THE STIFFNESS OF SPASTIC MUSCLE*

BY

JOHN FOLEY

From the Centre for Spastic Children, Chelsea

This study stemmed from an attempt to find out whether simple physical manoeuvres have any measurable effect on the spastic state as such in small children with diplegia. Muscle tone is difficult to define except in crude clinical terms, but for the purposes of the present paper it can be defined simply as that resistance which is felt by the examiner's hand on passively extending a muscle. It was recognized clearly by early workers with the electromyogram (Weddell, Feinstein, and Pattle, 1944) that in both normal muscle at rest and in spastic muscle at rest there is no electrical activity, though in the case of the latter during stretching the electrical response is excessive, hypersynchronous, and subject to widespread irradiation. Hoefer and Putnam (1940), Lindsley, Schreiner, and Magoun (1949) and later Hoefer (1952) confirmed this, and indeed much of this early work served merely to demonstrate that the electromyogram alone can contribute little to our knowledge of states of muscular hypertonus. Combined with differential procaine block of the gamma efferents the technique has proved more rewarding (Rushworth, 1960). Weddell *et al.* (1944), however, made it clear that muscle tone is not merely a matter of the stretch reflex but must in part be due to the viscous and elastic properties of the muscles and tendons. A ballistic method for the measurement of the elastic property of skeletal muscle *in situ* in man was developed by Simonson, Snowden, Keys, and Brozek (1949) but has not proved of clinical value. There has been a tendency to regard "muscle tone" and "postural tone" as synonymous, but this is confusing, as there is tone in a normally innervated muscle which is not maintaining posture. Postural tone is a state of activity required to maintain a posture against gravity and is found, for example, in the long cervical muscles or the temporalis muscle as rhythmic motor unit activity with a frequency of 7 to 10 a second, instantly abolished

by bringing the antagonists into action; while in the muscles of the back and legs it is found as occasional injections of activity into agonist and antagonist alternately to restore the body to a state of balance which is principally maintained by bones, tendons, and ligaments. Except in paraplegia in flexion the resting muscle of a spastic limb, if supported, is electrically silent, and yet its tone is high in comparison with normal or denervated muscle and becomes immediately higher on stretching. The purely mechanical component of muscle tone is present at rest and in movement, and both hypotonus and hypertonus are associated with a quantitative alteration in the physical property of the muscle. The neurogenic component of muscle tone is absent at rest, and is a complex state of hyper-reactivity of the phasic and tonic stretch reflexes; and what determines the nature of the hypertonus appears to be the behaviour of the tonic part of the stretch reflex, and the timing of the lengthening reaction once stretching has begun. From the neurological point of view the spastic state comprises a number of phenomena which can be listed as follows: (a) low threshold of the stretch reflex, (b) increased reflexogenic area, (c) augmentation of the response, (d) irradiation of the response, (e) hypersynchrony of motor unit discharges, (f) desynchronization of the lengthening reaction, (g) contraction in agonist and antagonist, and finally (h) a particular distribution in the antigravity muscles. Not all of these are susceptible to measurement. Measurement of the threshold is too difficult for clinical purposes. The strength of a tendon jerk can be measured, provided the stimulus is of constant force; the technique of Buller and Dornhorst (1957) can be used with adult subjects but is too difficult to apply to young children. Hypersynchrony of motor units cannot be measured. The irradiation of the response to stretch can be mapped out but not measured. The response to relatively slow stretch, *i.e.*, of a speed not sufficient to elicit a tendon jerk is, however, more measurable. But the intact muscle spindle system is so designed that it will adjust itself continuously to increase in length or

*The material of this paper formed part of an essay which was awarded a prize by the South West Metropolitan Regional Hospital Board in 1958.

FIG. 1

tension of the muscle. The activity of such a system can only be measured by pitting against it another servocontrolled system which will provide either constant force throughout the movement, while the velocity is recorded, or constant velocity throughout a movement irrespective of resistance, in which case the force required is measured. Servocontrolled myotonometers have been constructed by Spiegel Wycis, Baird, Rovner, and Thur (1956), but the apparatus is costly, involves fixation of the limb and the cooperation of the subject, and is quite inapplicable to children. But the normal adult nervous system is of course servocontrolled and it can maintain a constant posture, or provide constant velocity against a changing resistance with surprising accuracy; and this fact, which is merely an expression of manual skill, is the basis of the method devised by Tardieu and his co-workers (Tardieu, Rondot, Mensch, Dalloz, Monfraix, and Tabary, 1957; Rondot, Dalloz, and Tardieu, 1958) for use with children, and of the simpler and more limited method described in this paper. Tardieu applied his method to the manual extension of the biceps at constant velocity, the force being measured by means of a strain-gauge through which is fed an A.C. signal, while the angular velocity of the elbow joint is recorded by a potentiometer giving a D.C. signal. He demonstrated that above a certain critical velocity of extension, which is the hallmark of spasticity, the resistance is directly related to the velocity of stretch. He also demonstrated a

