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An Approach to the Objective Measurement of Spasticity

Evaluation of the effects of treatment of patients with spasticity is complicated by reliance upon subjective estimates of the response of their muscles to passive stretch. An electronic system has been devised to record objective measurements of spasticity; the device moves the subject's limb in a programed manner and records the resistance to the movement. During the movement, limb position, limb velocity, forces required to move the limb, and EMG data are recorded on a strip chart recorder and an XY recorder. Hysteresis loops reveal characteristic patterns for flexor and extensor resistance and for mixed flexor-extensor syndromes. Studies are described of the range of variation encountered on repeated measurements in ten normal subjects and nine patients with hemiplegia.

Although many theories have been proposed, the basic neurophysiologic mechanisms which produce the phenomenon of spasticity have not been clearly identified. This lack of knowledge regarding the mechanisms of spasticity has resulted in confusion and controversy over the treatment of patients exhibiting this problem. In order to dispel the confusion and controversy, at least two questions must be answered. First, can spasticity adversely affect the functional level of the patient? Second, can spasticity be modified, either favorably or unfavorably, by treatment programs? The ability to obtain objective measurements of the clinical manifestations of spasticity would greatly enhance the effective evaluation of physical therapy programs designed to treat patients with spasticity. The purpose of this project has been to develop a method for objective quantification of resistance to controlled passive movements and, thereby, to observe the effects of controlled variables.

Several attempts have been made to obtain objective measurements of spasticity. The information derived from electromyography (EMG) of spastic muscles has been used by some investigators as a quantitated parameter. Matthews[1] and Burry[2] used EMG to evaluate the effectiveness of muscle relaxants. Methods of wave analysis and recording of tendon jerks, clonus, and H-reflex responses were discussed. The results from a small number of subjects were inconclusive. Leavitt and coworkers presented a clinical drug study in which ten parameters, including EMG, clinical findings (mostly subjective), and the results of standard laboratory tests, were assessed in thirty-one patients.[3] The investigators concluded that the administration of diazepam resulted in a decrease in spasticity, but the mechanism of response eluded definition.

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Other investigators have reported studies of responses to standardized mechanically produced tendon jerks or passive joint movements, recording one or more related parameters, e.g., velocity, force, range, position, EMG. Erdman and Heather,[4] and Heather, Smith, and Graebe[5] used a spring-loaded reflex hammer at the ankle with a force recorder which measured foot deflection. Tests on twelve patients demonstrated the effectiveness of diazepam. Leavitt and Beasley described studies on one patient using tensiometers to record reciprocal tensions developed by passive stretch.[6] Timberlake described a gravity driven ergograph and its use on a patient with Parkinson's disease, but he stressed the inability to differentiate the effects of medications from the effects of daily spontaneous variations.[7]

More recently, electromechanical systems which are precisely controlled and which yield sophisticated data have been developed. In 1964, Long and others studied approximately seventy-five subjects employing a motor-driven finger flexor to record rheologic factors (elastic, viscous, and plastic forces), peak torque, phase angles, areas of hysteresis loops, and time constants of stress-relaxation.[8] Webster reported a similar system for use about the elbow and knee joints, which included programed test movement and analyses of the areas in hysteresis loops.[9] Herman and coworkers developed the rotational joint apparatus (RJA), a motor-driven device which measures length-tension relationships of muscles about the ankle joint.[10] A recent report, based on data derived from the RJA, attempts to develop physiological models for the phenomena observed in two hundred patients with hemiplegia.[11] Cohen has developed instrumentation for analyzing the sequence of muscle interactions in active movements, especially in the wrists and forearms.[12] His primary interest is in the measurement of rigidity, but the device can be used to measure spasticity. The most elaborate device with which we are familiar, the myotron, was developed at Cornell Aeronautical Laboratory under the direction of R. E. Kell.[13] This device, originally developed as a servocontrolled exoskeleton, has the capacity to measure resistance in two planes of movement, but has not been subjected to extensive clinical testing.[14]

Fig. 1. Normal subject positioned for measurement. A. Adjustable positioning bench. B. Seat belt. C. Shoulder harness. D. Stabilizing arm. E. Rotating arm. F. Multicompartment inflatable wrist cuff. G. Adjustable base.

