 18 periods is 72. Divide by 4, and we get the high-peak average of 18.

For the 40-wave, left, 9 periods, the four high positives add to 108, the negatives to 103, with an average of 105. For the 9 periods at the right, 90 and 113, which average to 101. The average for 18 periods is 103. Divide by 4, and get a high-peak average of 26.

For the 80-wave, we get 143 and 158 for positive and negative peak sums, the average being 150. Divide by 4, get a high-peak average of 37.

Recapitulation: for Q = 20, 40, and 80, the high peak averages, in order, are 18, 26, and 37.

Doubling the population from 20 to 40, the high peak ratio is 26/18 = 1.44. Doubling it again from 40 to 80, the high peak ratio is 37/26 = 1.42. Again, a square-root-of-two ratio is showing up, with a truly remarkable degree of precision.

Wave Characteristics Unchanged by Increasing Population

In addition to finding general resemblances among the Q = 20, 40, and 80 waves of Figure 2 by visual inspection, we now have three measures of mutual consistency. First, the average frequency, indicated by the number of axis crossings, is much the same in all. Second, the RMS varies with the square root of Q. Third, the higher-peak average also varies with the square root of Q. These measures seem strongly to suggest that the more important characteristics of the wave are not changed by population increase.

Now, what about population higher than the highest (Q = 80) used herein? In Figure 1b, the component impulses of a 20-wave are seen. Imagine how this chart would look if turned into an 80-wave: it would look extremely crowded. Then, what if a chart were made for four times that population - that is, for a 320-wave? It would look almost black. When put this way, one is bound to wonder if such far higher populations would continue to turn out waves of the same general characteristics as found for the lower populations.

But there is another way to think about it. Instead of worrying about a vast number of impulses per period, we can instead concentrate on waves. We have already found that when four 20-waves, Figure 2a, are added up randomly to produce 80-waves, Figure 2c, the two waves have the same general characteristics, and are related by definite laws. It follows that if four 80-waves are randomly added to make 320-waves, we will again come out with the same general kind of wave, again related in the same ways to those that gave it birth. This is one of the most striking results of this study. It should of course be verified by further work; but the argument above strongly indicates, for the present, that a low population of 20 and a vastly higher population of 320 (or even much higher than that) will turn out waves of the same general characteristics, with RMS values and high-peak amplitudes varying with the square root of Q.

Preliminary Discussion of Motor Unit Recruitment and Behaviour

Up to now, no attempt has been made to match muscle force with impulse population and wave properties. To get the thinking organized, let us temporarily adopt two assumptions: first, that muscle force is proportional to the number of motor units recruited; and second, when a unit is recruited, it instantly produces its maximum tension or force, and continues to do so. These assumptions are wrong, and will be abandoned later, but they will help to organize the picture.

The outcome is that impulse populations are proportional to the graded forces required of the muscle: if force is doubled, population is doubled. We have found that wave RMS varies with the square root of Q. The final outcome is that force varies likewise. That is, these assumptions predict that the RMS of the EMG wave varies with the square root of the force.

If this were true, it is convenient to re-interpret Figure 3. For a large muscle, think of three of the numbers on the horizontal scale, 20, 40, and 80, as now meaning pounds: then the curve gives (relatively) the increasing RMS values of the waves. This, we note, is far from being a linear (proportional) variation.

Let it be made plain at this point, that this paper is not in any sense directed toward supporting either a linear, or a non-linear variation. And now, the above too-simple assumptions must be replaced by something more nearly in accord with the facts.

Recruitment, and Motor Unit Response to Motoneuron Stimulus Frequency

Here, Ruch et al. (references) and those they cite will be followed. A motor unit consists of anywhere from three, to hundreds of of muscle fibers, all stimulated by a motoneuron, and all contracting when a stimulus comes. If a single stimulus arrives, there are two outward, or externally measurable responses. First, the fiber membrane fires, giving an electrical impulse to be picked up by the electrodes; second, mechanically, a twitch occurs, rising to a maximum twitch force and falling off again, and of much longer duration than the impulse. If two stimuli arrive close enough together, the two twitches fuse somewhat, giving a higher maximum; and with three, somewhat higher yet, and so on. If stimuli continue to arrive, and fast enough, fusion of twitches becomes virtually complete, giving a quite steady maximum force typically four times that of a single twitch maximum. Although the twitches thus overlap and fuse, the electrical impulses from the fiber firing never overlap.