decreasing tension in the isometric state at the end of the stretch which is clinically imperceptible; he termed this the "curve of decontraction" and implied that it is due to afterdischarge. This decline in tension in the isometric state after stretch can be recorded quickly and easily in the calf muscle using simple apparatus and only manual fixation of the knee, and the method can be employed in children under the age of 4, an age at which one can be clinically certain that no fibrous contracture is present. The principle is to apply an approximately constant stimulus in the form of dorsiflexion of the foot from its resting position to the right angle within a period of one second. This thrust was originally delivered through scales of the spring-balance type, registering either 0-10 or 0-20 pounds (Fig. 1). The operator sits in such a position that he can see neither the dial of the scales nor the clock; his task is to dorsiflex the foot and then keep it at a predetermined angle by eye for the next 30 seconds, during which time an electrically driven camera records the readings on the two dials and checks against the protractor that the angle of dorsiflexion is in fact constant. At the end of 30 seconds the foot is allowed to return to its original position for a rest period of similar length, and then the procedure is repeated. Any number of recordings can be made at 30-second intervals. After development of the film all the readings for tension and time are plotted as a tension-time curve. An electrical transducer, devised later, proved somewhat less accurate than the spring balance, but had the advantage that its signal could be recorded simultaneously with the integrated electromyogram of the calf muscles (Fig. 2). The result by either method is a series of exponential curves (Fig. 3), the peak occurring at the moment the foot reaches the right angle and stretching ceases. Even if the procedure is repeated at intervals of half an hour the shape and height of the curves are unchanged and it can be demonstrated that the tonic neck reflexes have no influence on

FIG. 2.—Spastic diplegia: calf muscle. Integrated E.M.G. (top trace), E.M.G. of calf muscle (second trace), and transducer signal (middle trace) during isometric stretch for 30 seconds after dorsiflexion of the foot.

muscle tone in the calf measured in this way. Though reproducible results are obtained at any given session, there is considerable variation in the tension recorded on the same child in successive weeks or months.

The curves for a normal adult and two normal children are shown in Fig. 4, from which it is plain that tone as measured in this way depends largely on the bulk of the muscle. If, in a child with spastic diplegia, the calf muscle voluntarily or involuntarily contracts during the declining phase of the curve, it causes only a transient deflection with a quick return to the original exponential curve (Fig. 5). Fig. 6 shows similar sharp deflections, caused by coughing, interrupting the flatter part of the curve, the important feature being that the tension drops from its peak abruptly and does not set off another exponential curve. This is the second clue to the purely physical component of tone.

If the speed of the initial stretch is varied, a family of curves is obtained, the height of the peak being proportional to the velocity of dorsiflexion, as would be expected (Fig. 7). From these curves it is clear that the tension after 15 seconds is quite independent of what has gone on before, that is, whether there has or has not been a peak. One must use the term peak and not "stretch reflex" because the assumption that the peak of tension on sudden dorsiflexion is due to a stretch reflex is not entirely warranted.

The independence of the tension and the velocity of stretch at any period after the first few seconds is the third clue to the physical component of muscle tone recorded in this fashion. The curve is exponential in character, in which case, if the time-base is prolonged, its shape should be preserved, which is in fact the case, as can be seen from Fig. 8. In this instance the isometric stretch was maintained for nine minutes instead of 30 seconds, readings being made every 15 seconds instead of every 2.5 seconds, the integrated electromyogram of the calf muscles being recorded simultaneously and plotted in arbitrary units. It can be seen that electromyographic activity has virtually ceased by one and a half minutes after the beginning of the stretch. Thus it would appear that part of a uniform curve is associated with electrical activity, while the rest is not; the relationship between the two, therefore, must be indirect. Proof that the stretch reflex is not directly responsible for the shape of the curve has not been possible in the spastic child, in whom temporary denervation is not a feasible procedure, and it was therefore necessary to have recourse to the normal adult, in whom the curve is also exponential. Complete denervation by intraneural procaine has no effect on the shape or height of the curve (Fig. 9), as might have been predicted. It has

not been established how long denervation must obtain before clinical flaccidity sets in, but it is believed to be a matter of an hour or thereabouts. Chronic denervation, on the other hand, yields a different picture, the muscle acting merely as a slack spring (Fig. 10). It is plain that although temporary denervation by intraneural block does not affect the curve, muscle activity over a substantial period is necessary for the maintenance of its height and its characteristic shape. It appears that the level of the curve can be raised slightly in the normal adult by exertion (Fig. 11), though this effect may be due in part to congestion in the muscle.