METHOD

Electromechanical System

The system developed at this laboratory rotates a limb segment around a joint axis in a programed manner and monitors the forces exerted by the subject in response to the movement. The drive mechanism is a three-quarter horsepower, direct current motor with a velocity servocontroller. The available constant and variable angular velocities range between 5 degrees per second (0.09 rad/s) and 180 degrees per second (3.15 rad/s). The maximum torque produced is approximately eighty pound-feet (108.8 N/m), with an upper torque limit for the safety of the subject.

The motor output is transmitted to the subject via two mechanical arms (Fig. 1). The proximal limb segment is secured to the stabilizing arm; the distal limb segment is secured by an inflatable cuff in an aluminum ring which is attached to the rotating arm. Two adjustable voltage comparators (electronic stops) control the range of motion by comparing the position of the rotating arm with two preset limits. In addition, two mechanical stops are used for safety. Two pairs of strain gauges, with sensitivity greater than 0.1 pounds force (0.44 N), measure forces exerted on the aluminum ring in flexion or extension and internal or external rotation. A potentiometer indicates the position of the rotating arm with respect to the stabilizing arm.

Equipment is available for recording three channels of EMG data. Each unit consists of a two-stage differential amplifier, followed by an active resistor-capacitor second order low pass filter as the averager. Silver-silver chloride surface electrodes are used.

General Procedures

The system is currently operational for the elbow and knee joints, bilaterally. For simplicity, a sample test procedure, designed for the right upper extremity is described. The subject is seated on a specially designed bench in a comfortable, erect position (Fig. 1). Shoulder straps and a seat belt are fastened and adjusted. EMG surface electrodes are placed on the right biceps, triceps, and brachioradialis. The right upper extremity is secured in the arm cuff and the wrist cuff is inflated. Pain responses are avoided by proper alignment and precise adjustment of the automatic stops.

After the subject is positioned, he is instructed to relax and to allow the machine to move his arm. The forearm is then moved passively through a cycle at 30 degrees per second (0.53 rad/s), 60 degrees per second (1.05 rad/s), and 100 degrees per second (1.75 rad/s). A cycle is defined as a motion from one position to a second, then back to the original, e.g., from flexion-to-extension-to-flexion, FEF cycle, or from extension-to-flexion-to-extension, EFE cycle. The time interval within the cycle, i.e., between reversals of direction, is five-tenths of a second, and the time interval between cycles is thirty seconds. During selected test cycles, the subject holds a standardized weight in the contralateral hand with the elbow flexed to 90 degrees (1.57 rad), in an attempt to produce facilitation of the reflex response to passive stretch in the affected arm (weight-holding cycle).

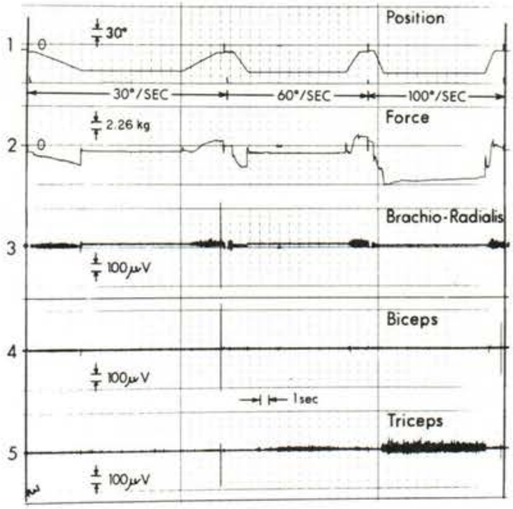

Fig. 2. Multichannel strip chart recording for EFE cycle, with ten second interval in flexion; for three speeds. EMGs are recorded on channels 3, 4, and 5.