Citing Adrian and Bronk, "During voluntary contraction the discharge of single motoneurons varied between 5 and 50 impulses per second as the contraction increased from light to maximal effort".

Again quoting Ruch et al.- "As more force is required, three things happen in an overlapping sequence: (i) more motor units are activated (recruitment); (ii) the active motor units discharge more frequently but not rapidly enough for muscular summation (i.e., the response is subtetanic); and (iii) with further increase in frequency, the motor unit twitches summate to form a tetanus". Thus, not only are there overlapping stages; but, as a unit is recruited, it joins in at first with twitches, and ends with a steady contraction force of about four times the maximum of a twitch.

Hypothetical Motor Unit Recruitment Schedule

The table, under this title, shows one attempt to construct a schedule of recuitment and envisage the outcome. First, it was assumed that the Adrian and Bronk range of 5 to 50 motoneuron stimuli per second could be replaced by a 4 to 64 range. This in turn was divided into the series of 4, 8, 16, 32, and 64 stimuli per second. It was further assumed that in the same order, the corresponding motor unit forces would be proportional to the numbers 1, 2, 4, 5 and 6. These are seemingly reasonable values that were adopted; others would no doubt exercise a different judgment and adopt other values.

Next, the muscle was divided into five equal groups of motor units, to be recruited in overlapping sequential order (Groups 1 -- 5), giving rise to five Force Levels (columns A -- E). For example (see table) at Force Level A, it was assumed that Group 1 had all of its motor units at maximum, with 64 stimuli per second arriving. For simplicity, $q = 64$ stands for two things: rate of stimuli, and also the EMG impulses contributed to the total population of Q. A group force of $f = 6$ is attained, this being the group's contribution to total muscle force F. Group 2 is recruited and is well along, at q and f of 32 and 5.

HYPOTHETICAL MOTOR UNIT RECRUITMENT SCHEDULE
Five Equal Groups of Motor Units

q means population coming from a unit group
f means force coming from a unit group

Force levels, increasing to the right, from one column to the next.

Group		A	B	C	D	E
1	q	64	64	64	64	64
	f	6	6	6	6	6
2	q	32	64	64	64	64
	f	5	6	6	6	6
3	q	16	32	64	64	64
	f	4	5	6	6	6
4	q	8	16	32	64	64
	f	2	4	5	6	6
5	q	4	8	16	32	64
	f	1	2	4	5	6
	Q	124	184	240	288	320
	$\sqrt{Q}$	11.2	13.6	15.5	17.0	17.9
	F	18	23	27	29	30

Group 3 is less further along, 16 and 4, and so on. Total Q, 124; the square root being 11.2; and total F, 18. Inspection of the table shows how the groups are increasingly activated for higher force levels. In Force Level E, all groups have achieved maximal force. The outcome, in part: Q ranges from 124 to 320, with square roots ranging from 11.2 to 17.9; and total force F ranging from 18 to 30.

How Does the RMS of the EMG Wave Relate to Muscle Force?

If, from the table, the square roots of Q are plotted against the respective forces F, a straight line from the origin can be drawn to fit the points, the worst disagreement being about 6%. Since, earlier herein, it was found that the RMS of a synthesized wave varied with the square root of Q, it follows that in this case, we have found the RMS to vary directly with (proportional to) force. The table covers approximately the upper half of the total muscle force range (18 to 30). Presumably, a recruitment table could be devised for the lower half, to give the same law of variation.

de Vries (references) has found essentially this result, for the biceps brachii. Do these essentially identical results (de Vries' and the foregoing) validate each other? Emphatically not. The present study can neither prove nor disprove a linear variation, for it is a devised, or rigged, set of values seen in the table. A different scheme for bringing the five groups into action, can lead to quite a different outcome. Before arriving at this table, the writer tried various other combinations, and most of them tended more nearly to let Q vary with F, instead of Q-squared varying with F. When Q varies with F, the square root, representing the RMS value of the wave, by no means rises as fast as linearly. The curve bends over (see again, the re-interpretation of Figure 3).

Something like what is shown in the writer's table may well happen. But it is difficult to believe that a muscle would follow through in such a regularly-advancing manner, as force builds up. Even if the advances made by the groups occur like this, it does not follow that the groups should be of equal size. Moreover, the build-up in Group 1 may, for all we know follow a schedule quite different from that of a later group.

And even if, by some miracle, the table holds for one striated muscle, it may not hold for another. Evolution has a tidy way of warping a particular muscle to fit the needed requirement, and seeing to it that it does its job to the best advantage of the organism - and not to give pleasure to those of us (like the writer, for instance) who like to admire an orderly series of numbers.