Though it is fairly constant on a given day, the height of the curve in the calf of a diplegic child varies from day to day and week to week, and the method is therefore of no value in following progress. It can, however, be shown that certain physiotherapeutic manoeuvres reduce it significantly. The effect of generalized passive flexion of the trunk and limbs for 18 minutes is shown in Fig. 12, tone being reduced by about half; this affects both the general level and the initial peak. The posture adopted in this case, of course, included full dorsiflexion of the feet, and the effect on the calf muscle is probably mainly that of stretching, though subsequent tests have suggested that the effect of pure stretch of the calf muscle with the leg extended is less marked than that of generalized flexion of the trunk and limbs. The reduction in tone after the manoeuvre is, however, transitory, and the curve regains its initial height and shape within 15 minutes.

These results raise the interesting question whether, after prolonged stretching, the reduction of the initial peak is due merely to the halving of all the values of the curve, or whether there is any true reduction in the amount of reflex activity as the result of prolonged extension. The procedure was therefore repeated using the spring-balance technique, the integrated electromyogram being recorded simultaneously. A base-line of resting activity in the integrated electromyogram was first obtained, after which the test procedure was carried out three times. The calf muscle was then continuously stretched for 15 minutes, after which three more tests were recorded. The electrical activity evoked by the test procedure after the period of passive extension shows a significant reduction (Fig. 13). In Fig. 14 the curves for tension and the electromyographic activity in arbitrary units for the three tests before the period of extension and the three tests immediately following it are plotted out; these show the reduction in tension of 2 or 3 lb. throughout the curves, and the considerable reduction in electrical activity. Prolonged stretching, in effect, alters the responsiveness of the stretch reflex. But since it has

FIG. 3.—Spastic diplegia: calf muscle. Five consecutive tension-time curves recorded at 30-second intervals.

FIG. 4.—Tension-time curves for one normal adult and two normal children aged 4 and 3 respectively.

FIG. 5.—Spastic diplegia. Tension-time curves, one being disturbed by an extensor thrust caused by coughing.

FIG. 6.—Spastic diplegia. Tension-time curves before (continuous lines) and after (interrupted lines) a period of standing with support. The latter curves are disturbed by extensor thrust caused by coughing.

FIG. 7.—Spastic diplegia. Relation between the height of the peak and the velocity of dorsiflexion of the foot.

FIG. 8.—Spastic diplegia. Tension-time curve during isometric stretch lasting nine minutes (heavy line). The integrated E.M.G. of the calf muscles is shaded, and the integrated E.M.G. of the anterior tibial group is shown by the dotted line. The curves are disturbed by one involuntary extensor thrust.

FIG. 9.—Normal adult. Comparison of the curves in the normal right calf (hollow circles) with that of the left calf paralysed by intraneural procaine injection (solid circles). Acute denervation has no effect on the height or shape of the curve.

FIG. 10.—Motor neuron disease. The "curve" of a completely denervated calf muscle is flat.

FIG. 11.—Normal adult. Curve before (thick line) and after standing on tiptoes to the point of exhaustion (upper two lines) showing that the tension-time curve can be raised by exertion.

FIG. 12.—Spastic diplegia. Four consecutive tests before (continuous lines) and after (interrupted lines) a period of passive general flexion of trunk and lower limbs for 18 minutes, showing the reduction of "tone".

FIG. 13.—Spastic diplegia. Integrated E.M.G. records from calf. Top trace: resting record over a period of 30 seconds; time base 0.5 second. Middle trace: integrated E.M.G. during 30-second period of isometric stretch before period of "treatment". Bottom trace: integrated E.M.G. during 30-second stretch after a period of 15 minutes passive dorsiflexion of the foot, showing the diminution of the tonic stretch reflex.

FIG. 14.—Spastic diplegia, the same case as Fig. 13. Column A: tension-time curves (open circles) and integrated E.M.G. units (solid areas) for three consecutive tests before a period of 15 minutes' passive dorsiflexion of the foot. Column B: the same after the period of passive dorsiflexion of the foot, showing the reduction of "tone" and of the E.M.G. response during isometric stretch.

been shown, in the normal at least, that the actual height and shape of the curve is not affected by acute denervation, it would seem probable that the change in the electromyographic activity of a spastic

muscle which has been subjected to prolonged extension is secondary to a change in the rheological property of the muscle itself. One visualizes a postural muscle, therefore, as a kind of adjustable viscoelastic springboard, modifiable by prolonged stretching or vigorous activity, the resilience of which is governed, not immediately but over a period of time, by reflex postural activity.

Summary

A simple method of measuring "tone" in the calf muscle of children with spastic diplegia is described. In the isometric state after a stretch, the decline in tension in the muscle follows an exponential curve. The height of the peak of the curve is proportional to the velocity of the initial stretch; although the curve is uniform in shape, electromyographic activity is associated only with its first part, and reasons are advanced for the hypothesis that the actual height and shape of the curve are not directly related to stretch reflex. Prolonged stretching modifies the height of the curve for about 10 minutes, and also indirectly modifies the stretch reflex obtainable from the muscle.

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