NECK MUSCLE ENDURANCE AND FATIGUE AS A FUNCTION OF HELMET LOADING: THE DEFINITIVE MATHEMATICAL MODEL

Annual and Final Report

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**Title:** Neck Muscle Endurance and Fatigue as a Function of Helmet Loading: The Definitive Mathematical Model

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**Abstract:** A series of experiments were conducted in which the neck muscles of volunteer subjects were dynamically and statically loaded by systematic variations of twenty-four headgear configurations consisting of eight different centers-of-gravity (CGs) times three different weights. Six subjects would rotate their heads laterally (from side-to-side) for 30 min with each of the headgear loading combinations. Immediately thereafter, the subject would position his head in an isometric head dynamometer and exert a sustained right lateral neck contraction or forward neck contraction at 70% of his maximum strength, during which endurance time (to fatigue) was recorded. The results indicate that the computer model makes reasonable predictions within the boundary conditions. Input data outside the boundary conditions is rejected. The assumption of insensitivity to vertical loading is demonstrated. The assumption of bilateral symmetric response was confirmed for the 1.45 kg and 2.27 kg helmet loads. However, this assumption was not confirmed for the 4.09 kg helmet load. It is concluded from the computer model that afterward, midline loading is the optimal CG location (i.e., maximal endurance) for heavier helmets in the 3-4 kg range.
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SUMMARY

A series of experiments have been conducted to supplement our current data bank of helmet loading configurations (then at fifteen different helmet weight and center-of-gravity combinations). The neck muscles were dynamically and statically loaded by systematic variation of nine additional headgear configurations consisting of three different combinations of centers-of-gravity (right-forward-low, left-lateral-low and right-aftward-low) and three different weights (1.45 kg., 2.27 kg. and 4.09 kg.). Six subjects would rotate their heads laterally (from side-to-side) for 50 minutes with each of the headgear loading combinations. Immediately thereafter, the subject would position his head in an isometric head dynamometer and exert a sustained right lateral neck contraction or forward neck contraction at 70% of his maximum strength, during which endurance time (to fatigue) was recorded, the EMG over the right sternocleidomastoid muscle, over the posterior trapezius/splenius muscles, and the systolic and diastolic blood pressure and heart rate were continuously recorded. Of the twenty-four resultant combinations of helmet weights and centers-of-gravity: (1) 18 combinations were used as the boundary conditions for an empirical mathematical model to predict both forward and lateral neck muscle endurance for any weight-C.G. combination within the boundary conditions; (2) 3 combinations were used to test the assumption of insensitivity to vertical loading; and (3) 3 combinations were used to test the assumption of bilateral symmetric response. Finally, a statistical analysis program was supplied to perform paired T-tests for comparison of different headgear loading configurations. The results indicate that the mathematical model makes reasonable predictions within the boundary conditions. Input data outside the boundary conditions is rejected. The assumption of insensitivity to vertical loading is demonstrated. The assumption of bilateral symmetric response was confirmed for the 1.45 kg. and 2.27 kg. helmet loads. However, this assumption was not confirmed for the 4.09 kg. helmet load. It is concluded that the computer model is valid for midline, vertical and lateral headgear loading within the boundary conditions specified. (This work was supported by U.S. Army contract DAMD17-80-C-0089.)
FOREWORD

Citations of organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

For the protection of human subjects the investigator(s) have adhered to policies of applicable Federal Law 45CFR46.

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INTRODUCTION

This section will outline the objectives of the research and its significance to the U.S. Army. The previous work by the investigators will be reviewed.

OBJECTIVES

The following objectives were addressed during the course of this study:

A. Supplement our current data bank of helmet loading configurations (then at 15 different helmet weight and center-of-gravity combinations) with additional experiments (9 additional helmet weight and center-of-gravity combinations) in order to define the necessary boundary conditions for a realistic mathematical model;

B. Develop an appropriate empirical mathematical model (using the technique of piece-wise linear analysis) to predict both forward and lateral neck muscle endurance for any weight-C.G. configuration within the boundary conditions;

C. Deliver to the U.S. Army, the results of this research in "software" package form that is (1) conveniently formatted, (2) easily accessible, and (3) readily interpretable.