RESULTS

In Figure 2 (strip chart record for a hemiplegic patient), position was recorded on the first channel, force (resistance) on the second channel, and EMG recordings from brachioradialis, biceps, and triceps on channels three through five, respectively. An EFE cycle, with a ten-second interval in flexion, is shown for three speeds. Note that brachioradialis firing increased during the interval in flexion. The biceps was essentially silent throughout. The triceps was silent at the slow speed, but firing increased progressively as speed increased, with activity primarily during the ten-second interval when the muscle was on stretch. Analysis of EMG data collected on multiple normals and patients is not yet sufficient to justify further interpretation of the findings. The figure is shown to illustrate the capability for correlating the muscle activity with position and force data.

Hysteresis Loops

During a movement cycle, an XY recorder plots force versus position and displays the data in the form of a hysteresis loop. The total curve in Figure 3-1 represents the theoretical result expected for a two-kilogram rotating limb segment if both mechanical arms are vertical at the beginning and end of the movement, and if there is no muscular resistance during the movement. The line curves because the effect of gravity varies relative to the position of the rotating limb segment, e.g., at 90 degrees (1.58 rad), the rotating limb segment is parallel to the ground and, therefore, the force resulting from the weight of the limb segment is at its greatest value. A trace from left to right corresponds with a movement toward flexion, and a trace from right to left corresponds with a movement toward extension. A complete absence of muscular resistance produces identical traces in both directions. Any muscular resistance results in a deviation of the trace from the theoretical curve and creates an area between the two

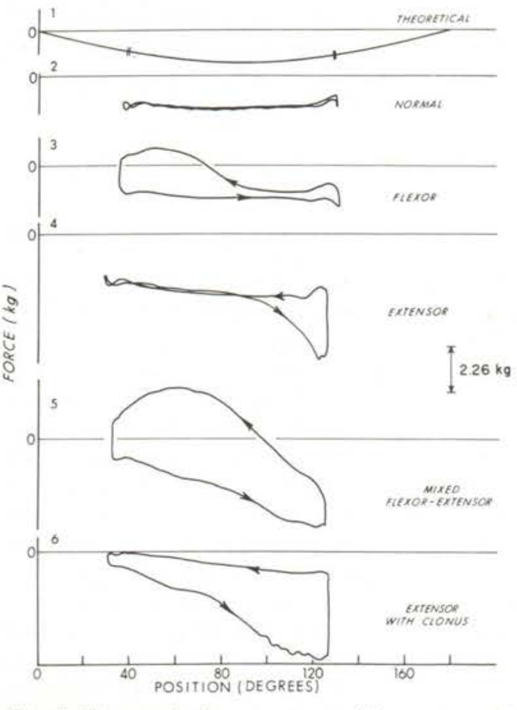

Fig. 3. Hysteresis loop patterns (force vs. position) for passive movement about the elbow. Full extension with the subject's arm vertical is represented as 0 degrees on the abscissa. The theoretical curve represents the effect of gravity on a two kilogram rotating limb segment under conditions of absolute flaccidity. Deviation above the theoretical curve represents force in flexion; deviation below the theoretical curve represents force in extension.

traces. This area is equivalent to the excess amount of work required to move the segment through a cycle. The value of this area provides a quantitated expression of the amount of resistance to passive movement.

Clinical testing of patients and normal subjects has revealed four basic loop patterns. The pattern of a normal subject (Fig. 3-2) most closely resembles the theoretical pattern, since the two traces are essentially superimposed and there is negligible area within the loop. In the typical flexor spasticity pattern (Fig. 3-3), resistance encountered during the movement from flexion to extension produces a convex, upward deflection of the upper trace in the left half of the loop. Muscle resistance encountered during the movement from extension to flexion produces an extensor pattern (Fig. 3-4), with a concave, downward deflection of the lower trace in the right half of the loop. In some instances, resistance is encountered in both directions and the resultant mixed pattern shows deflections in both halves of the loop (Fig. 3-5). Clonus is exhibited by cyclic undulations as illustrated by the lower trace in Figure 3-6.

