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RELATIONSHIP OF THE ELECTROMYOGRAPHIC SIGNAL TO MUSCLE ACTIVITY

TECHNICAL DOCUMENTARY REPORT No. MRL-TDR-62-52

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BIOMEDICAL LABORATORY
6570th AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Contract Monitor: Jack E. Steele, Major, USAF
Project No. 7232, Task No. 723201

2307

(Prepared under Contract No. AF 33(616)-8302
by
David O. Ellis, Ph.D.
Litton Systems, Inc., Beverly Hills, California)

NOTICES

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FOREWORD

This report was prepared by the Medical Electronics and Bionics Department of the Applied Sciences Division of Litton Systems, Inc., 336 North Foothill Road, Beverly Hills, California. Dr. David O. Ellis served as Principal Investigator. The report deals with work accomplished under Contract Number: AF33(616)-8302, Project Number 7232; "Research on the Logical Structure and Function of the Nervous System," and Task Number 723201, "Neurological Servomechanisms." Major Jack E. Steele of the Biomedical Laboratory served as Contract Monitor for Aerospace Medical Research Laboratories. Aid in the scientific and engineering aspects of the program was furnished by F. Ludwig, M. Sosnow, C. Gordon, F. Kaatz, D. Pierce, W. Howard, Jr., and J. Guerra. The help of several other Litton employees who volunteered as experimental subjects is acknowledged. The work reported was accomplished between May 1961 and October 1961.

ABSTRACT

Experimental data was obtained by two alternate techniques on the spike frequency (spike repetition rate) in the electromyographic signal obtained with surface electrodes on the biceps of experimental subjects vs. tension developed in controlled isometric contraction of the biceps. These data when appropriately smoothed to account for non-uniformity of spike occurrence and other extraneous factors, indicate a characteristic non-linear functional dependency between spike frequency and tension developed.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Jos M Quashnock
JOS. M. QUASHNOCK
Colonel, USAF, MC
Chief, Biomedical Laboratory

INTRODUCTION

Between 1958 and 1961, a program was carried out at Litton to investigate the feasibility of servo-systems activated by electromyographic signals (EMG). Pursuit of this concept was based on three hypotheses:

1. The energy contained in a segment of EMG waveform from a single muscle is functionally related to the average tension developed in the muscle during the corresponding time segment.
2. The energy contained in a segment of EMG waveform from a single muscle is well approximated by a function of the average spike repetition rate (hereafter called frequency) in the waveform segment.
3. The EMG waveform obtained from suitably designed surface electrodes appropriately placed with respect to a selected muscle is a good approximation, except for amplitude, to the EMG waveform obtained from penetrating electrodes placed directly in the single muscle (hereafter called needle electrodes).

   It is well to note that reasonable approximations were quite allowable since our intention was to build open-loop servos and then close the loop with visual, tactile, audial, or complementary myostimulus feedback.

   It is also to be noted that the first hypothesis has had general acceptance in the scientific community for some years, the second hypothesis is intuitively plausible from a visual examination of many EMG recordings, and the third hypothesis has been controversial.

Our first approach was to combine Hypotheses 1 and 3. We built a breadboard which would amplify, rectify, and integrate the EMG waveform and apply this energy function to the windings of a d-c motor. Thus, muscle tension should result in a functionally related motor shaft rotation and it should be possible to accurately position the shaft using visual feedback. This breadboard was utilized with EMG obtained from the biceps with both surface and needle electrodes. Similar results were obtained in both cases, thus lending credence to Hypothesis 3. The system was, however, unsatisfactory due to poor response to low frequencies, and an inertial effect in the d-c motor which led to an exponentially decaying angular velocity following a desired positive position stop.

To obtain the desired positive positioning, we then constructed a breadboard of a digital system utilizing Hypothesis 2 with output to a stepping motor. This system is shown in block-diagram form in Figure 1.

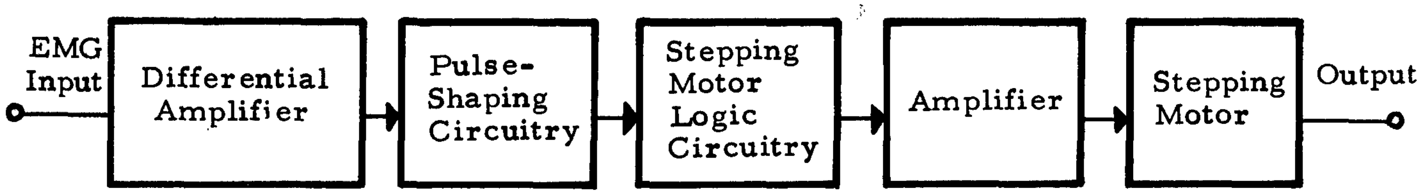

Figure 1. Block Diagram of an EMG-Input, Open-Loop Control System

This system did in fact operate under the control of various operators as expected insofar as subjective observation could determine; that is, the operator could speedup, slowdown, or stop the shaft rotation by voluntary control of tension developed in the biceps. Identical results were obtained with both surface and needle electrodes. Since needle electrodes are undesirable in our envisioned applications of such servo-systems, our final concept rested on the combination hypothesis:

4. There is (statistically) an approximate functional relationship between the average tension developed over a time interval in a single muscle and the average frequency (spike repetition rate) of the EMG waveform over the same time interval as obtained with suitably designed surface electrodes appropriately placed with respect to the muscle.

It was the purpose of the present study to experimentally test Hypothesis 4.

EXPERIMENTAL TEST

The experimental tests were carried out utilizing two alternate techniques. These are called The Muscleometer Technique and The Stepping Motor Technique, respectively, and are described below.

1. The Muscleometer Technique

1.1 Design of the Muscleometer

The Muscleometer is an instrument that measures the tension developed by an isometrically contracting muscle. The design is based on several factors of human muscle and machine capabilities. The muscle chosen for the measurement of both development tension and electromyographic potentials is the biceps. The human biceps is capable of developing 100-pounds tension and is convenient of access for detection of the electromyographic potentials. The muscleometer is an electromechanical device synthesized by the combination of such standard apparatus as a torquometer and a low-torque voltage-dividing potentiometer. Coupling is achieved in several ways and will be described later in this Section. The Torquometer (Model TQ-200) utilized in this study is manufactured by the Snap-on Tools Corporation of Kenosha, Wisconsin. The tension developed is ordinarily observed visually from a dial.

The Torquometer is made of steel with a polished chromium-plated surface. The torque is transferred to a square lug with a ball-bearing lock. An appropriate socket is snapped on to the square lug. There is a shaft with a universal joint and the shaft is parallel to the Torquometer. The excursion of the Torquometer is perpendicular to the rack holding the apparatus. The excursion of the shaft is also perpendicular to the rack but in the opposite direction to the Torquometer. In this manner a constant tension can be maintained. Figure 2 shows the Torquometer unmodified. Figure 3 demonstrates the muscleometer in the wooden rack. Note convenient handles on the flexible shaft and the palm grip on the Torquometer. A potentiometer is coupled to the shaft of the dial and rotation of the shaft changes the "resistance" of the potentiometer. This is very well shown in Figure 4.

1.2 Methods of Operation

A subject is seated comfortably in a chair. The forearm is flexed but relaxed and lying on a table. The arm is approximately perpendicular to the forearm. The grip is placed in the palm and the fingers are not contracted on the grip. The forearm is lying on the table in such a manner as to be free from constraints by the table. The subject is instructed to just oppose the tension applied by one of the observers. The limb is not permitted any excursion. The contraction is therefore of an after-loaded isometric type.

1.2.1 Electrode Placement

A bipolar placement (both electrodes on the biceps) was used and showed a differential activity of two areas of the biceps.

1.3 Data Acquisition

The channels of information comprise three separate observations. The three channels are:

a. The Electromyogram
b. The tension developed (output of the coupled potentiometer)
c. A time line

Each datum channel will be discussed more fully to explain our records.

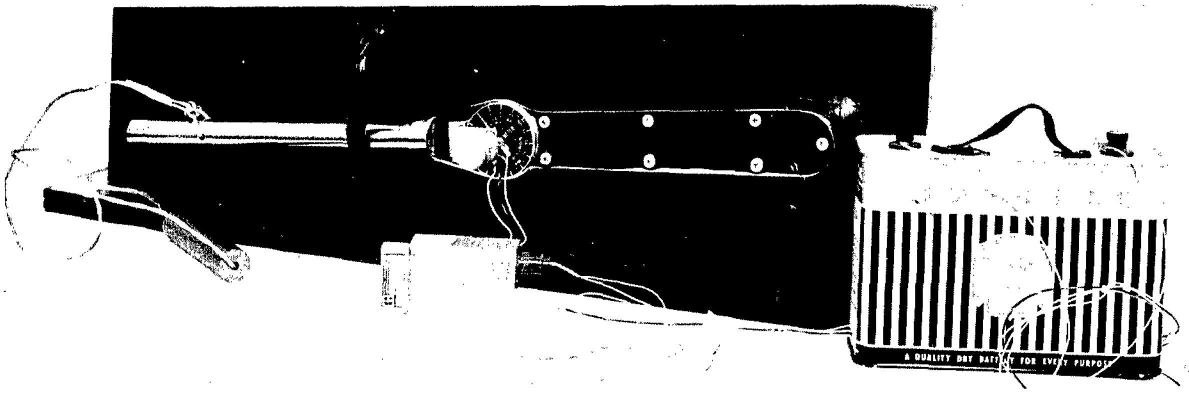

Figure 2. Torquometer, Unmodified

1.3.1 Electromyogram

The electromyogram (EMG) is detected with disc electrodes adhered to the subject's skin overlying the biceps. The bioelectrical signal is amplified by a Litton B-30A bio-amplifier and conducted to a Honeywell Visicorder with compatible galvanometers and recorded. Care must be taken to eliminate the electrostatic and electromagnetic noise of 60 cps. This is achieved by selection of time of operation when other electrical apparatus is not in use; by utilizing a common ground to minimize ground loops; and grounding of subject when it is feasible.

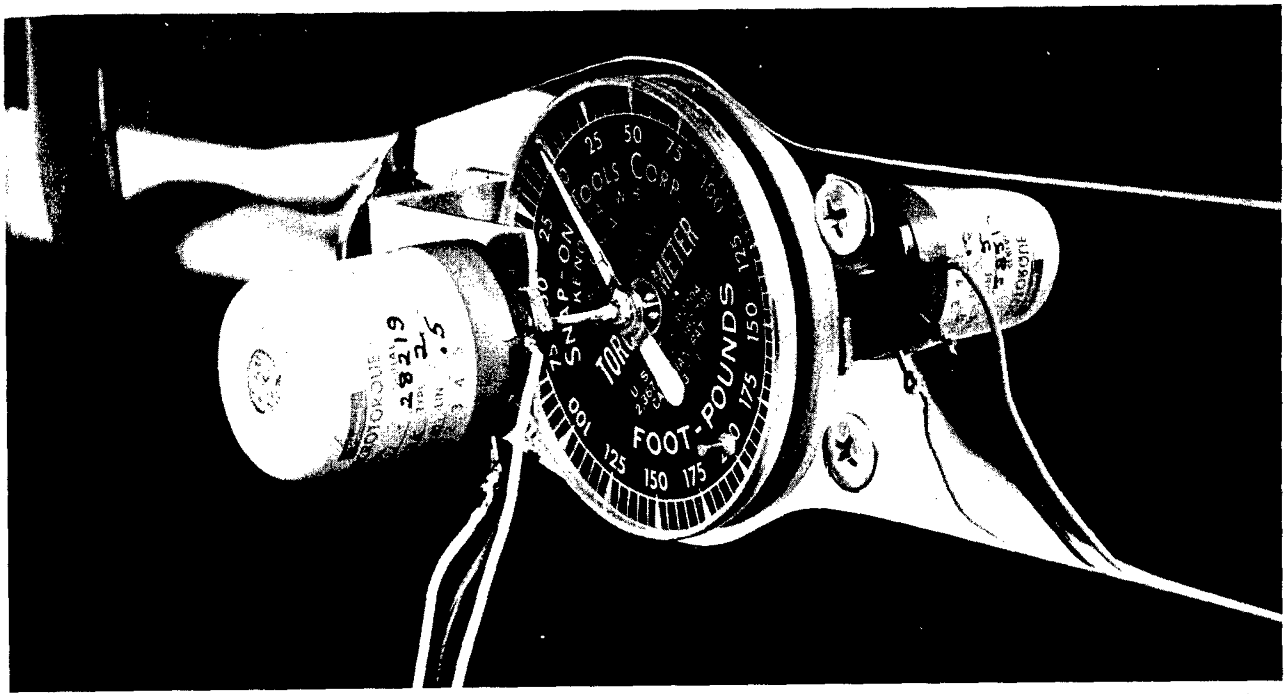

Figure 3. Muscleometer in Wooden Rack

1.3.2 Tension Developed

A potentiometer is supplied with a constant external voltage. As the shaft is rotated the output changes proportionally to the rotation. The rotation is proportional to the tension. The output of the potentiometer is conditioned to be acceptable and compatible with the Visicorder galvanometer. Figure 5 is a composite of the records of a resting state; a small developed tension called STATE A; a slightly larger tension called STATE B; a large tension state called STATE C.

1.3.3 Time Line

A signal generator supplies the time line and is designated for each individual observed record.

1.4 Calibration

Since we were primarily interested in the frequency characteristics of the electromyogram we did not calibrate the amplitude of the EMG. The frequency characteristics were investigated only as visible to the observer's eye. Instead of frequency, we counted pulses.