SIGNIFICANCE

Our results are directly applicable to several objectives of the U.S. Army Aeromedical Research Laboratory (USAARL). It will provide for systematic understanding of how different headgear designs load the cervical muscles, affect the fatigue end-point, and therefore the subject's ability to tolerate various headgear loading. Consequently, it will enable better (or optimal) helmet design which will minimize both muscle loading and fatigue in the various driving or flying environments, and therefore maximize operational endurance time.

Pilots are currently being asked to wear and use additional headgear. For example, night vision goggles are now being worn in combination with a helmet. An objective evaluation of the cumulative effects of various helmet weights and center-of-gravity combinations on neck muscle tension and fatigue is now needed to establish the optimal "trade off" between headgear requirements and physiological capabilities.

Finally, the U.S. Army continues to design and evaluate new helmets for crew members. Impact protection, noise protection and visual protection (among other parameters) are all capable of objective quantitative evaluation with respect to helmet design. Successful application of this experimental project will yield a system of equations that will allow the designer to input important helmet design parameters (i.e., weight and center-of-gravity), and the equations will output isometric endurance time for the neck muscles in the forward and lateral contraction mode.

BACKGROUND

In our laboratory, support from Army contract DAMD17-80-C-0089, began in June, 1980. The Biomechanics Laboratory at Wright State University has subsequently developed a unique capability to evaluate neck muscle endurance and fatigue as a function of helmet loading. In pursuing our studies for the Army, two unique pieces of equipment were developed. First, an isometric helmet dynamometer was designed. This allows us to quantitate the
strength of neck muscle contractions in the forward, backward and both lateral modes (Phillips and Petrofsky 1981b, 1981c). Furthermore, it allows subjects to hold a "target" tension less than their maximal contraction tension while simultaneously measuring (1) endurance time, (2) neck muscle EMG, and (3) cardiovascular parameters. Second, a variable weight and variable C.G. helmet simulator was developed. This helmet simulator has been calibrated for five weights (1.4 to 4.1 kgs.) and twenty-one center-of-gravity locations (in the X, Y and Z plane). Furthermore, the helmet simulator can be recalibrated for any desired weight and C.G. combination within its design limits. The helmet simulator was validated during the first year of our army contract (Phillips and Petrofsky 1982b), and during our second year (commencing June, 1981), allowed us to observe the effects of fifteen different weight and C.G. combinations on neck muscle endurance and fatigue.

Between June, 1980 and May, 1981 a number of important parameters were evaluated. For the first time, our group determined the basic strength-endurance curves for neck muscle in forward, right-lateral, and backward contraction modes and compared them to the hand-grip muscles in the same subjects (Phillips and Petrofsky 1981a; Petrofsky and Phillips 1982). The research program then investigated the effects of no helmet (CONTROL), a standard SPH-4 helmet (HELMET), and the above helmet combined with Night-Vision-Goggles (NVC) on the cardiovascular responses (Phillips and Petrofsky 1982c), the neck muscle isometric endurance time and EMG response (Phillips and Petrofsky 1982a, 1983a). Finally, the variable center-of-gravity and variable weight helmet simulator (VCGW) was validated against the SPH-4 helmet and Night-Vision-Goggle combination (H/NVC) with respect to neck muscle endurance time and EMG response (Phillips and Petrofsky 1982b). The final contract report has not yet been released for general distribution pending some technical and format revisions (Phillips and Petrofsky 1981d).