Clinical Studies

To date, a wide variety of measurements has been carried out on forty normal subjects and on thirty-four patients.

Discussion will be limited to part of one specific study which was undertaken to explore the reproducibility of test results. This investigation involved duplicate measurements of the upper extremity of ten normal subjects and nine patients with hemiplegia. The test procedure employed an extension-to-flexion-to-extension cycle, at a speed of 100 degrees per second (1.75 rad/s), first without weight holding and second, with weight holding in the contralateral extremity. The interval between duplicate testing sessions was generally less than two weeks. The longest interval between duplicate tests was forty-eight days. Quantification of the results was accomplished by deriving three values for each hysteresis loop: the total loop area, the area of the left half of the loop, and the area of the right half of the loop.

A comparison of total loop areas from duplicate measurements of a single EFE cycle,

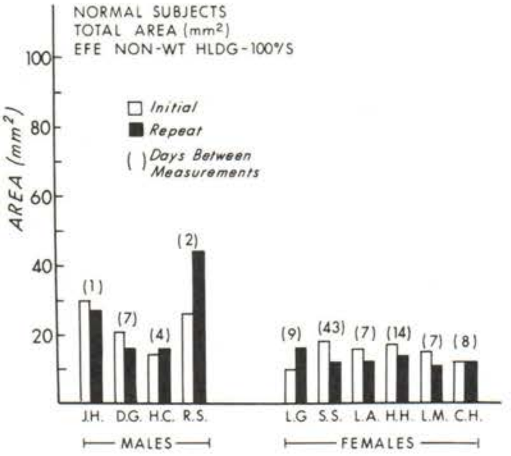

Fig. 4. Total hysteresis loop areas (excess work required to complete movement cycle–100 mm² of area equals 66 joules) for duplicate measurements of a single EFE nonweight holding cycle at 100 degrees (1.75 rad) per second for ten normal subjects. Interval between measurements varied from one to forty-eight days, indicated by numbers in parentheses.

nonweight holding, at 100 degrees per second (1.75 rad/s) is shown for the ten normal subjects in Figure 4. The blank bar represents the initial measurement; the solid bar represents the repeat measurement days or weeks later. There is reasonably close agreement between duplicate measurements. In general, the male subjects had larger areas than the female subjects, especially J.H. and R.S. The duplicate measurements for the nine patients are shown in Figure 5. Note that all of the values exceed those obtained for normal women, but that three patients, A.S., L.B., and H.K., fall within the range of the normal men. The duplicate measurements agree fairly well, with two exceptions, J.C. and T.D. (See Discussion).

During the EFE cycle, with contralateral weight holding, at 100 degrees per second (1.75 rad/s), a marked increase in the areas and greater variation between duplicate measurements are seen in the normal subjects (Fig. 6). There is a greater difference between the nonweight-holding and weight-holding cycles for the normal women than for the normal men. A similar increase in area and in variation between duplicate measurements are observed

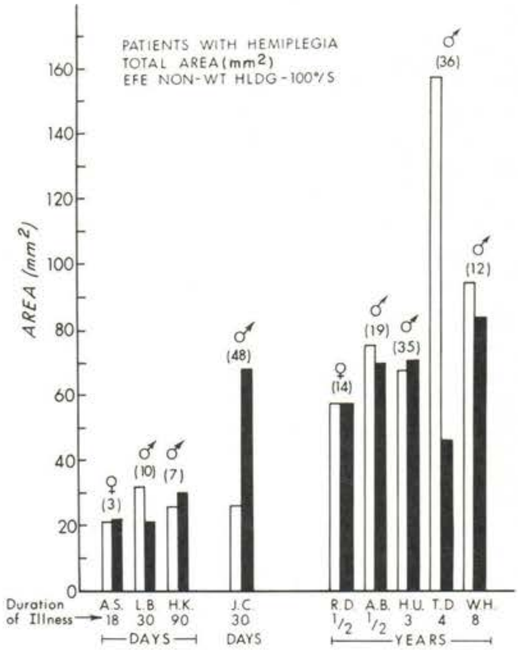

Fig. 5. Total hysteresis loop areas for duplicate measurements of a single EFE nonweight holding cycle at 100 degrees (1.75 rad) per second for nine patients, expressed as in Fig. 4. Duration (days) of illness refers to status at the time of initial measurement.