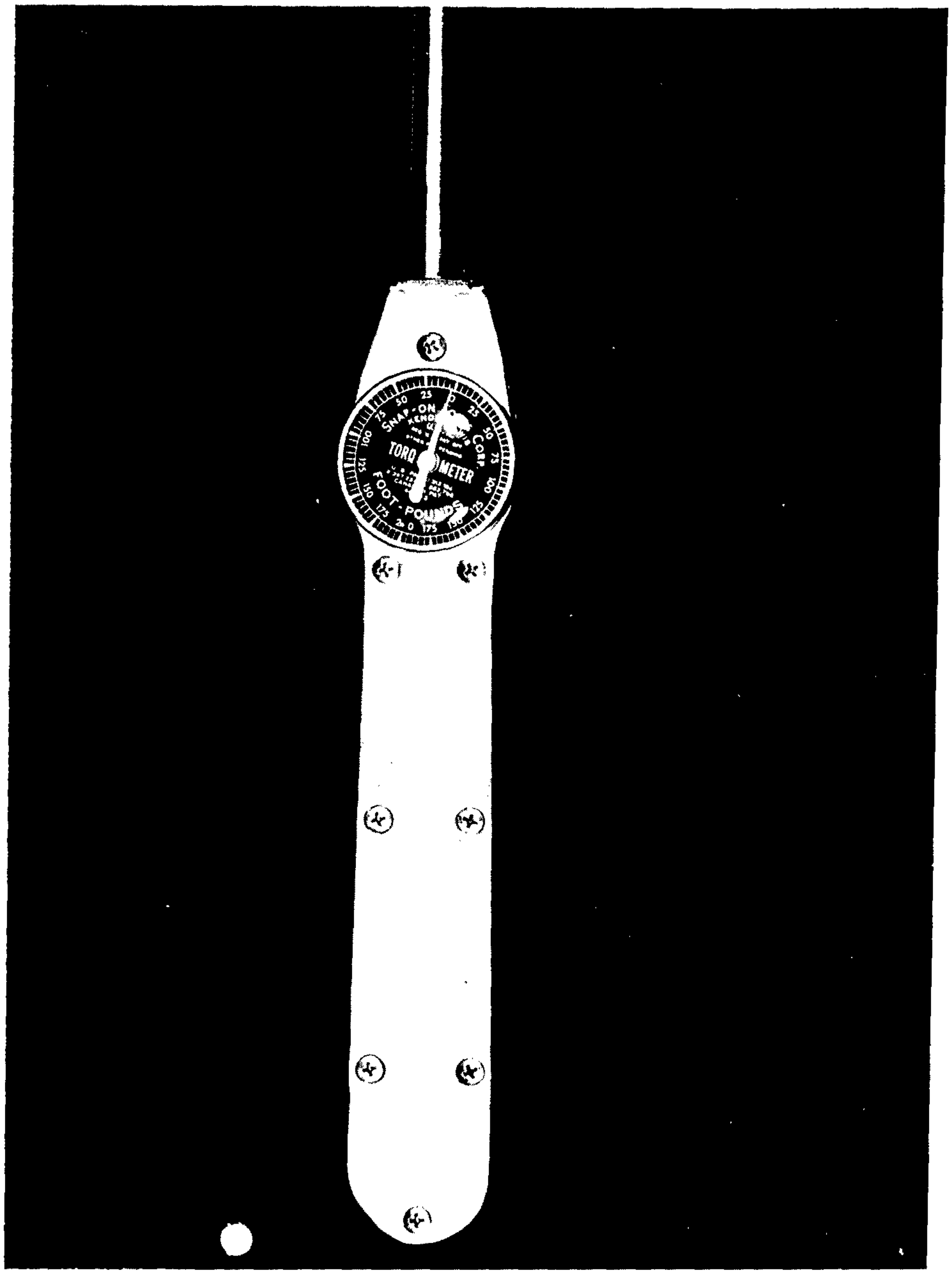

Figure 4. Torquometer, Modified

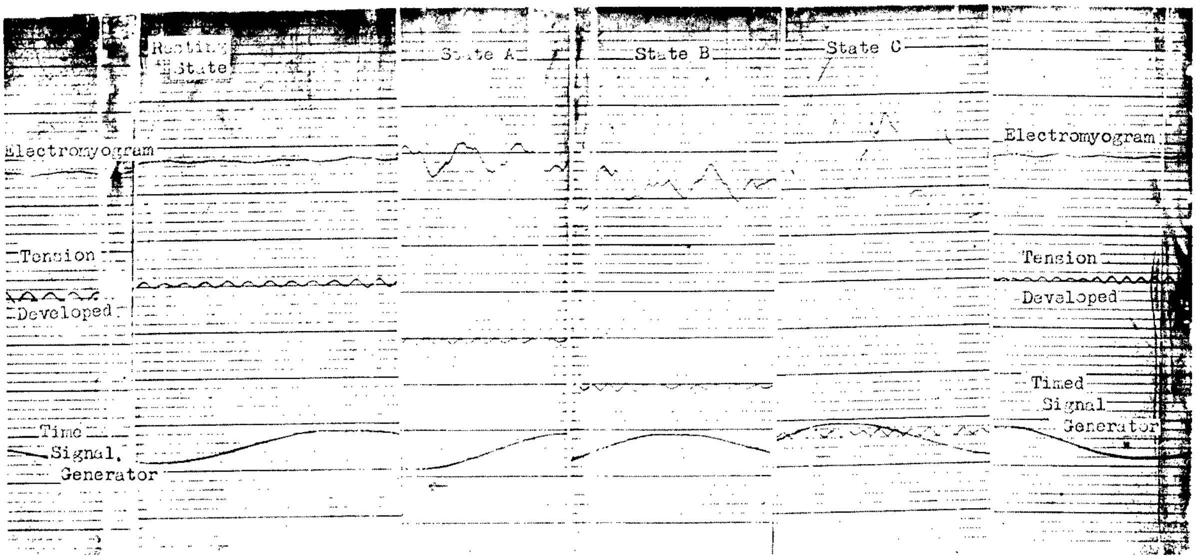

Figure 5. Composite Chart, Recording of Electromyogram, Tension, Time

1.4.1 Tension

The Torquometer measures torque in foot-pounds (the force applied to the wrench handle multiplied by the distance from the point of application to the point of rotation of the wrench). Torque measured is thus proportional to force applied. Tension developed in the biceps muscle is applied through the tendon to the forearm, which it tends to rotate about the elbow. If the rotation is prevented by a load on the hand, the force developed against the load is proportional to the tension existing in the muscle. Thus, the Torquometer indication is proportional to the tension in the muscle.

1.4.2 Time Line

No effort was made to determine the very accurate characteristic rate of the signal generator. It is assumed to be within the experimental accuracy of the other measurements being observed.

2. The Stepping-Motor Technique

1.1 The Digital Subsystem

The Digital Subsystem by Pace Controls Corporation is described in block diagram form in Figure 6.

The motor in the system actually purchased is Model M115BX. It is in a BuOrd No. 15 case. Its performance data are:

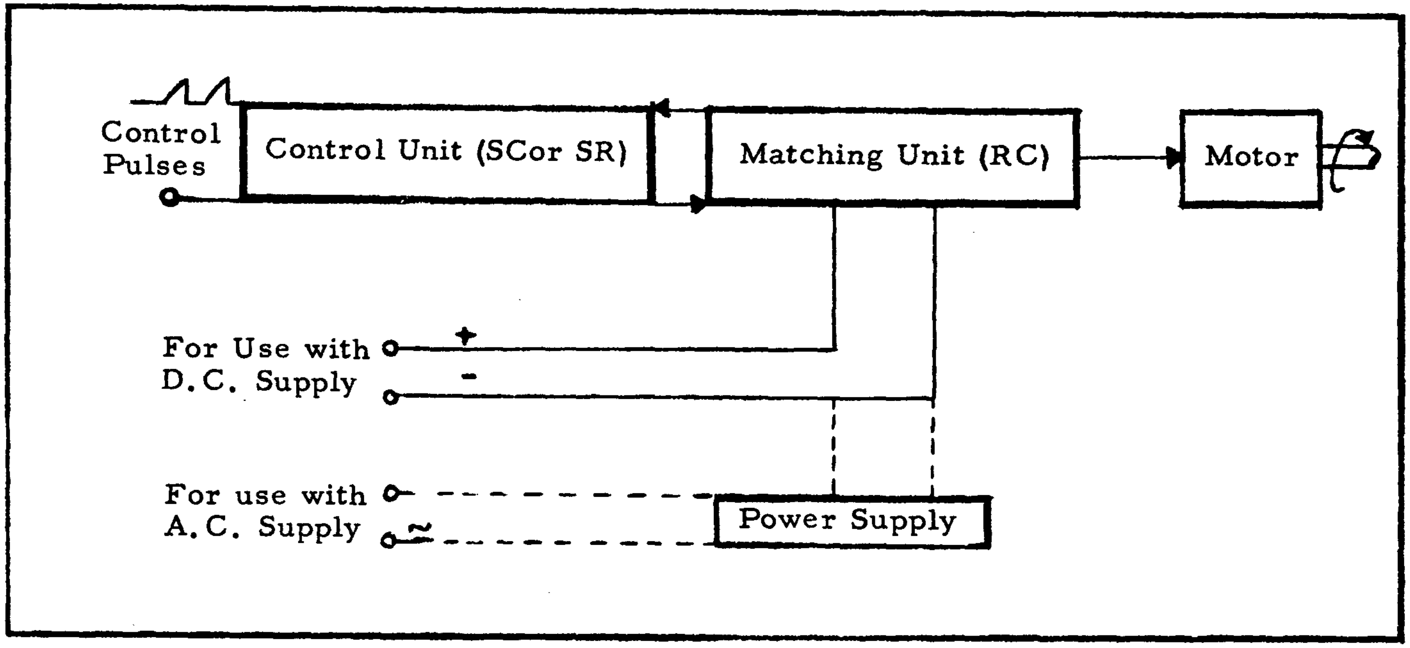

Figure 6. The Digitork System

Speed Range: 0-2400 steps per second (See Figure 7)
Rated Torque: 1.00 ounce inch minimum -0-1600 steps per second
Instantaneous Starting and Stopping Rate: 200 steps per second maximum at 1.00 ounce-inch rated load and 0.000132 ounce-inch seconds^2 maximum load inertia
Ambient Temperature Range: 0 to +55 degrees C
Steps Per Revolution: 36
Degrees Per Step: 10 degrees nominal
Accuracy of Step Position: Position of each individual step ± 1 degree; cumulative error after each series of 3 steps is negligible
Shaft Rotation: 3 models - clockwise, counterclockwise, reversible

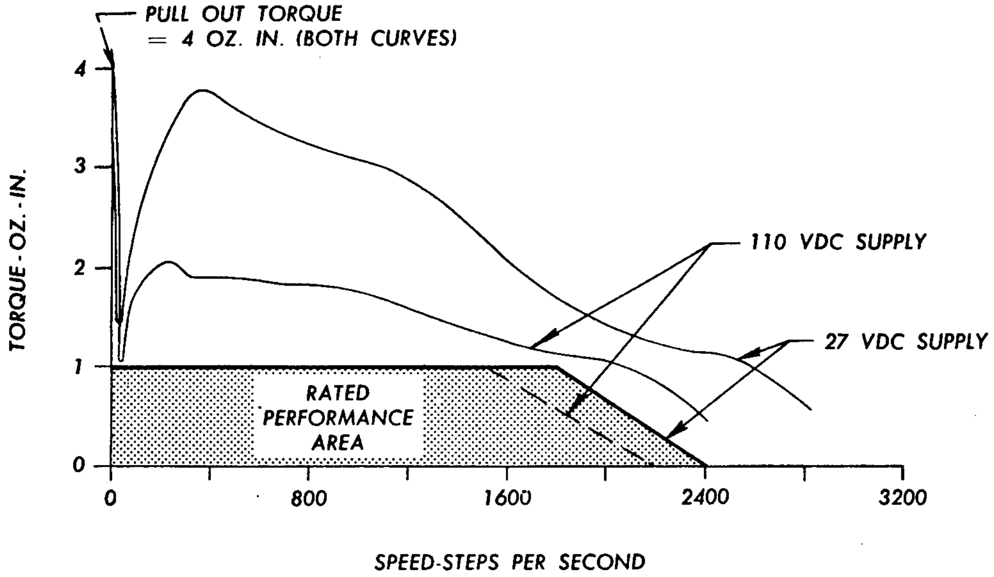

Figure 7. Torque Speed Curves

Purchased with the motor were Control Unit SCIBFP and Matching Unit RC15BC1F. The SC1BFP Control Unit receives the control pulses from an external signal. It shapes and amplifies them and sends the amplified pulses to the matching unit in the correct sequence for operation of the motor. Its electrical characteristics are:

Control Signal

Voltage: 8-30 volts peak
Duration: 10-30 microseconds
Rise Time: 0.5 microseconds maximum
Polarity: Positive or negative
Input Impedance: 1500 ohms nominal
Maximum Steady State
DC Across Terminals: 200 vdc (input is a-c coupled)

Ambient Temperature Range: 0 - +55 degrees C
Supply Voltage: Received from matching unit
Power Dissipation: 20 watts

The RC15BFP Matching Unit serves as the central distribution point for the Digital Subsystem. It receives DC supply voltage from an external source, supplies power to the control unit, receives the amplified control pulses from the control unit, and applies the pulses to the motor windings. Its characteristics are:

Supply Voltage: 27 VDC
Current Supply: 2 AMPS
% Ripple: 5% MAX
Power Dissipation: 45 WATTS
Ambient Temperature Range: 0-+55°C

Figure 8 shows a photograph of the Digital Subsystem.