Between June 15, 1981 and May 1982, the isometric endurance time, EMG response, cardiovascular response (Phillips and Petrofsky 1983c, 1984b) and strength-recovery response were evaluated as a function of fifteen different helmet stimulator configurations. These represent a combination of three different helmet weights (i.e., 1.4, 2.2, 4.1 kg.) and five different centers-of-gravity (i.e., center-low [CL], center-high [CH], forward-low [FL], rearward-low [RL] and right-lateral-low [RLL], as shown graphically in Figure 1. After analysis of these results, it was concluded that there were optimal C.G. locations for 1.4 and 2.3 kg. (forward-low and right-lateral low) and for 4.1 kg. (aftrward-low) (Phillips and Petrofsky 1983b). The final contract report for this period was submitted in November, 1982, and is still undergoing technical and editorial review by the U.S. Army (Phillips and Petrofsky 1982d).

It can be appreciated that any helmet system (whether current or projected) will have its own unique weight and C.G. location which will rarely fit one of the 15 combinations studied during the second year's work. Furthermore, it would be highly impractical to test the large number of configurations required so that any present or projected helmet system could be closely approximated.

Referring again to Fig. 1, a conventional three-dimensional reference system is shown and those configurations noted which were determined at the conclusion of second-year study (O) and during the first half of the present study (●), see Methods and Materials section. The arrow notation refers
to positive movements about each axis, and numbers beside each C.G. configuration are weights (in pounds).

The additional data points (C) provided the additional boundary conditions necessary to apply piece-wise linear analysis. The resultant equations are capable of predicting the useful operational endurance time as a function of any helmet weight and center-of-gravity combination within the boundary conditions (Phillips and Petrofsky 1984a, 1986).

METHODS AND MATERIALS

This section describes how the study was conducted, including use of subjects. This section also includes a brief description of materials and apparatus used in the study. The fifteen headgear combinations reported for the second year study are combined with the nine headgear combinations evaluated in this final year study (a total of twenty-four headgear combinations). This was done since the objective of the final year study was a mathematical model which required all twenty-four headgear configurations in order to derive the model.

SUBJECTS

Six subjects were used in these experiments. The subjects were male volunteer university students whose ages, heights, neck sizes, and weights are listed in Table 1. All subjects were informed of all experimental procedures and were medically examined including a thorough history and a complete physical exam. All procedures were fully approved by the committee on human experimentation.

TRAINING

All subjects were first trained to produce a maximum voluntary effort and to sustain that effort to fatigue at the tension used in the study and with the various muscle groups examined here. Isometric training consisted of a series of brief (<3 sec.) maximal voluntary contractions (MVC) with an intercontraction interval of 3 minutes. These were followed by a fatiguing isometric contraction. The tension exerted during the fatiguing contraction was set at 70% of the MVC. On any one day, only one direction of contraction was performed and all fatiguing contractions were held at the same percentage of isometric tension. This procedure was repeated on Monday, Wednesday, and Friday of successive weeks until, for any one muscle group (direction), the coefficient of variation (standard deviation divided by the mean) of endurance from day to day was reduced to less than 5%. In practice, the coefficient of variation of strength in these trained subjects was less than 3% from day to day by the end of the training period. Training was conducted at 70% MVC and with both muscle groups examined here. For most subjects, training for any one muscle group averaged about 3 weeks.

ISOMETRIC HEAD DYNAMOMETER

A helmet dynamometer has been developed which can be used to measure the strength and endurance of neck muscles in man in either one of four directions (forward flexion, backward extension, right and left lateral flexion). The dynamometer is based around the army SPH-4 type helmet, but
is easily adaptable to other types of military helmets as well. The dynamometer makes it possible to evaluate the effect of various types of dynamic activities and other flight activities on neck muscle strength and neck muscle endurance. It is, therefore, a useful tool in the study of military helmet design and evaluation of the stress induced by flight maneuvers. The isometric head dynamometer has been described in detail by Petrofsky and Phillips (1982) and is shown in Figures 2, 3 and 4.

HELMET SIMULATOR
The systematic assessment of significant helmet design parameters employed a helmet simulator in which both the weight and center-of-gravity were methodically and controllably altered. Such a helmet was developed by Simula, Inc., under subcontract to Wright State University.