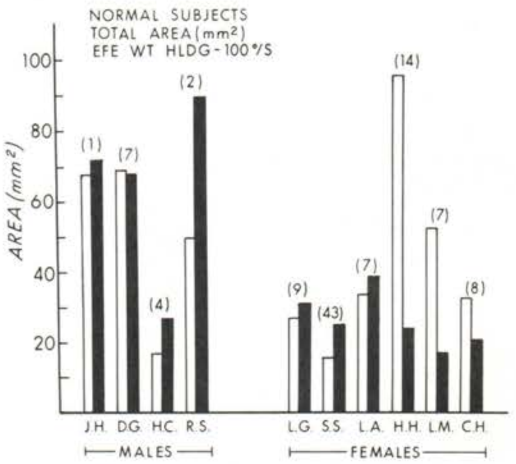

Fig. 6. The effect of weight holding on total hysteresis loop areas on duplicate measurements for ten normal subjects under conditions otherwise identical to those illustrated in Fig. 4. Note increase in total areas for all subjects and in variation between duplicate measurements for H.H., L.M., and C.H. in comparison to Fig. 4.

for the patients (Fig. 7). In three patients, A.S., L.B., and H.K., weight-holding cycles produced a negligible increase in area compared to the nonweight-holding cycles (See Discussion).

A comparison of the left and right areas of individual loops for the ten normal subjects is shown in Figure 8. Duplicate measurements are again shown as a pair—the initial measurement, the blank bar; the retest, the solid bar. The left area of the hysteresis loop is shown on the left, with the right area immediately adjacent on the right. These data are from the same cycles illustrated in Figure 4. The left and right areas are approximately equal in all of the normal subjects. Comparable data for the nine patients are shown in Figure 9 (same test cycles as in Fig. 5). Here the patients are distributed into three groups. For patients H.U. and A.B., the left area is always greater than the right area; these patients have predominantly flexor spasticity. Patients H.K., L.B., and A.S., with flaccid extremities, resemble the normal subjects since the area is distributed equally in both halves of the loop. For patients R.D., W.H., J.C., and T.D., the right areas exceed the left areas; these patients have predominantly extensor spasticity. Weight-holding cycles in the normal subjects tend to increase the area equally in both halves of the loop, with the exception of male subjects D.G. and H.C. who show a moderate extensor predominance (Fig. 10). In the patients, weight-holding cycles produce a generalized increase in all areas (Fig. 11). The relative differences between right and left areas, however, are consistent with the findings in Figure 9. Both in normal subjects and patients, a greater variation exists between duplicate measurements for weight-holding than for nonweight-holding cycles.

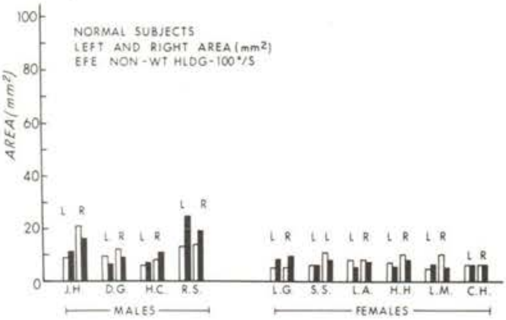

Fig. 8. Comparison of areas of right and left halves of hysteresis loops for duplicate measurements of a single EFE nonweight-holding cycle at 100 degrees (1.75 rad) per second for ten normal subjects. Note that right and left areas are approximately equal for all subjects, indicating no predominance of flexor or extensor resistance to the passive movement.