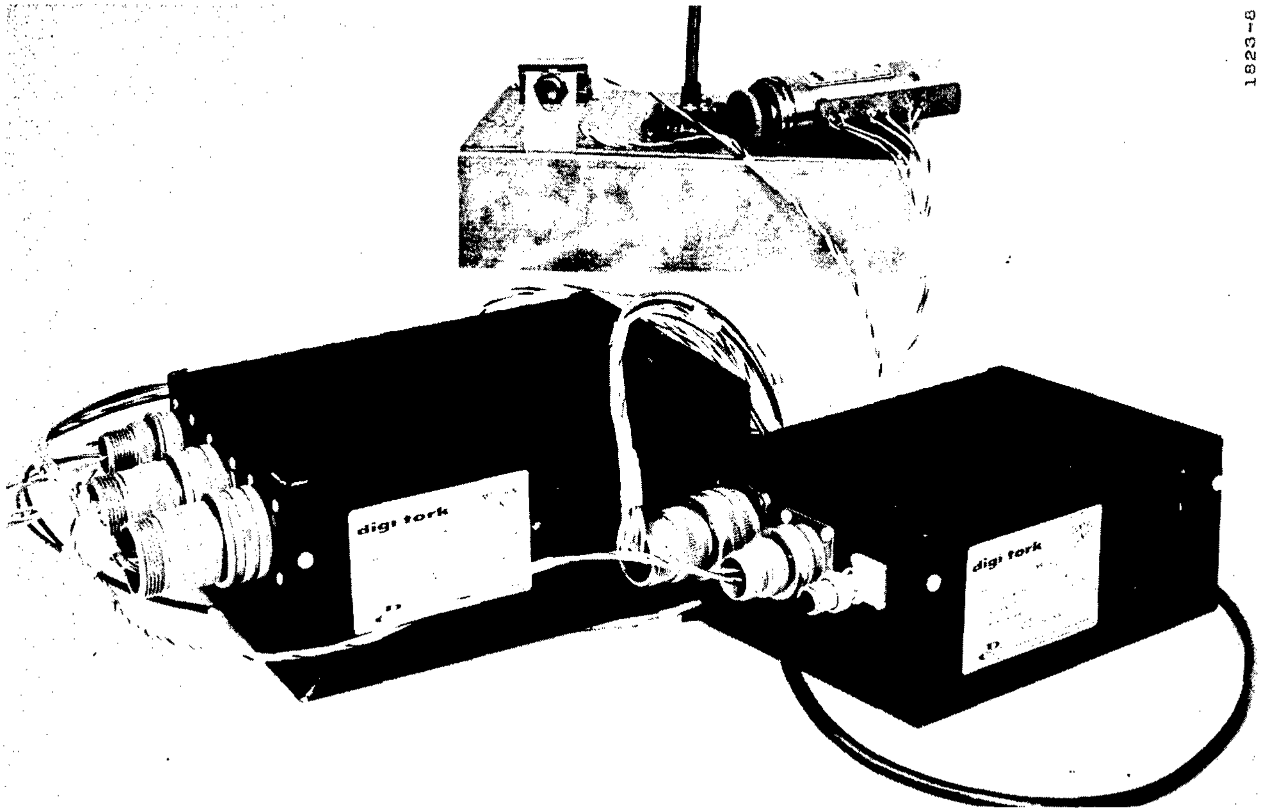

Figure 8. Digital Subsystem

1.2 Function

The Digital Subsystem accomplishes the function of the Original Litton Breadboard System described in the Introduction. That is, it handles the functions of the Pulse-Shaping Circuitry, Stepping Motor Logic Circuitry, Amplifier, and Stepping-Motor Blocks of the Block Diagram of Figure 9.

Since the Digital Subsystem requires an 8-volt input, the B30A Differential Amplifier was not suitable as a preamplifier. Rather than construct another preamplifier the Biopack B30ATP was utilized with a Sherwood S-3000 III FM Tuner so that the tuner acted as a preamplifier. This is shown in Block Diagram Form in Figure 10.

Characteristics of the B30A are:

Voltage Gain	3800 single-ended output 7600 differential output	fixed
Frequency Response	±3db -0.5 cps to 8K	
Common Mode Rejection	10,000 to 1 or better at 60 cps	
Size	0.8 cubic inch	
Weight	18 gms (without case)	
Power Requirements	±8.4 volts, -1.5 volts	
Input Impedance	0.5 megohm	
Output Impedance	30 kilohms	
Noise	Equivalent input noise referred to input (with 20,000 -ohm source) 4 microvolts peak to peak - over bandwidth 0.4 cps to 60 cps.	

Characteristics of the B30T are:

Frequency Range	Tunable 88 mc to 120 mc
Sensitivity for 100% Deviation	50-75 mv
Input Impedance	high (100 kilohms or better)
Frequency Response	dc to 10 kc
Power Output	25 mw
Power Requirements	8.4v at 4.8 ma
Size	0.8 cubic inch
Weight	12.5 gms (without case)
Range	100 yds - maximum

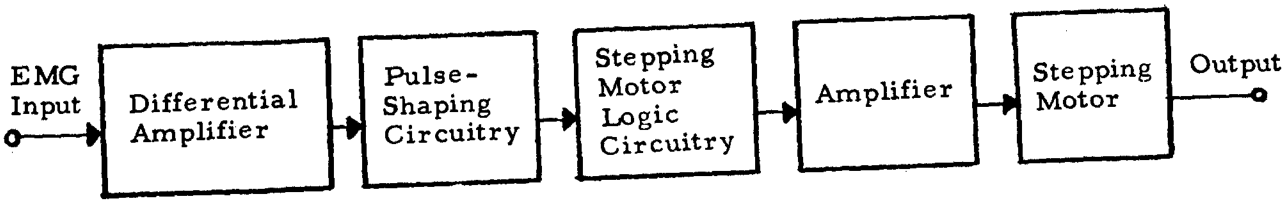

Figure 9. Block Diagram of Digital Subsystem

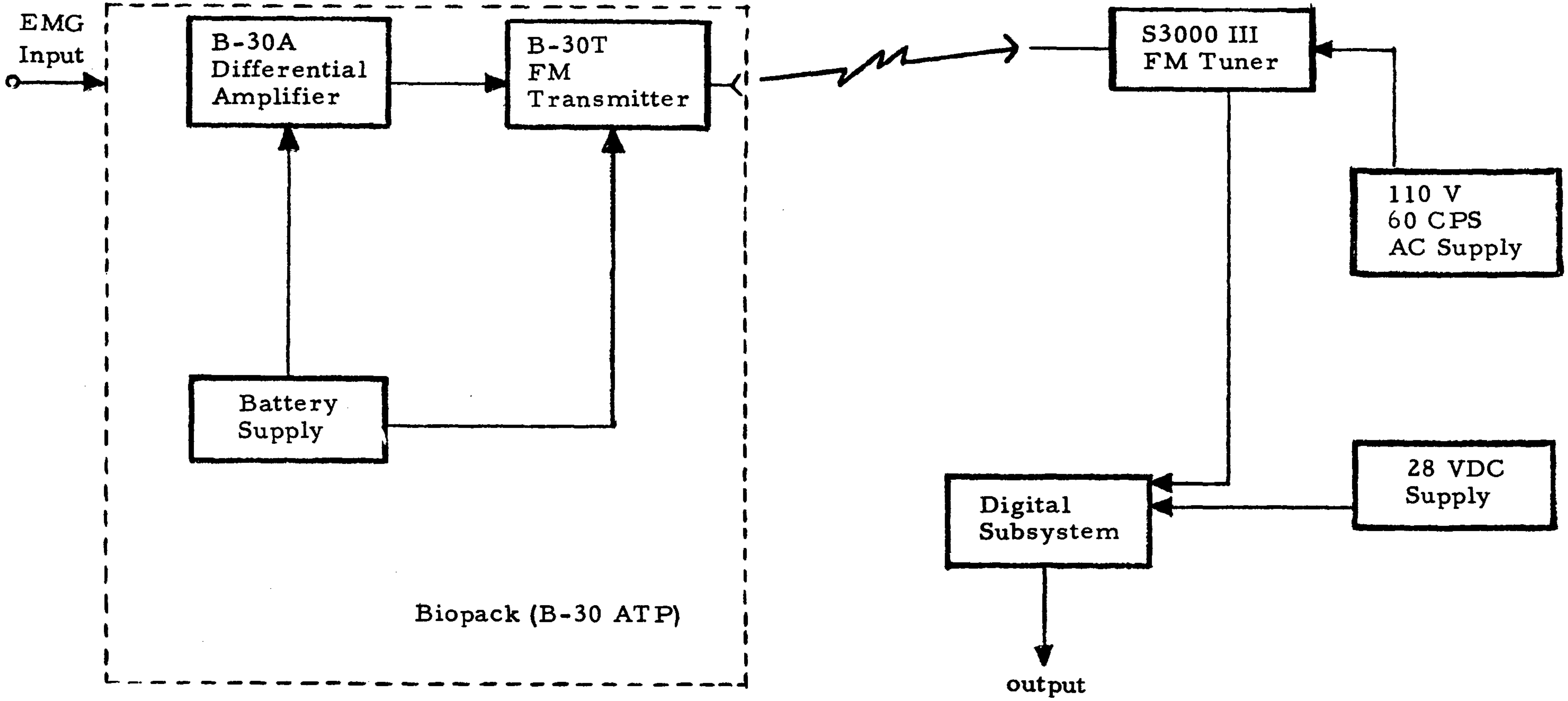

Figure 10. Block Diagram of Electronics Subsystem

The Electronic Setup was used in conjunction with the Muscleometer in the direct-dial-reading mode (i.e. without potentiometer) for higher tensions and with an ordinary fish-scale for low tensions to provide spike-rate-vs-tension-developed data from the surface-electroded biceps. Spike rate was deduced directly from stepping rate of the motor since a one-one correspondence between spikes and steps was established by System Design. Figure 11 (A) shows subject with Muscleometer and figure 11 (B) illustrates placement of the electrodes on subject's arm.

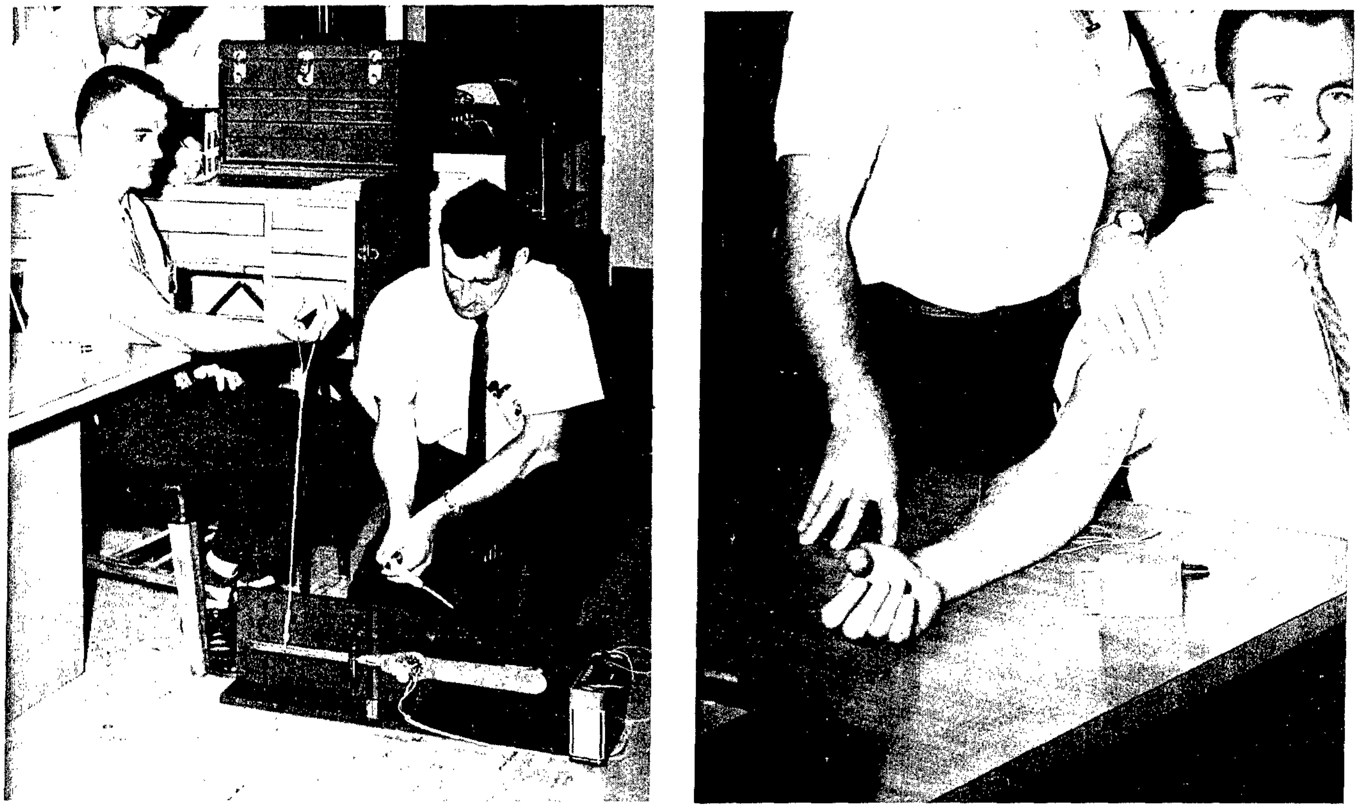

Figure 11

(A) Subject with Muscleometer

(B) Detail Showing Electrode Placement

RESULTS

1. Raw Data

Five series of data were obtained. Series 1, 2, 3, and 5 were obtained by The Muscleometer Technique and Series 4 was obtained by The Stepping Motor Technique. The raw data is displayed in graphic form in Figures 12 thru 21.