Two kinds of skeletal muscle occur in higher vertebrates. Red muscle, typically slower, manages the sustained contraction jobs. White muscle, faster, handles the quick motion duties. In EMG work done on animals, this distinction demands close attention, for the details of recruitment may turn out to be different in the two; and if so, the RMS-force relationship may differ.

In man, the highest vertebrate, we find a remarkable exception: his skeletal muscles are a mixture of the two kinds. Tokizane and Shimazy (references) have done what seems to this writer to be a superb job at showing that these two sets of motor units operate under different controls, and respond in different ways; and that "every muscle differs from every other in these respects".

The linear variation of RMS with force found by de Vries is backed by what appears to be admirably careful and accurate techniques. However, it does appear that other workers have definitely found a less-than-linear rate of rise for some muscles; and with a tendency for the wave to change little in amplitude as maximum force is approached.

The purpose of this paper is to do what it can to illuminate the subject, and assist some of the thinking that should go along with EMG research. It may well turn out that after carefully contrived techniques have been applied to different muscles by an adequate number of workers, various muscles will be found to have different ways of responding to demand; and that the RMS (or other measure) as related to force, will have to be settled on the individual muscle basis.

Random vs. Synchronous Motor Unit Action

In the low end of the force range, a muscle would appear to have relatively few motor units activated, with many of these yielding only twitches or poorly fused twitches. If they operated synchronously, jerkiness would ensue. Instead, in acting at random, the overlapping of the little forces gives a steady force in isometric contraction, or smooth control in movement. High in the force range, most of the motor units that can be recruited by conscious effort are at maximal, producing steady forces. Here, steadiness of total force and control of movement would depend much less on random action.

This opens the way for suggesting that some degree of synchronization may enter in, at high force, for some muscles. First, in a way as yet unknown, it may automatically happen; or second, it may be built in to give an advantage yet to be discovered. The point is that if, as force demanded rises, there is a small shift from complete randomness toward synchronism, a relatively large increase in RMS and in high-peak ordinates would take place. This is seen by returning to the showcase example, Figure 1b; where, to repeat, in moving only one impulse out of 20 to make it coincide with another, the high-peak rose from 5 to 11.9, and the RMS rose from 2.8 to 5.2. Such a shift would tend to make a muscle's RMS rise more nearly linearly with force, when otherwise it would rise less fast. Thinking in terms of the table showing the Recruitment Schedule, this shift would not change the Q-values, but certainly would change the maximum amplitudes and RMS values. This offers one more item to think about in planning EMG research. Possibly, patient work with implanted electrodes will prove, or disprove, a shift.

Then, there is the opposite possibility: that a small degree of synchronism is present in the intermediate range of some muscle, which drops out at near-maximal effort. This could account for what happens when the EMG refuses to rise much, as the force increases at near-maximal.

Non-uniform Populations

The actual EMG wave is, of course, a summation of impulses of all sizes, due to nearness or farness of electrodes to motor units. That is, it has non-uniform populations. To look into this aspect a little, one case was carried through. Figure 2d shows a wave made by hybridizing. It is a hybrid of Q = 40, made up of the first 9 periods of Q = 20; plus the next 9 periods of Q = 20, taken at half-amplitude values. We again see a general similarity to the other waves.

More than that, its RMS can be predicted as the square root of the MS values of the two waves that were combined. The prediction is 10.35 for the RMS. The computed, from the wave, is 11.0, which checks to within 6 per cent.

This seems to encourage the idea that if these studies are computer-extended to combine several populations graded as to impulse amplitudes, the simple relationships brought out in the present study might still prevail.

Synthesized Wave's Resemblance to Actual EMG Wave

Some EMG workers may not be accustomed to waves that are as magnified and stretched as those in Figure 2. When the first 5 periods of the 20-wave, Figure 2a are squeezed down, we get the rendition in Figure 4. It is indistinguishable from any number of actual waves now on record.

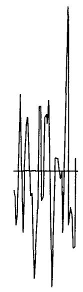

Figure 4. Resemblance of Synthetic Wave to Actual EMG Records. This is the First 5 Periods of the Figure 1a Wave Compressed.

Limitations of the Study; Further Studies

It must again be emphasized that this is a simplified and limited study. Simplified, by dealing with a series of uniform populations of impulses, except in one case; and perhaps too limited in scope to warrant drawing final conclusions. The least that should be done is for someone independently to repeat the study, to find if the same laws and relationships again show up. Preferably, the repetition would extend for considerably more periods.