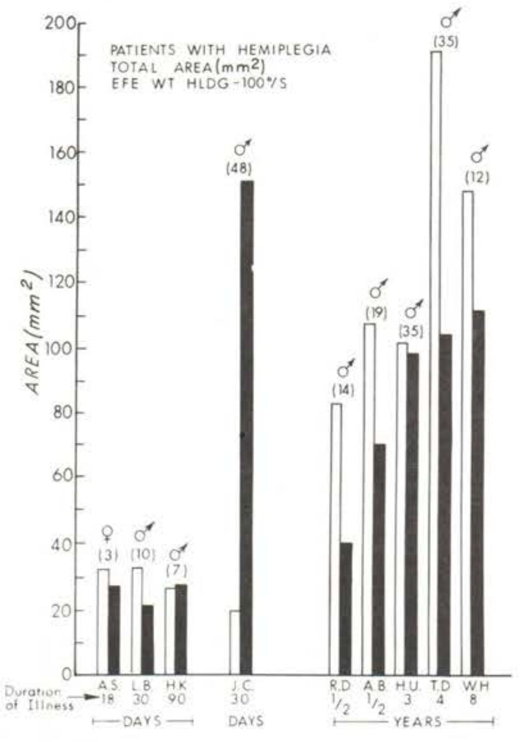

Fig. 7. The effect of weight holding on total hysteresis loop areas on duplicate measurements for nine patients under conditions otherwise identical to those illustrated in Fig. 5. As with normal subjects, weight holding resulted in increased areas for most patients; notable was the lack of increase for patients A.S., L.B., and H.K., whose upper extremities were essentially flaccid at the time of both measurements.

DISCUSSION

The studies reported here concern too small a number of subjects to warrant statistical analysis; however, several general observations can be made. The nonweight-holding values for the normal subjects fell within a fairly small range, with two major exceptions. Subject J.H.

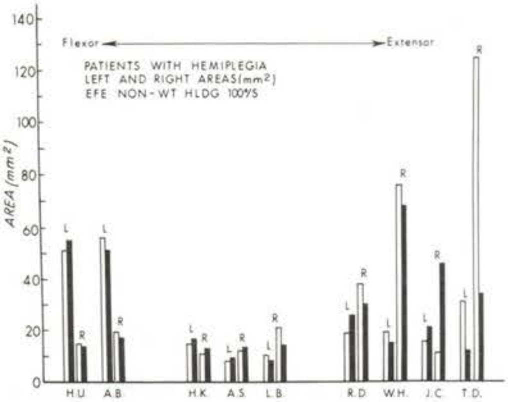

Fig. 9. Comparison of the right and left halves of hysteresis loops (illustrated in Fig. 5) for nine patients. Note that the patients can be arranged into groups depending on the predominance of flexor (on the left) or extensor (on the right) spasticity. Patients H.K., A.S., and L.B. were essentially flaccid at the times of measurement and resemble normal subjects.

was a tense, muscular individual and had great difficulty in relaxing. Although subject R.S. denied pain, his relatively high value may reflect unconscious resistance or stiffness secondary to a chronic elbow injury. The overall results with the normal subjects, therefore, suggest that the nonweight-holding test system is capable of satisfactory reproducibility.

The three patients, A.S., L.B., and H.K. (Fig. 5), whose results showed good reproducibility and fell within the range for normal men, were all tested relatively soon after onset of stroke and were all essentially flaccid on clinical examination. The resemblance of their response to the response of normal subjects was expected considering the lack of hyperexcitability of the motoneuron pool in both groups. There are great discrepancies between the duplicate measurements for J.C. and T.D. (Fig. 7). The initial measurement of J.C. was made early in the course of his illness (30 days after onset of stroke); the retest was made forty-eight days later. Marked clinical spasticity developed in the interval and, consequently, the response greatly increased on retest. Patient T.D., with hemiplegia secondary to a severe head injury sustained four years prior to measurement, showed a marked decrease in area on retest. This difference could not be clearly correlated with consistent improvement in the patient's overall status and must be considered an example of the wide, currently unexplained variations that may be observed in patients with chronic spasticity. Extensive sequential testing of patients with chronic spasticity is presently under way to define the range of variability to be expected and to determine test conditions least likely to introduce technical stimuli