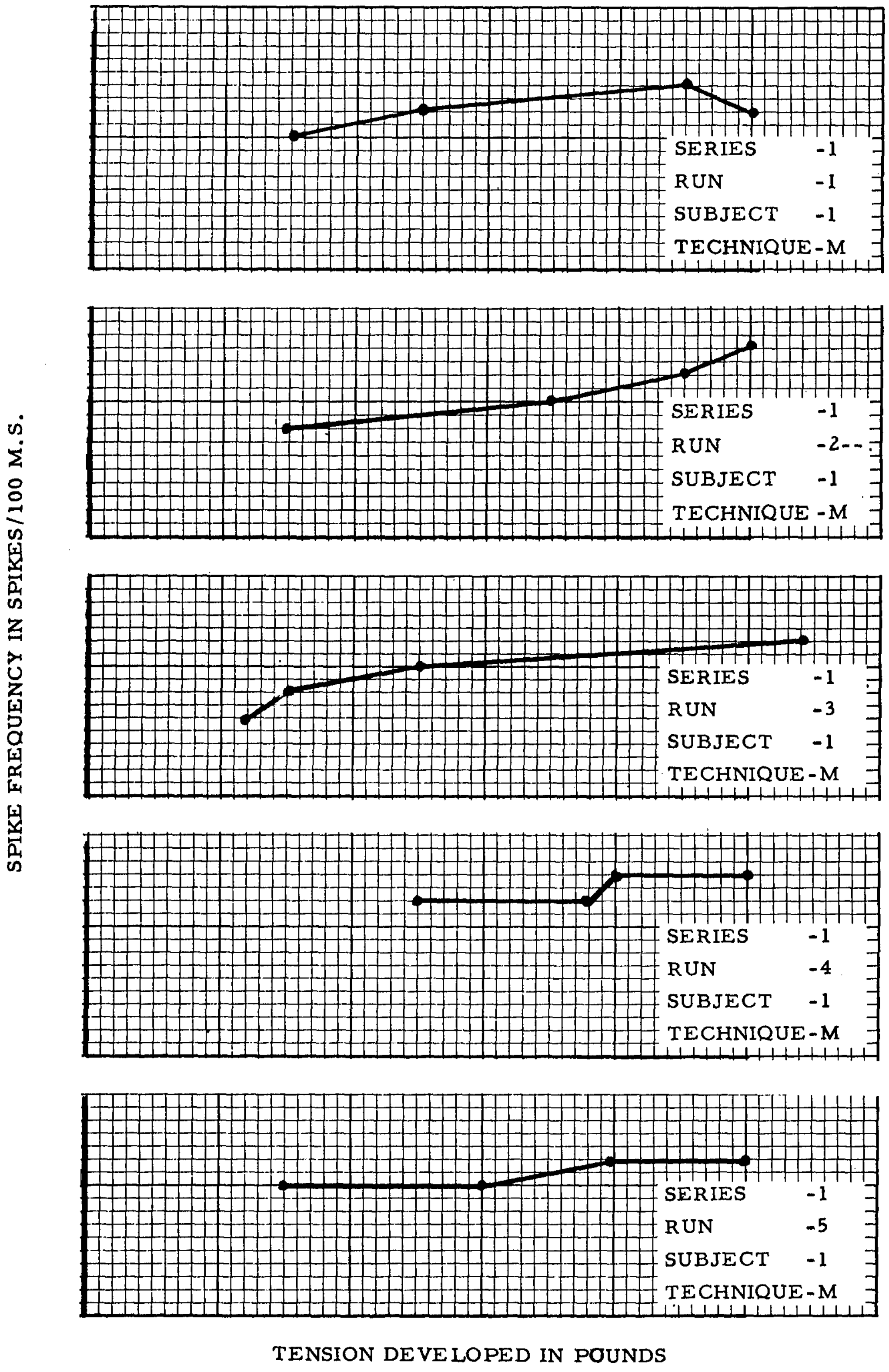

Figure 12. Graphs of Frequency vs. Tension

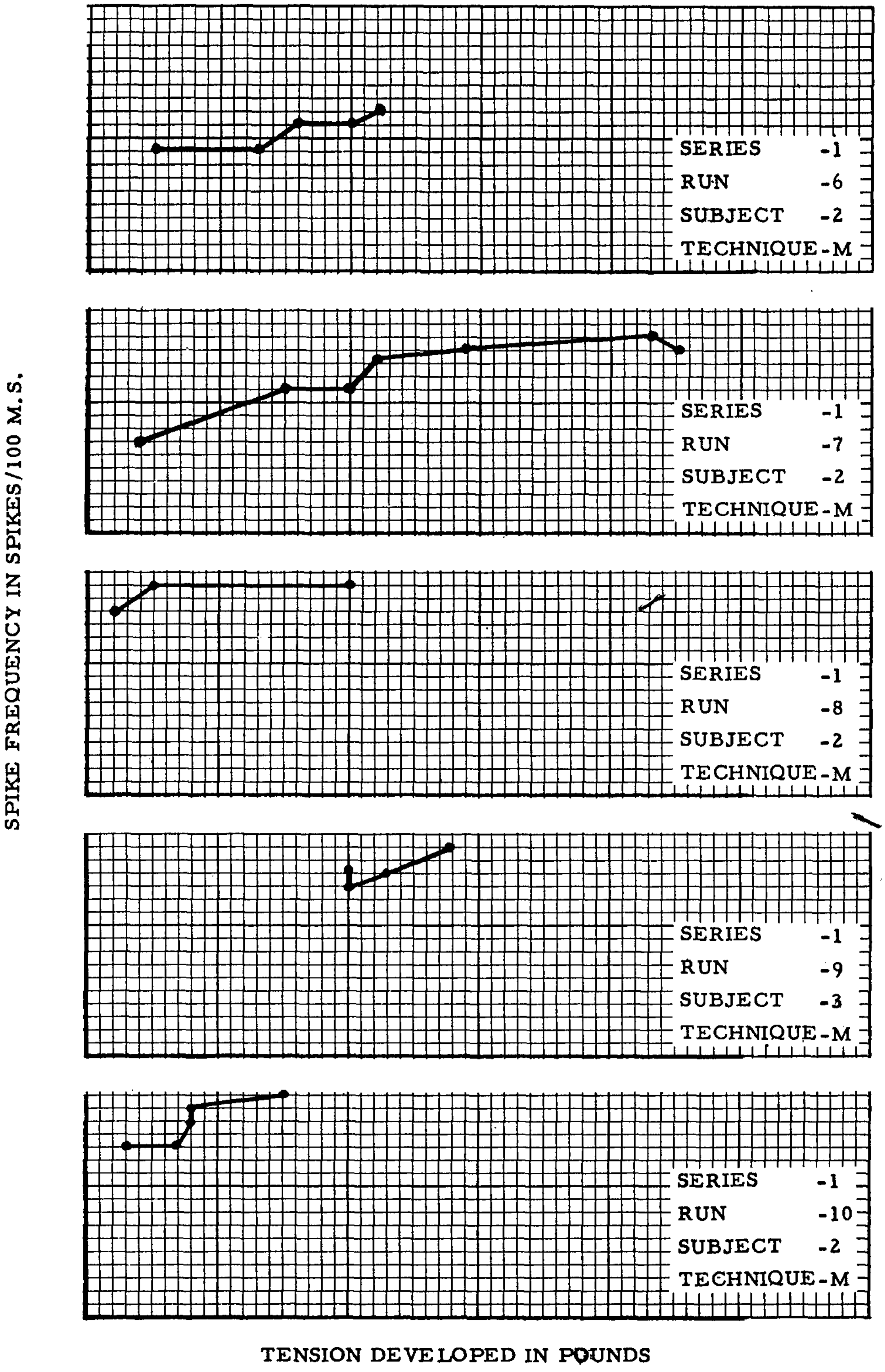

Figure 13. Graphs of Frequency vs. Tension

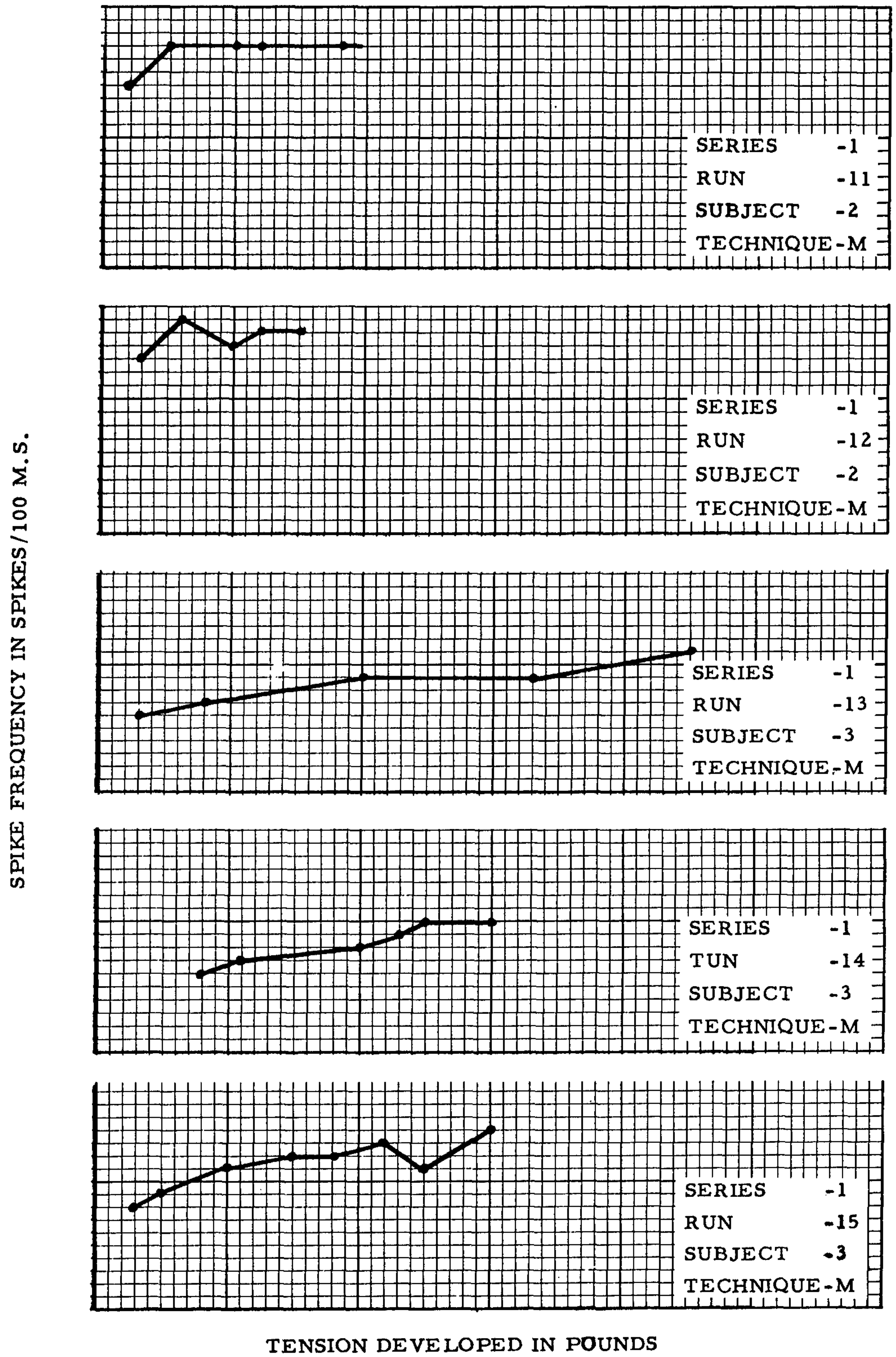

Figure 14. Graphs of Frequency vs. Tension

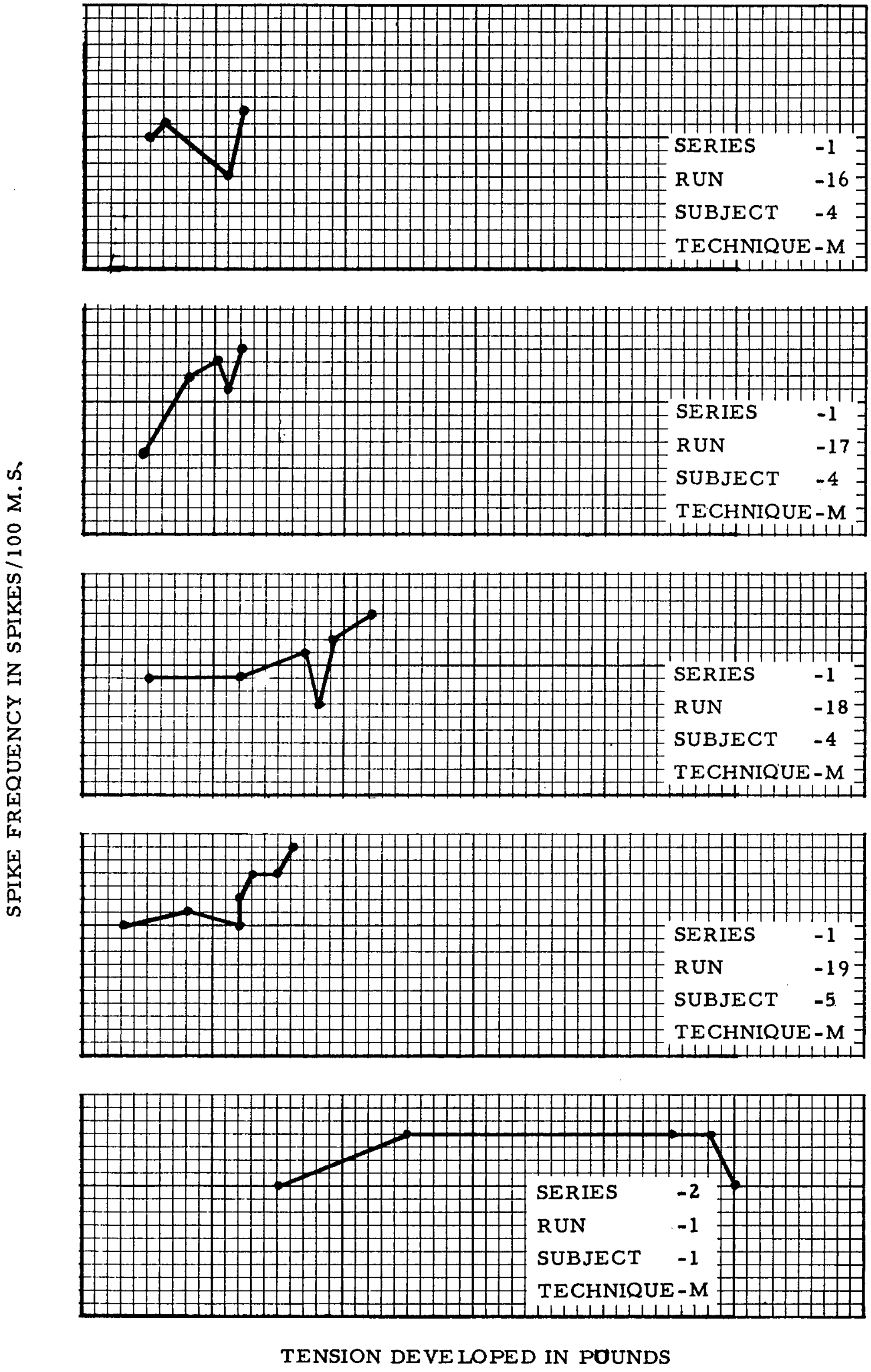

Figure 15. Graphs of Frequency vs. Tension

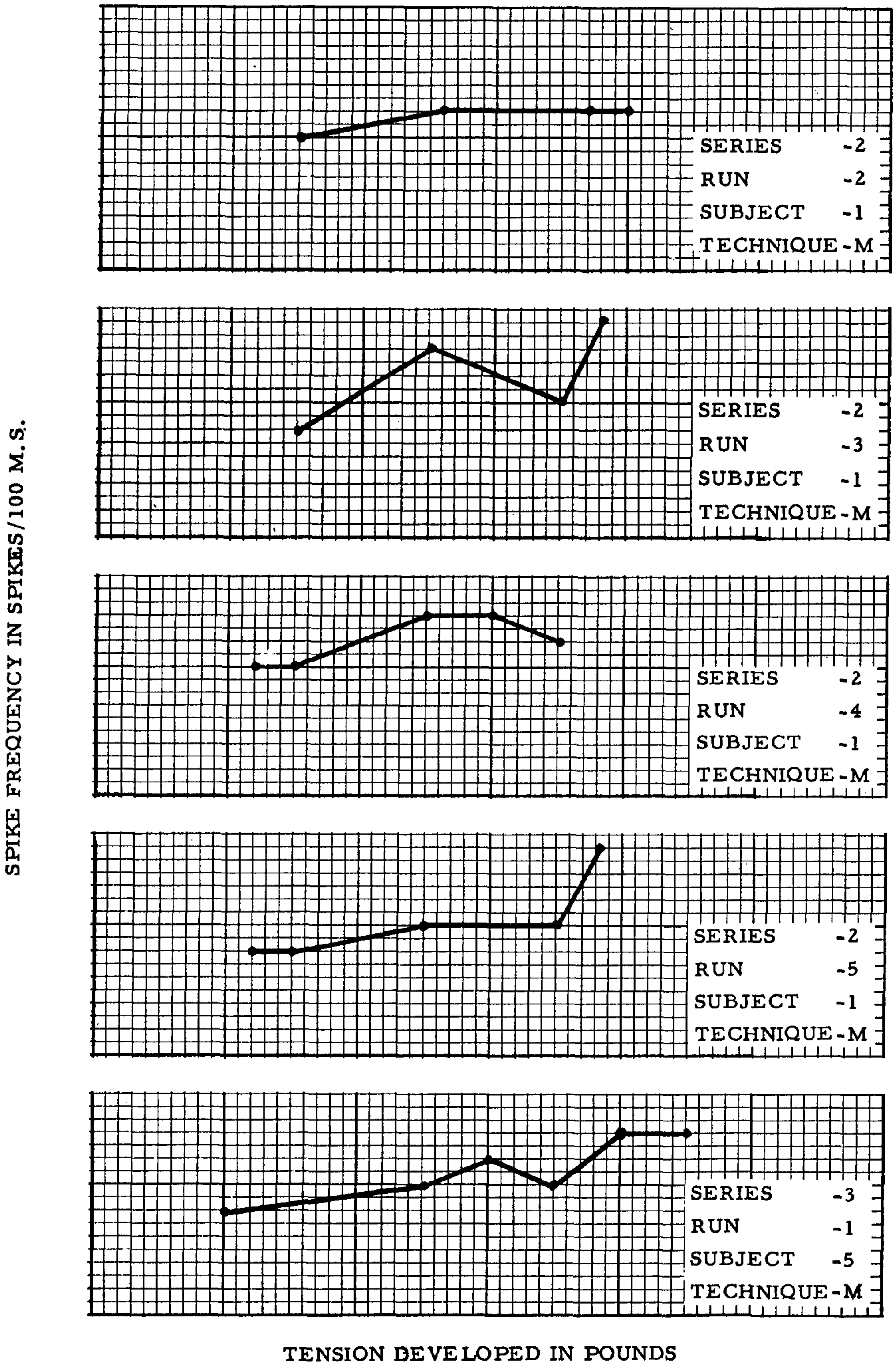

Figure 16. Graphs of Frequency vs. Tension

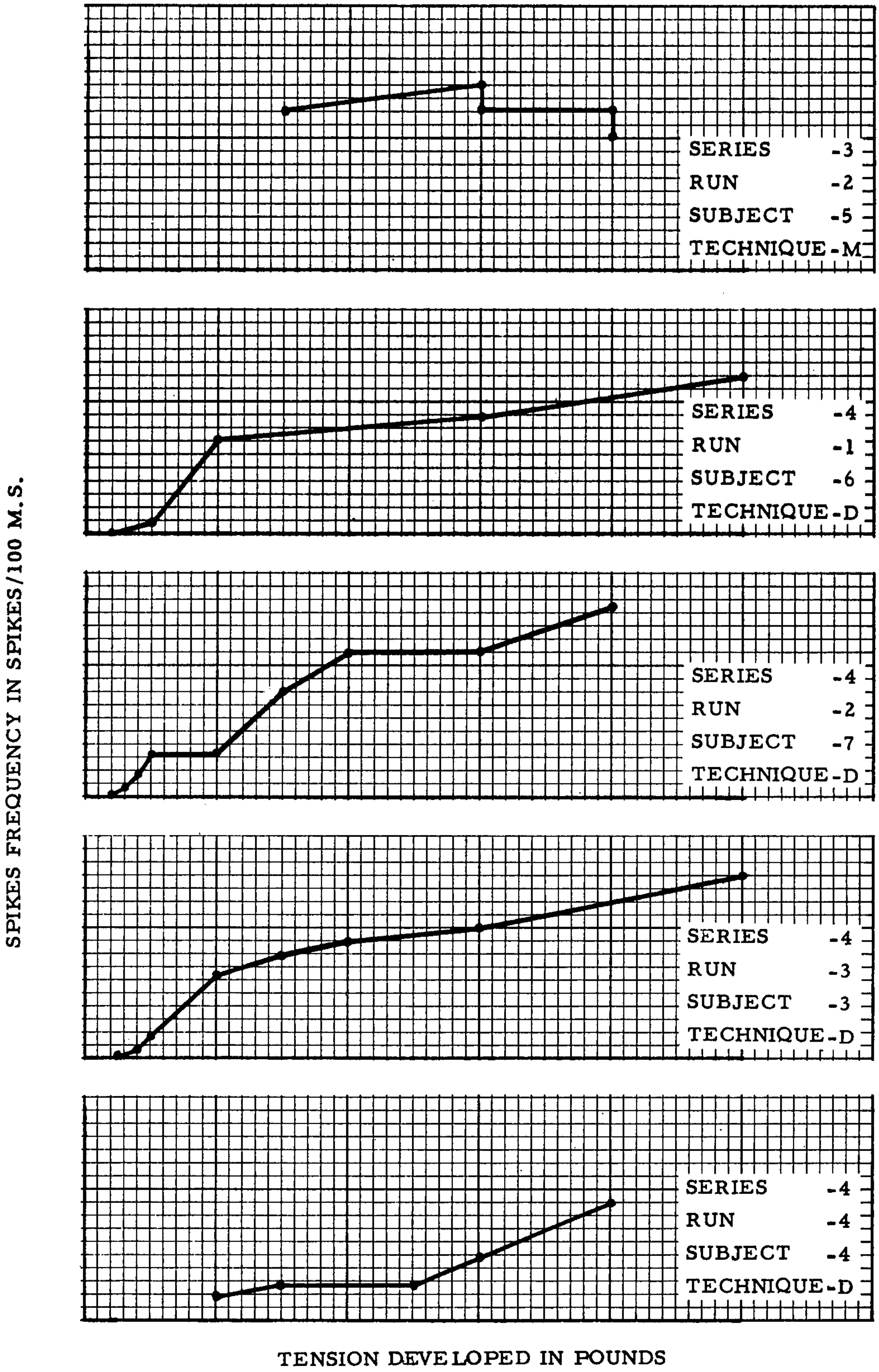

Figure 17. Graphs of Frequency vs. Tension

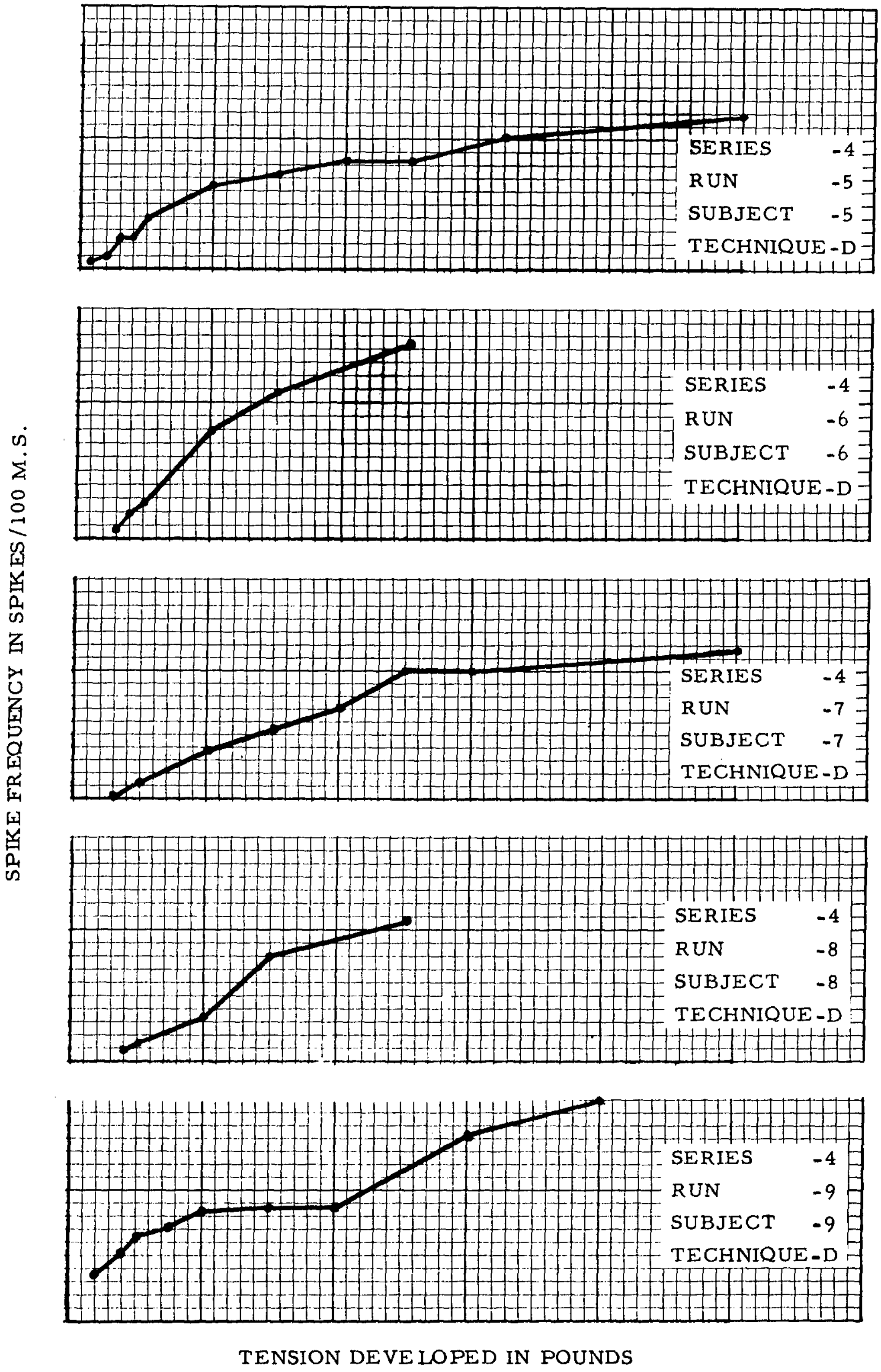

Figure 18. Graphs of Frequency vs. Tension

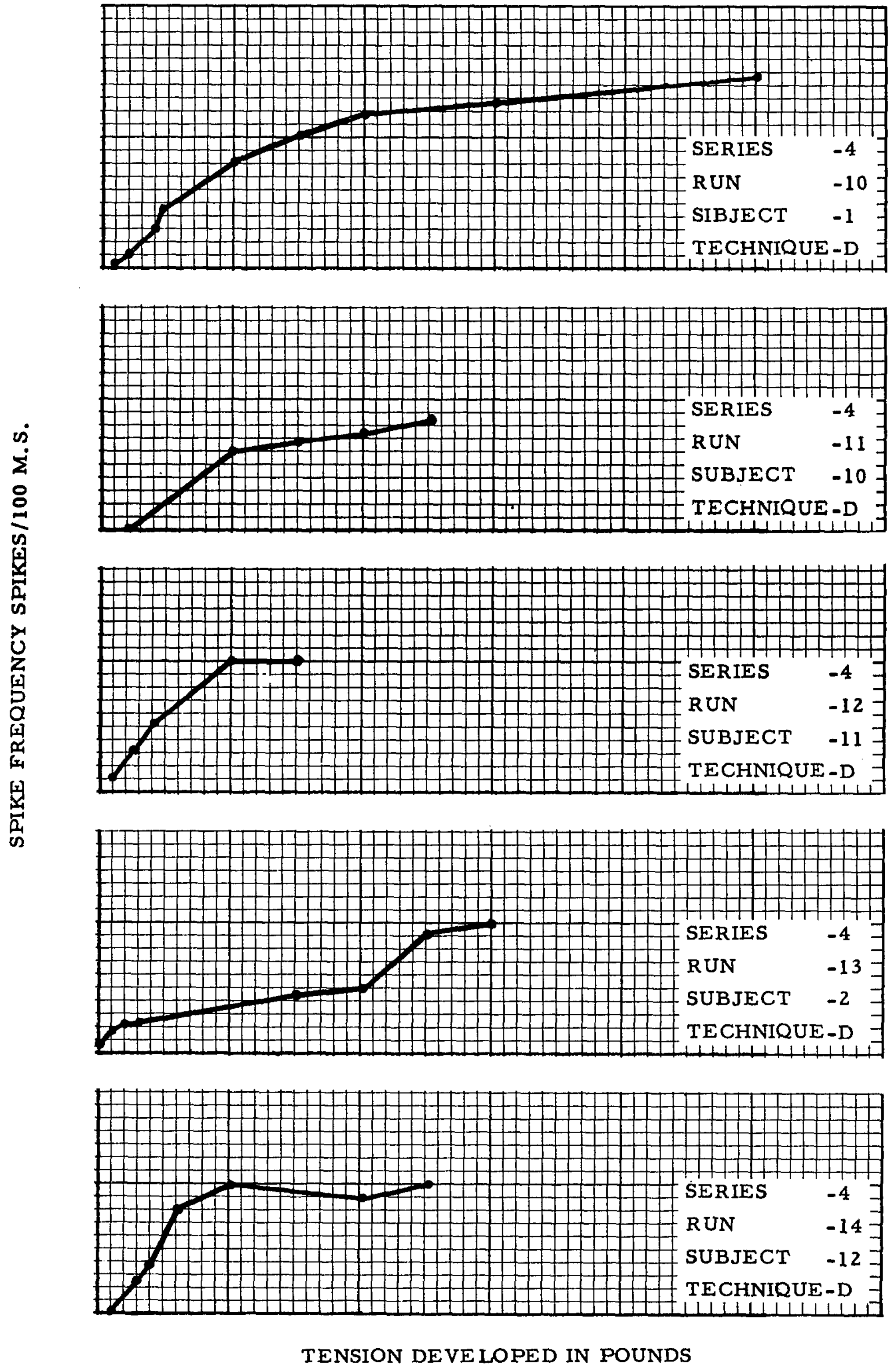

Figure 19. Graphs of Frequency vs. Tension