If that work is done, and this study is verified, then a more expanded study would be warranted, to include (a) several amplitude-graded but otherwise like-shaped populations of impulses; (b) populations of impulses alike as to amplitude but different as to shapes; and (c) a combination of (a) and (b). After that, other variations might be justified.

SUMMARY

1. EMG waves obtained with twin surface electrodes are extremely complex summations of anywhere from a few to a great many emf impulses generated by individual motor units in the muscle. The understanding and interpretation of such a wave is obscured by the fact that it is made up of unknown components. Except for extremely simple cases involving a very few impulses, these components are at present unknown, and there is little prospect of ever making them known. This is a fundamental and probably insurmountable difficulty.
2. The other approach to understanding is to start with known components and build them up to synthesize waves resembling EMG waves.
3. An arbitrary biphasic impulse was adopted, its length (time duration) being called a period. The number of randomly-spaced impulses per period is called the population. With computer aid, waves synthesized from populations of 20, 40, and 80 have been produced, closely resembling EMG waves. These waves differ much in minor detail for short spans, within themselves; but they have a broad general resemblance.
4. It was found that the wave RMS value, and the average value of the four highest positive and four highest negative peaks, in 9 periods, both vary with the square root of the population. Separately, a "noise theorem" predicts precisely this relationship. Although an 80-population was the highest studied, a wave-comparison argument indicates that far higher populations may continue to yield the same wave characteristics, having the same relationships.

5. A hypothetical motor unit recruitment schedule has been worked up to relate muscle force to wave RMS, resulting in an approximately linear variation of RMS with force; however, the adoption of different assumed values in such a table can equally well yield a non-linear relationship in which RMS rises more slowly than force.

6. It is shown that if, in going from low to higher forces, a small shift from completely random motor unit action toward synchronism were to occur, a relatively large increase in high-peak amplitude and in the RMS would ensue. An opposite shift would have the opposite effect.

7. The relationships in (4) above hold for 9 periods or more. For short wave trains, say, of one period, all rules fail. Short spans are not and cannot be comparable. There may be the possibility that if brief muscle contractions were accurately repeated, the several short-span waves, while much unlike, might be hitched end to end to make an informative long-train wave.

8. One non-uniform population of 40 impulses was synthesized, by hybridizing a 20-population at full impulse amplitude with another at half amplitude. The wave's RMS agreed closely with the predicted value.

9. With that exception, this is a uniform-population study, based on 9-period wave trains. While the relationships agree remarkably well with predictions, they should be verified by an independent repetition of the study.

10. This study is only a beginning. With computers so readily available, it should be extended in several ways. First, a uniform population of, say, 320 would show whether the wave characteristics

and relationships for the lower populations extend this far. Second, non-uniform populations of like-shaped impulses of graded amplitudes should be summated and studied. Third, populations of equal amplitudes but graded in shapes could be tried. Fourth, combinations of the two preceding effects could be carried out. In the present study, the computer furnished only the wave ordinates, and much tedious work remained. Undoubtedly, a computer program could be made up to save most of this work.

11. One of the pre-computer cases, done graphically, used saw-tooth impulses, and the resultant wave appeared to look much as it would have if coming from the impulse used in this study. Perhaps if saw-tooth impulses could replace the shaped kind, there might be a saving on computer programming.

12. It is hoped that the present study will at least help beginners in EMG work to understand better, the kind of phenomena they are dealing with.

13. Perhaps, with further work plus creative thinking, this kind of synthesis may lead to wave instrumentation or interpretation, that will more solidly relate some measure of the wave to muscle performance.

14. The variation of the RMS (or other measure) of the EMG wave with increasing force demanded of the muscle may turn out to be quite different for different muscles in the higher vertebrates and in man.

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APPENDIX

The ordinates as used in the computer, for the first half of the adopted symmetrical impulse, are given here in order, after first having been multiplied by 100 to avoid putting in decimal points:

0, 1, 3, 6, 10, 12, 18, 23, 30, 35, 41, 50, 56, 65, 73, 83, 95, 108, 120, 135, 150, 166, 182, 200, 215, 231, 250, 265, 279, 290, 302, 312, 320, 328, 334, 339, 341, 342, 342, 340, 333, 324, 310, 291, 270, 243, 220, 170, 120, 60, 0.