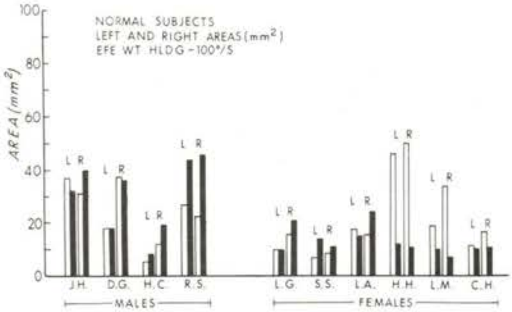

Fig. 10. Comparison of areas of right and left halves of hysteresis loops for weight-holding cycles for ten normal subjects (illustrated in Fig. 6). Although areas are increased over those shown in Fig. 8, right and left areas again are approximately equal, except for D.G. and H.C. who show a moderate extensor predominance.

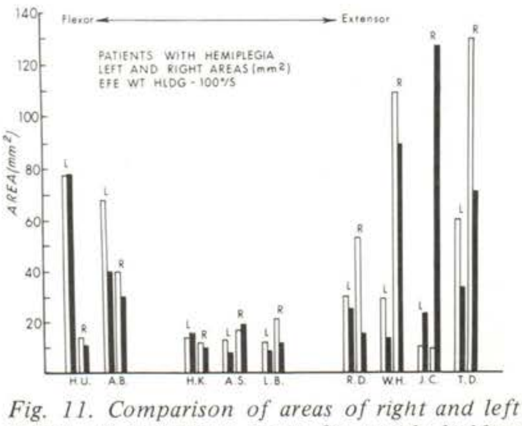

Fig. 11. Comparison of areas of right and left halves of hysteresis loops for weight-holding cycles for nine patients (illustrated in Fig. 7). Except for patients H.K., A.S., and L.B. (flaccid paralysis), all patients showed increased areas compared to Fig. 9 but maintained their basic patterns of flexor or extensor predominance.

contributing to variability.

Bishop and others reported that facilitation of the Achilles tendon reflex could be achieved by a simple handgrip maneuver.[15] They also demonstrated that a stronger handgrip maneuver facilitated the reflex response more than a weaker handgrip, and this was attributed to increased excitability of the motoneuron pool with the stronger handgrip. In an attempt to produce a facilitation of the reflex response during tonic passive stretch, the contralateral weight-holding cycles were used. All normal subjects (men and women) showed a two- to three-fold increase in hysteresis loop areas in response to holding a ten-pound (4.5 kg) weight in the opposite hand during the machine measurements (Fig. 6). Similarly, all the patients who demonstrated clinical manifestations of spasticity showed increased areas (Fig. 7) and increased EMG activity during the contralateral weight-holding cycles. The three who were tested soon after onset of stroke and before onset of clinical signs of spasticity showed negligible increase in area during the weight-holding cycles and, thereby, reflect the lower excitability of the motoneuron pool in the flaccid stage of hemiplegia. Although contralateral weight holding produced noteworthy changes in the loop areas for both normal subjects and spastic patients, the net effect was to diminish the difference between the two groups. In addition, the weight-holding cycles produced a marked increase in variation among repeated measurements with a corresponding increased difficulty in interpretation of serial records. This was true for normals and patients and may reflect slight differences in muscular stabilization patterns or slight differences in postural adjustments with each weight-lifting repetition.

It must be emphasized that the objective measurements of increased resistance to passive movements reported here are of limited value if considered in isolation. Correlation of the machine data with performance of gross and fine functional activities is essential for placing the objective measurements in proper diagnostic and evaluative perspective. A standardized functional test protocol, which has been designed to evaluate muscle strength and fine and gross motor coordination, is currently under test in patients and normal subjects.