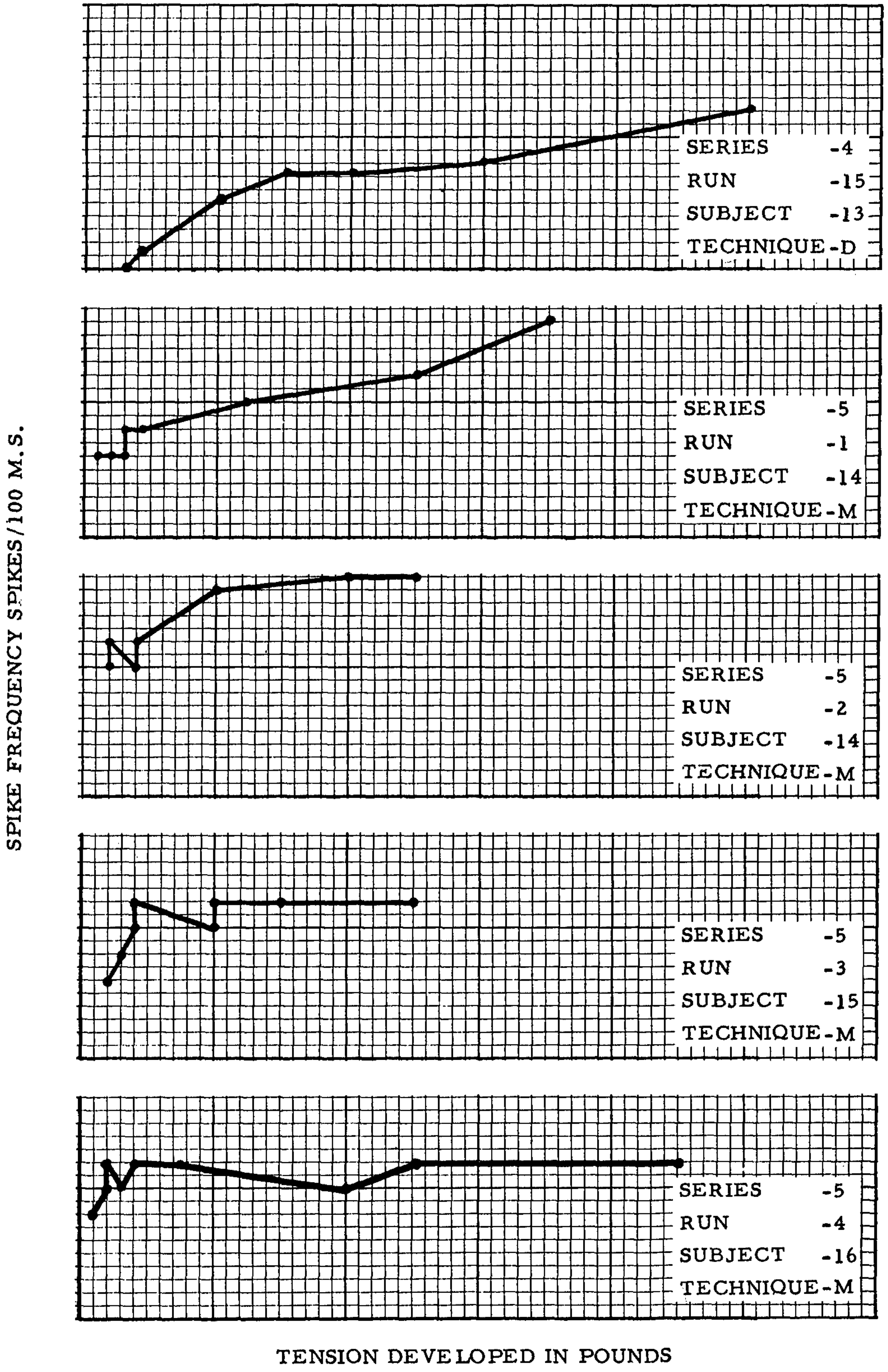

Figure 20. Graphs of Frequency vs. Tension

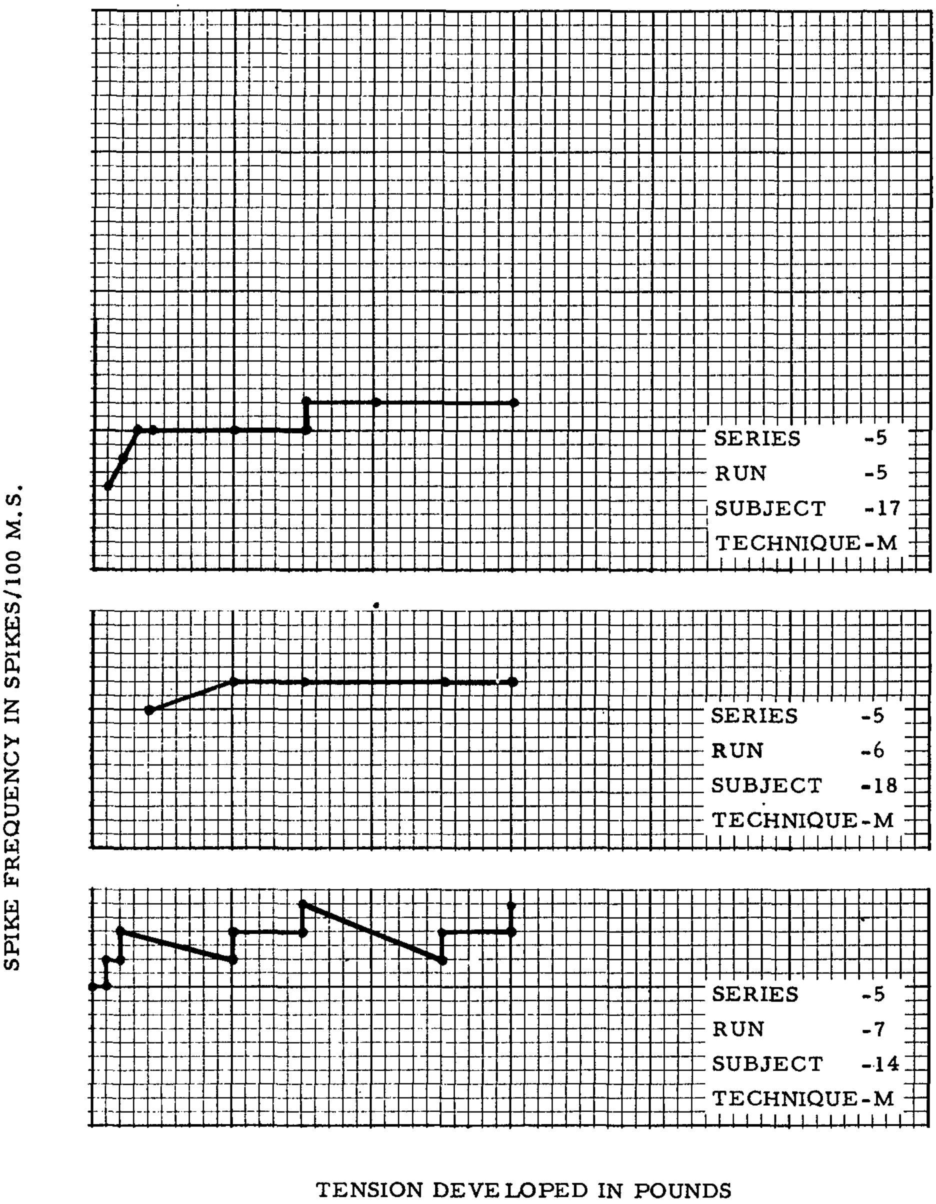

Figure 21. Graphs of Frequency vs. Tension

2. Smoothed Data

The electromyogram (surface electroded) arises from a totality of underlying muscle activity and, therefore, masks the number of motor units in action at any one instant, the threshold of the individual motor units, and the rotation of the individual motor units. It is thus an "averaging" signal. In addition, the EMG spikes are not uniformly distributed in time and our frequencies taken over 100 ms time intervals require time smoothing to indicate true average frequency over time intervals of longer duration. It was decided to utilize 3-point arithmetic smoothing as the method most likely to minimize spurious effects without significant distortion of the actual underlying data. In this method each run is smoothed individually. Abscissas and ordinates of Data Points 1, 2, and 3 in raw data are separately averaged to yield, respectively, the abscissa and ordinate of Point 1 in smoothed data. Similarly, Points 2, 3, and 4 in raw data yield Point 2 in smoothed data, etc.. Since a raw data run of four data points yields only two smoothed data points, these were ignored. The smoothed forms of all raw data runs of more than four points are shown graphically in Figures 22 - 29.

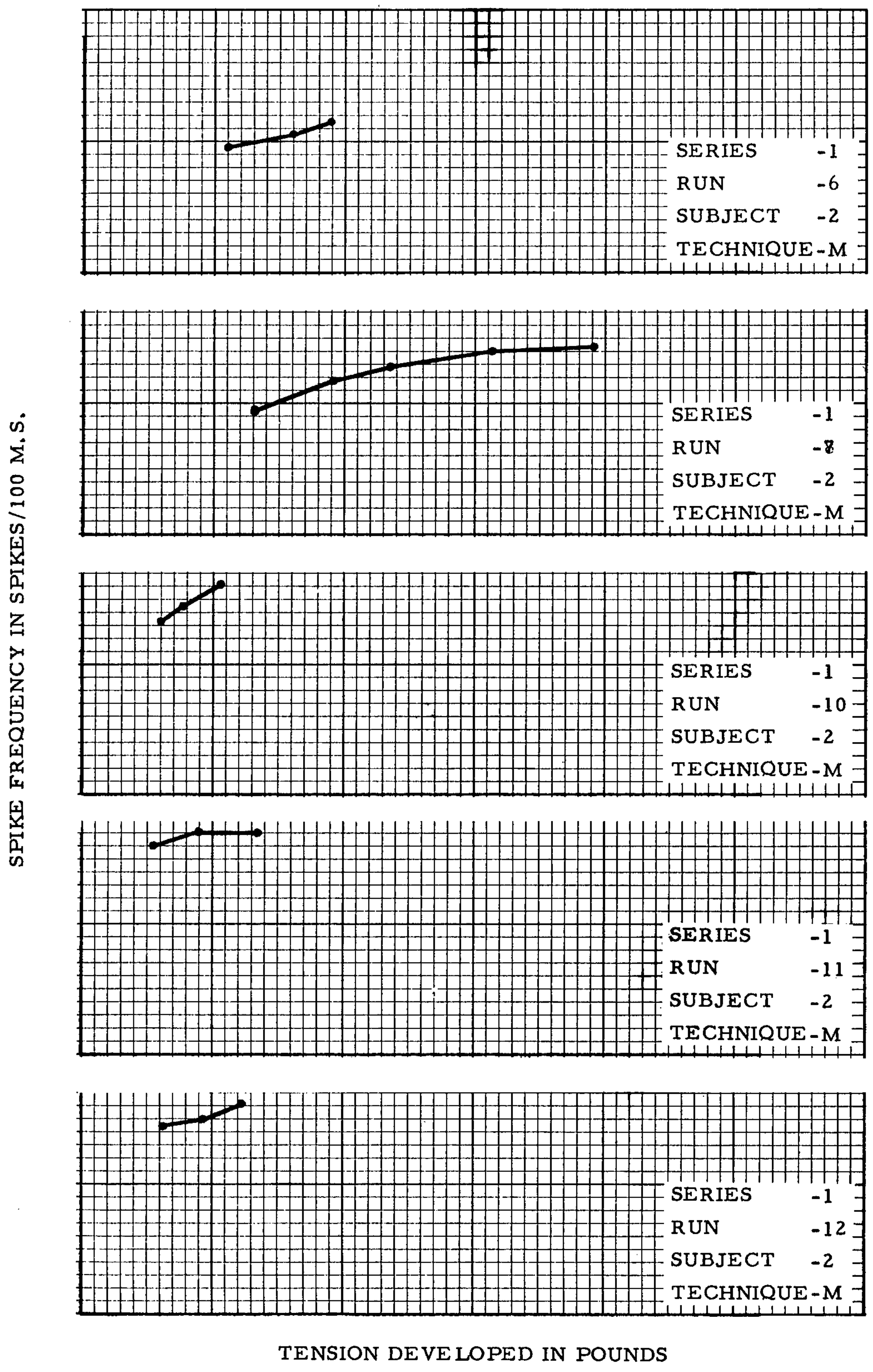

Figure 22. Graphs of Smoothed Data

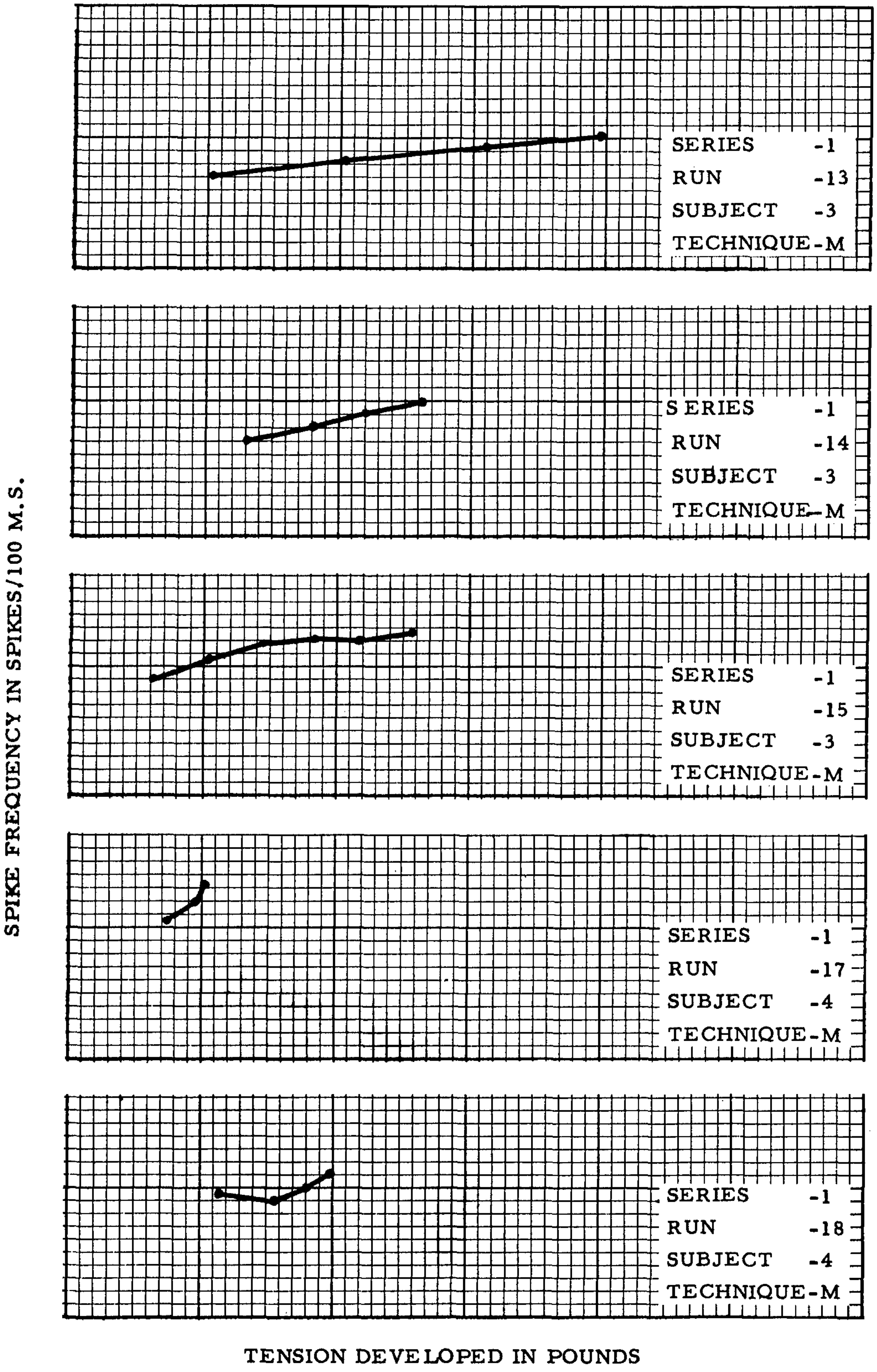

Figure 23. Graphs of Smoothed Data

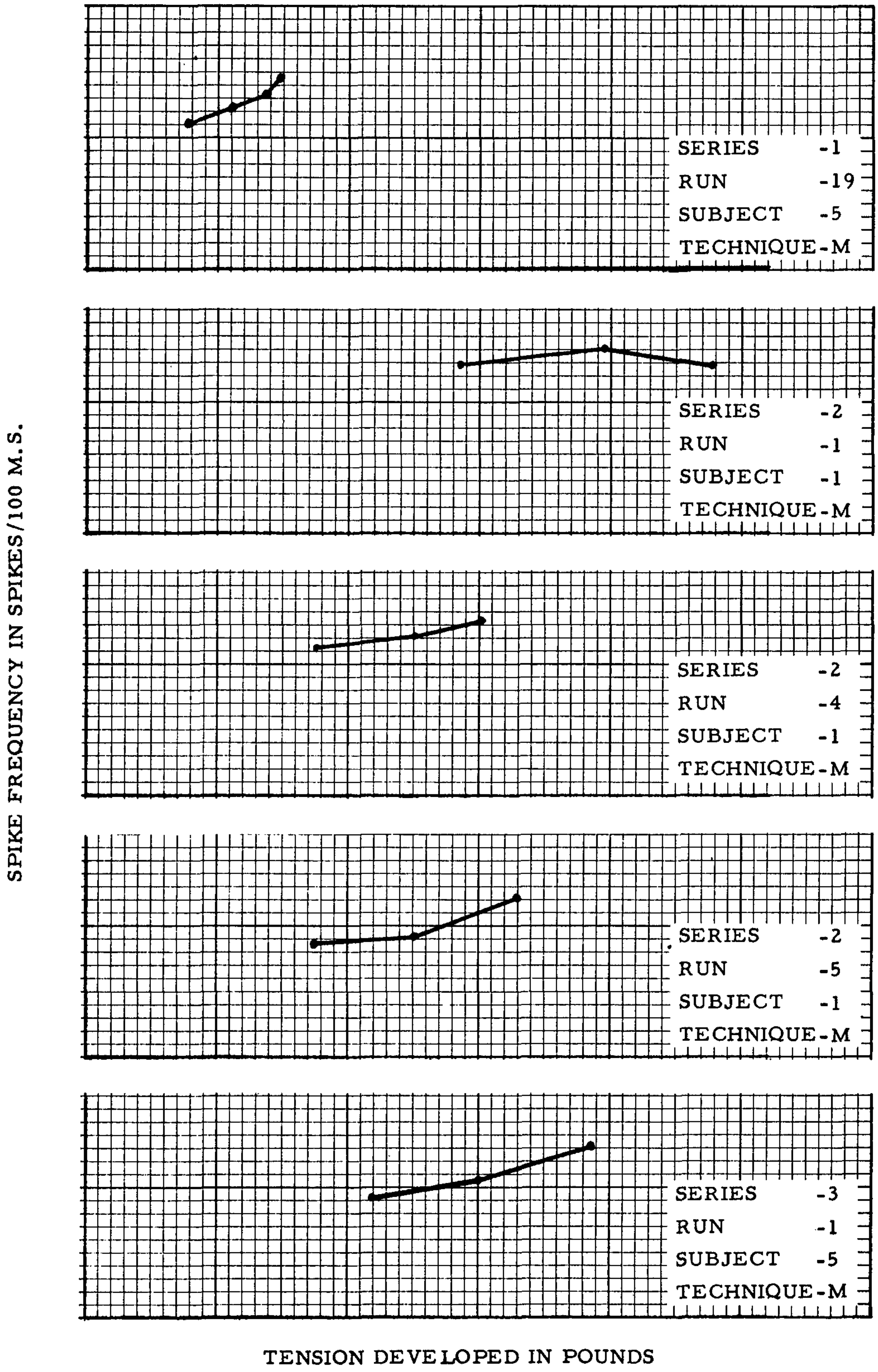

Figure 24. Graphs of Smoothed Data

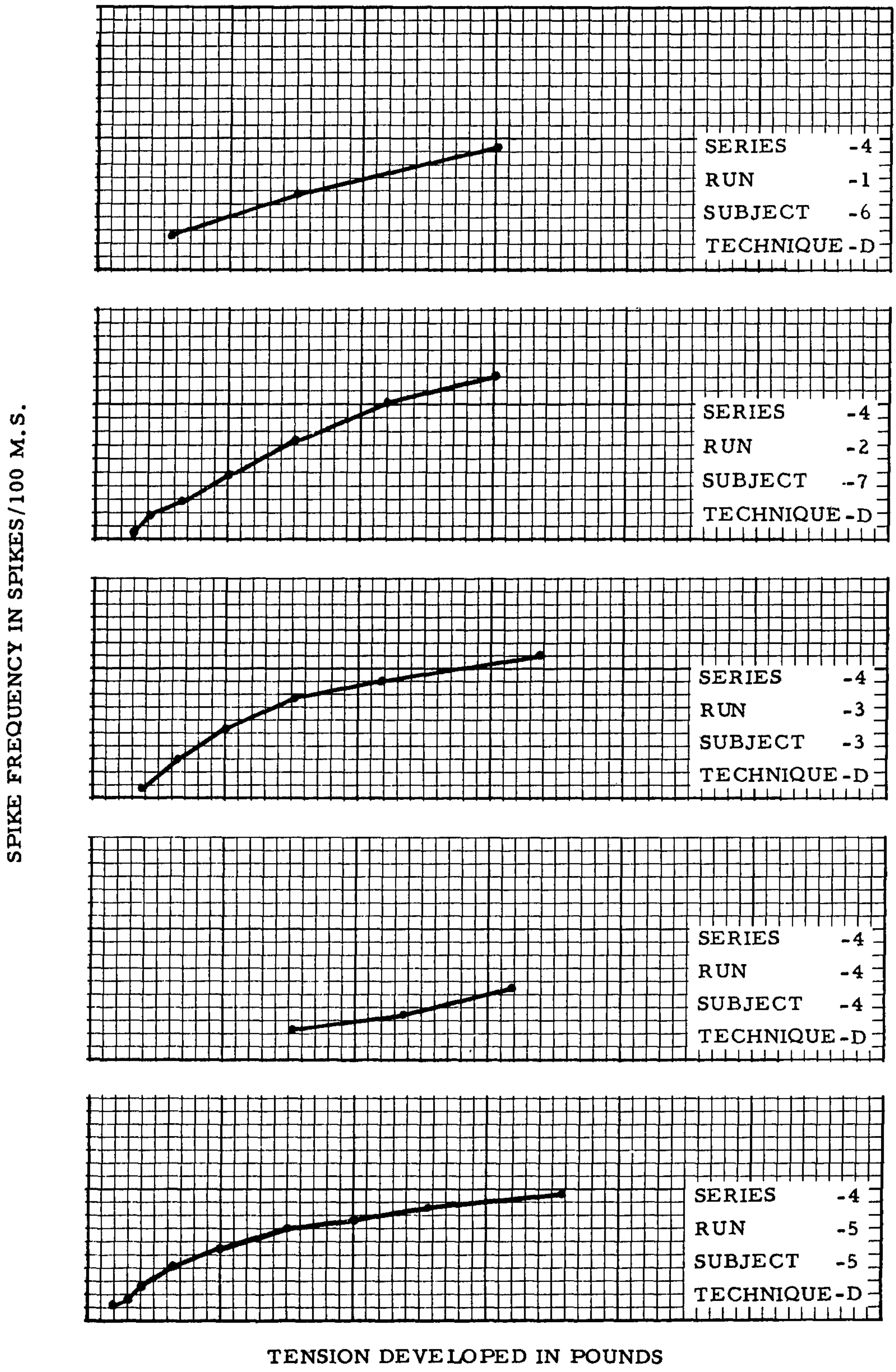

Figure 25. Graphs of Smoothed Data

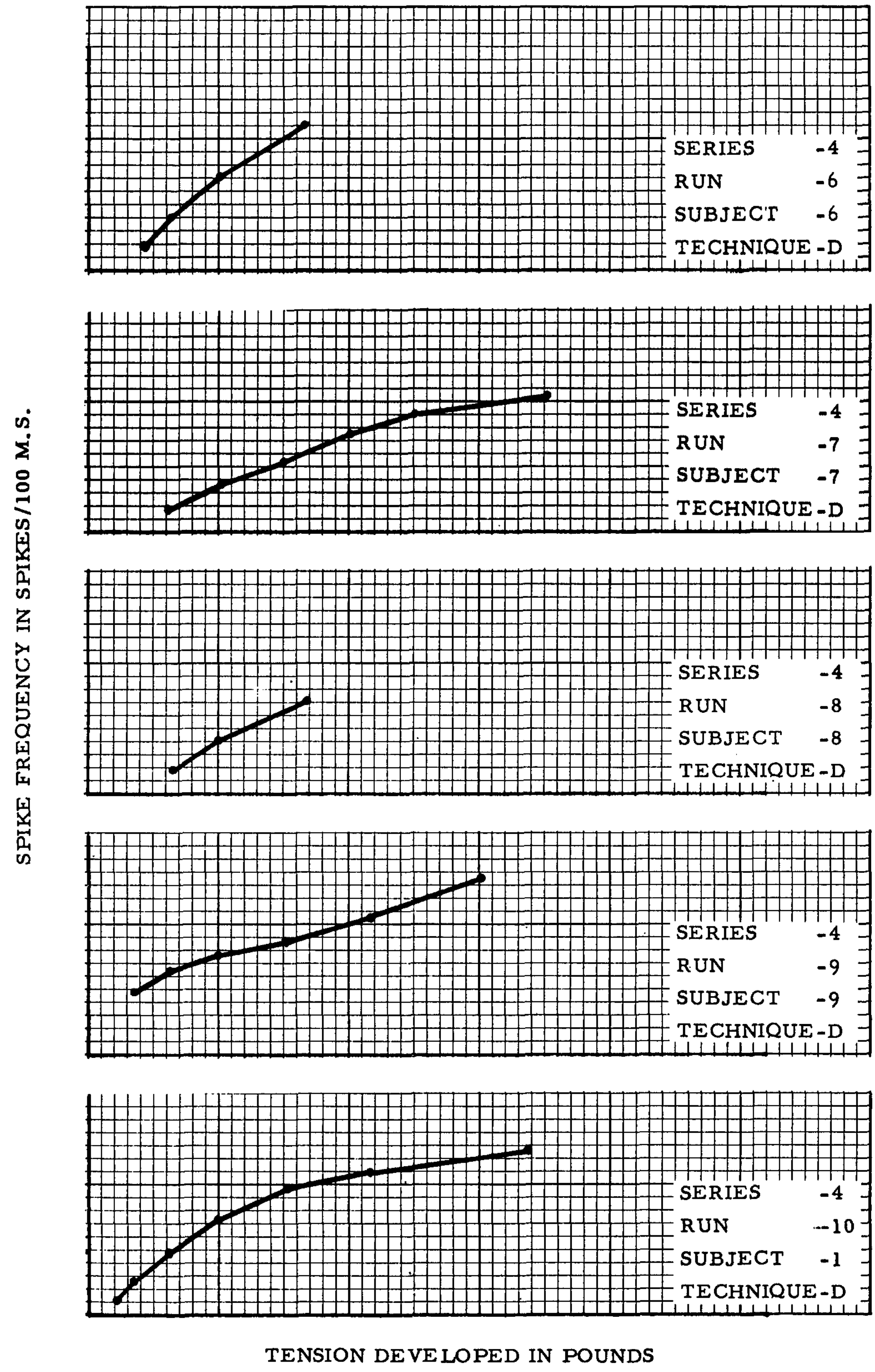

Figure 26. Graphs of Smoothed Data

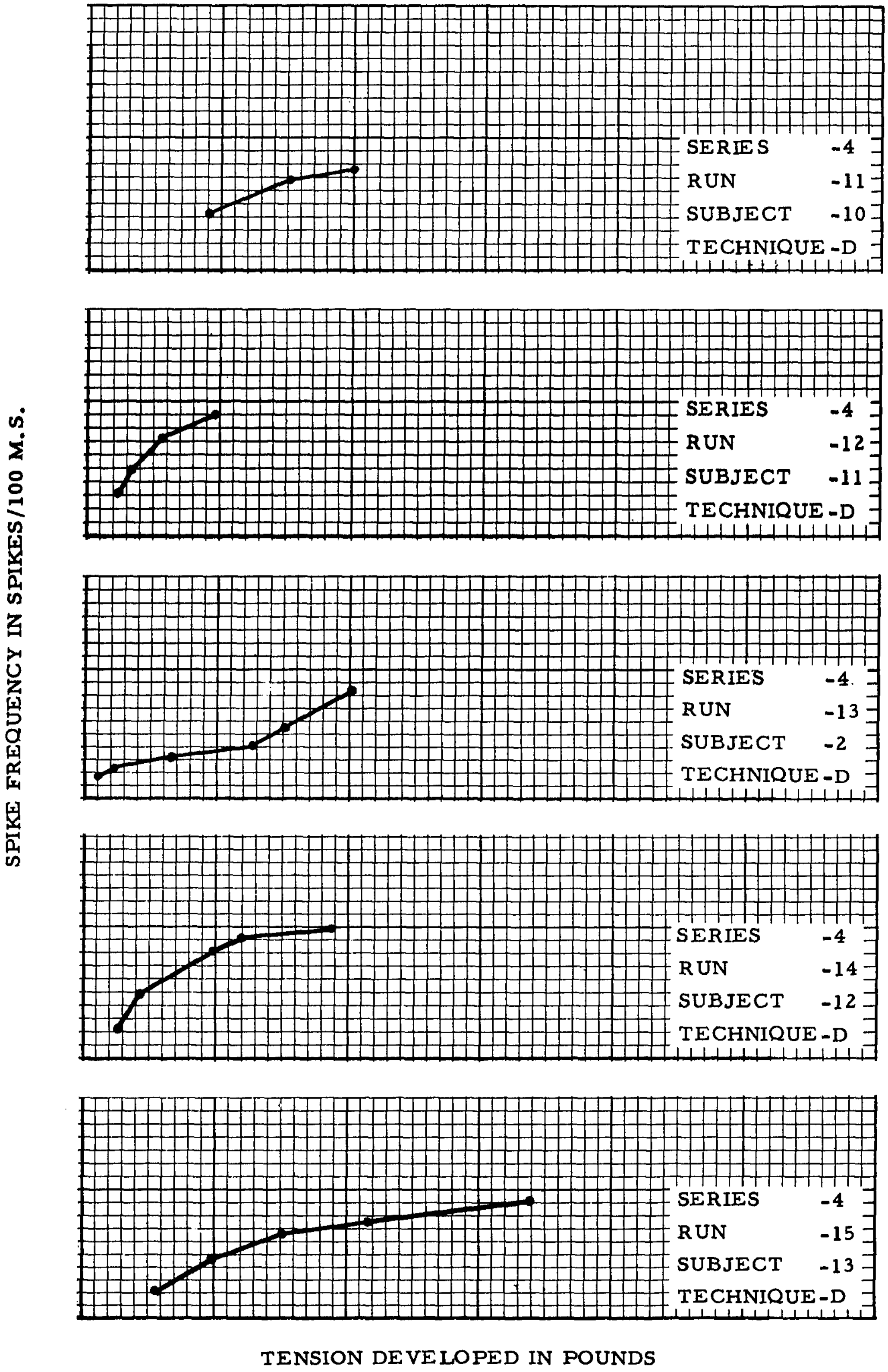

Figure 27. Graphs of Smoothed Data

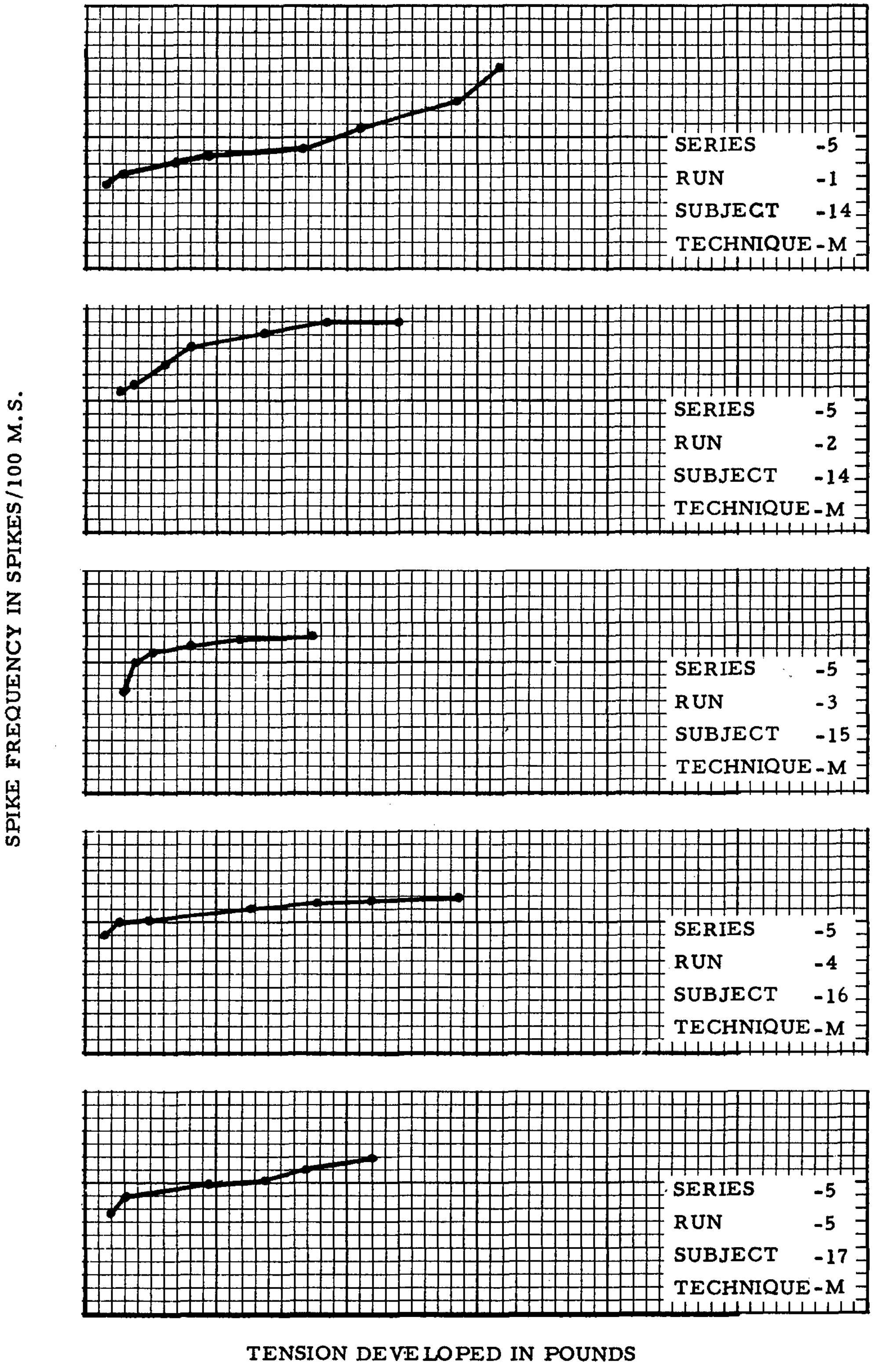

Figure 28. Graphs of Smoothed Data

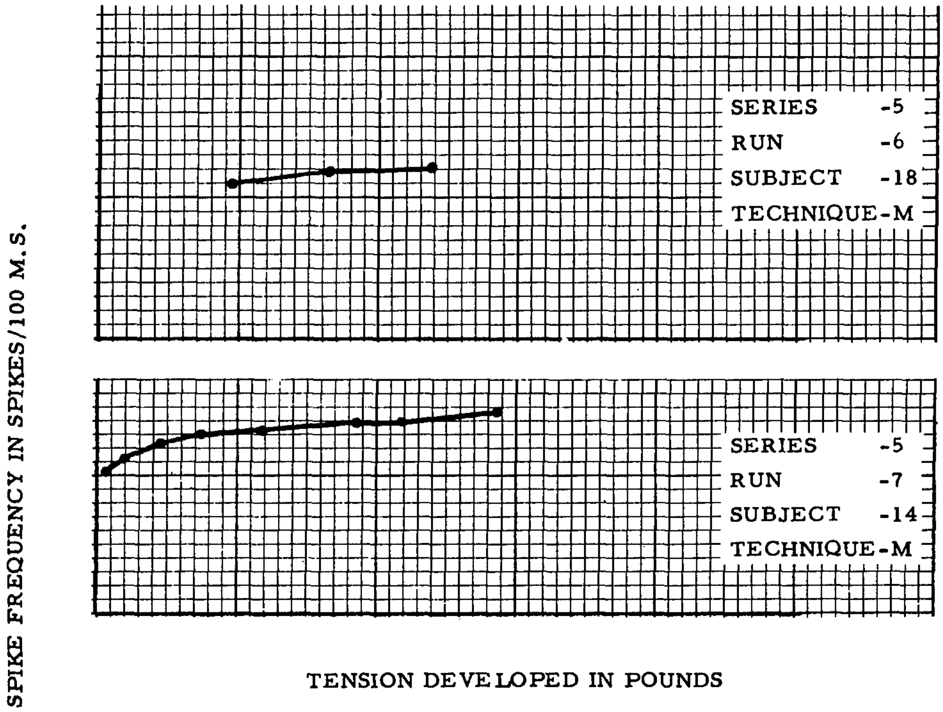

Figure 29. Graphs of Smoothed Data

CONCLUSIONS

The data obtained in Series 1 is not considered reliable. This is due to the fact that several difficulties were encountered during runs of Series 1 which were corrected in later series. The most drastic of these difficulties was notching of the EMG spikes due to amplifier saturation.

Cursory examination of the smoothed data from Series 2, 3, 4, and 5 shows that with one sole exception frequency is a monotone increasing function of tension developed. This fact in itself provides an adequate basis for our servo-systems where the loop is closed by visual or other suitable feedback. While the patterns vary somewhat in shape they for the most part approximate segments of parabolas or semicubical parabolas. The following observations may also be of interest.

1. More consistent pattern formation was observed with varying male subjects than with varying female subjects.

2. More consistent pattern formation was observed within several runs on a single subject than within runs on varying subjects. However, variations were encountered in a single subject and appeared to be primarily a function of degree of fatigue prior to experimentation.

3. Consistency of pattern formation could definitely be increased in a given subject by even short periods of training and indoctrination.

Aerospace Medical Division,
6570th Aerospace Medical Research
Laboratories, Wright-Patterson AFB, Ohio
Rpt. No. MRL-TDR-62-52. RELATIONSHIP OF THE ELECTROMYOGRAPHIC SIGNAL TO MUSCLE ACTIVITY. Final report, Jun 62, iii + 35 pp. incl. illus. Unclassified report

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2. Muscles
3. Bionics
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II. Biomedical Laboratory
III. Contract AF 33(616)-8302
IV. Litton Systems, Inc., Beverly Hills, Calif.
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