SUMMARY AND CONCLUSIONS

A device has been developed to produce objective measurements of resistance to precisely controlled passive stretch in patients with spasticity. The instrument has been applied in studies of forty normal subjects and twenty-six patients with spasticity resulting from neurologic damage. Characteristic hysteresis patterns were obtained for flexor, extensor, and mixed spasticity syndromes. Duplicate measurements on ten normal subjects and nine patients revealed satisfactory reproducibility among the normals and in seven of the nine patients. Weight holding in the contralateral upper extremity during measurements resulted in enlarged hysteresis loops in normals and patients; these effects were associated with an increased range of variation between duplicate measurements and an overall decrease in the differences observed between normal subjects and patients. These preliminary results suggest that, with further standardization and experience, objective measurements of resistance to passive stretch can provide a valuable contribution to critical evaluation of treatment programs for patients with spasticity, especially when correlated with the results of rigorously standardized functional testing.

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Howard A. Bomze graduated from Drexel Institute of Technology in 1966 with a bachelor's degree in electrical engineering and, in 1968, he received a master's degree in biomedical engineering from the same institution. He has been involved in the development of the Biomedical Research Unit since its inception and is responsible for the design and fabrication of the instrument. He is especially trained in computer science, and will be responsible for the instrument's operation, its further development, and all data analysis.

Hugh Chaplin, Jr., M.D., graduated from Princeton University in 1943, and received his Doctor of Medicine degree from Columbia University, College of Physicians and Surgeons in 1947. Dr. Chaplin has been director of the Irene Walter Johnson Institute of Rehabilitation since 1964. He was instrumental in establishing the Biomedical Engineering Research and Development Unit within the Institute and has served as project director of the NIH Contract under which the present device for measuring spasticity was developed. He is an established researcher with eighteen years experience in clinical investigation.

COMMENTS OF DISCUSSANT

MARY E. MILES

Mrs. Norton and her colleagues should be commended for developing both equipment and a method to obtain objective measurements of spasticity. The use of more sophisticated equipment clinically in the evaluation process is needed in physical therapy. Patient comfort was achieved in the design of the equipment without interfering with the accuracy of the recordings. Explanation of the hysteresis loops and their interpretation was clearly stated.

Admittedly, the population was small, ten normal and nine hemiplegic subjects. It might have been of interest to note the localization of the brain lesions of the hemiplegic population to see if that might affect performance or the ability to cooperate.

Scrutiny of the study revealed that attention to stricter control of the variables might produce more reliable data upon which to generalize. For example, in the normal population, one subject had a prior injury to the tested elbow. Another was unable to relax, which is of importance in a study of this nature. Elimination of these types of individuals might be of benefit to the study in order to

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establish norms.

Any study of hemiplegic patients has to consider many unknown factors. A homogeneous population is almost impossible. Recovery rate is unpredictable. Site and size of lesion influence the clinical picture. An attempt, however, to localize the lesion and to use only those patients that fit a strict criteria should be made. For instance, only patients with lesions involving the area supplied by the middle cerebral artery might be studied. One might then determine if the development of spasticity has some indicators.

Other variables which might be controlled are 1) the fatigue factor, especially with hemiplegic patients, 2) activities just prior to the testing session where the extremity to be tested is used, 3) time lapse between testing sessions, 4) age, and 5) handedness, especially if the study were expanded to include active motions.

Of interest are the data collected on the weight-holding cycles which confirms already existing theories of the overflow phenomenon. I would be interested in knowing if there was a correlation between machine measurements and functional testing batteries.

This study raises other questions which justify further study. Might there be some diagnostic implications for the data collected on the normal subjects who tended to have slight extensor predominance during the weight-holding cycle? Is there an explanation for the differences according to sex?

The researchers have developed data which indicate that good reproducibility exists between duplicate measurements in the non-weight-holding cycles. They are aware of the magnitude of the job before them before such information can be translated into working models for clinical use. It is gratifying that physical therapists are devising sophisticated tools to enhance the quality of patient evaluation and resultant treatment.