The helmet simulator consists of two weight concealment boxes attached to opposite sides of a support ring (headring) which in turn is supported upon the wearer's head by a suspension system taken from an SFH-4 helmet. The weight and C.G. can be altered by positioning variable weights within the concealment boxes. Fabric covers over the boxes prevent the test subjects from obtaining visual clues as to the C.G. location.

The minimum weight of the helmet simulator, without any variable weights in the boxes, is 2.5 lb., slightly less than the weight of most quality crash helmets made by reputable manufacturers. The addition of variable weights to the boxes can alter the center of gravity to simulate the effect of equipment attached to the outside of a helmet. The helmet simulator has been calibrated for weights of 1.4, 1.8, 2.3, 3.2, and 4.1 kg. for each of the C.G. locations shown in Table 2. Figure 1 illustrates the range of C.G. variations together with definition of the coordinate axes by which the C.G. locations are measured.

As shown in Figure 5, a point midway between the left and right ear canals has been chosen as the origin of the coordinate axes. The helmet simulator is pictured in lateral (Fig. 6), oblique (Fig. 7) and frontal (Fig. 8) views. It has been provided with adjustment to ensure that an index point on it can be aligned with the ear canals, and also with independent adjustment to permit the suspension system to be made comfortable.

Eight headgear centers-of-gravity for three different headgear weights (a total of twenty-four headgear combinations) were evaluated (as per Tables 3 and 4) utilizing the variable center-of-gravity and variable weight helmet simulator. The "essential equivalency" between the variable center-of-gravity and variable weight helmet simulator and selected headgear loading configurations has been reported by Phillips and Petrofsky (1982b).

EXPERIMENTAL PROTOCOL
The experimental protocol may be summarized as follows:

Pre-Exercise MVC
With the subject seated in the helmet dynamometer, the subject would then either perform a brief (3 second) forward MVC (with EMG recorded from the sternocleidomastoid muscle) or a brief (3 second) right lateral MVC (with EMG recorded simultaneously from both the posterior neck muscles and sternocleidomastoid neck muscle). The contraction mode selected, would then be repeated at 3 minute intervals until 3 such contractions were performed.
The strongest contraction (highest strength and highest RMS amplitude of the EMG) would then be taken as the reference contraction.

**Head Loading Configuration and Exercise Duration**

With the subject removed from the isometric head dynamometer, alternating right and left lateral neck rotations were performed while wearing the variable center-of-gravity and variable weight helmet simulator which was set to one of the fifteen headgear combinations. The exercise duration was 30 minutes.

**Post-Exercise Contractions**

Immediately upon completion of the exercise period, the subject repositioned himself in the isometric head dynamometer, and a target tension of 70% of the pre-exercise MVC was sustained (in the direction of the pre-exercise MVC), and held to fatigue. The duration of this was called the endurance time.

The order of presentation of the direction of the pre-exercise MVC, the head loading configuration, and post-exercise contractions selected were all randomized for all of the subjects.

**DEFINITION OF BOUNDARY CONDITIONS**

The limits of displacement along the X- and Y-axes are shown in Figure 9 for the helmet simulator. The purpose of this section is to convert this frame of reference into a rectangular system of an equivalent area. The new X and Y coordinates are the boundary conditions for the computer model.

The area ($T$) of the shaded sections of Figure 9 is calculated as follows:

$$T = (0.5)(0.7)(1.8) + (0.5)(0.7)(1.8) + (2.5)(0.7) + (0.5)(0.7)(1.8) + (0.5)(0.7)(1.8)$$

$$T = 0.63 + 0.63 + 1.75 + 0.63 + 0.63$$

$$T = 4.27 \text{ cm}^2$$

The total area ($T_1$) is the area of A and B plus $T$:

$$T_1 = (4.3 + 1.8)(1.8) + 4.27$$

$$T_1 = 10.98 + 4.27 = 15.25 \text{ cm}^2$$

Next define an incremental $\Delta X$ and $\Delta Y$ such that:

$$(6.1 + 2\Delta X)(1.8 + \Delta Y) = 15.25$$

Simplify by defining:

$$\Delta X \equiv \Delta Y$$

Also, the boundaries are radial arcs, not straight lines, so that $T$ is slightly (12%) larger than previously calculated:

$$T \equiv 4.76 \text{ cm}^2$$

So rewriting:

$$(6.1 + 2\Delta X)(1.8 + \Delta X) \equiv 15.74$$

Expanding:

$$10.98 + 5.1\Delta X + 3.6\Delta X + 2\Delta X = 15.74$$

Rearranging:

$$(\Delta X)^2 + 4.85(\Delta X) - 2.38 = 0$$
Solving the quadratic for $\Delta X$:

$$\Delta x = \frac{-4.85 \pm \sqrt{[(4.85) - (4)(1)(-2.38)]}}{(2)(1)}$$

$$\Delta x = \frac{-4.85 \pm \sqrt{(23.52) + (9.52)}}{(2)}$$

$$\Delta x = \frac{-4.85 \pm 5.75}{2} = 0.45; -5.3$$

Since a negative distance is physically not realistic:

$$\Delta y = \Delta x = 0.45$$

Check:

$$(6.1 + 0.9)(1.8 + 0.45) = 15.75$$

So that the rectangular x-y coordinate system is:

$${x_1}^+ = 4.3 + 0.45 = 4.75 \text{ cm}$$

$${x_1}^- = 1.8 + 0.45 = 2.25 \text{ cm}$$

$${y_1} = 1.8 + 0.45 = 2.25 \text{ cm}$$

which is shown in Figure 10.

**TESTING OF ASSUMPTIONS**

Referring once again to Figure 1, the important physical parameters of the system are: $F$, the load; $M_X$, the moment with respect to the $X$-axis; and $M_Y$, the moment with respect to the $Y$-axis.

Note that at these specific loading points, there is no moment with respect to the $Z$-axis (i.e., they are still parallel to it). That the $Z$-axis is not considered to be physiologically significant is why we chose point CH for our original study. In essence, the origin of the three axes ("0") sees the same $F$, whether at CL or at CH, and (of course) $M_X = M_Y = 0$. This was tested by observing whether forward and lateral contraction endurance times (for the neck muscles) with either the CH or CL configuration were similar (i.e., not statistically significantly different). Furthermore, we tested whether the effects of neck muscle loading were axi-symmetric (physiologically). That endurance times for C.G. displacement along the $-Y$ axis (left side of the head/helmet) were similar to endurance times along the $+Y$ axis (right side of the head/helmet) is why position LLL was selected in our final study. This was tested by observing whether forward and lateral neck muscle contraction endurance times were similar for either the LLL or RLL configuration (i.e., not statistically significantly different).
MATHEMATICAL METHODS

The model utilizes a three-dimensional space defined by the X, Y and F axes (see Fig. 11). The X-axis defines the location of the C.G. forward from the system origin to 4.75 cm anterior. The Y-axis defines the location of the C.G. lateral from the system origin to 2.25 cm right lateral. The F-axis defines the helmet configuration load from 1.45 kg, minimum weight to 4.09 kg, maximum weight.

The boundary conditions of the three-dimensional space are twelve endurance times (E1 to E12), which can be either the forward contraction or lateral contraction endurance time to sustain an isometric neck muscle contraction at 70% of the muscle's MVC. The boundary conditions are specified as Ey,X,F, i.e., the endurance time after 30 minutes of dynamic exercise with a helmet C.G. located y cms along the Y-axis, x cms along the X-axis and a helmet weight of F kgs.

The three-dimensional system consists of eleven element faces (A through L) as shown at the bottom of Figure 11. Each element face requires a set of four subsidiary equations (1 to 4) and three primary equations (5 to 7) to describe the coordinate (E, endurance) point for that face. Face A is shown in Figure 12.

Face A equations are:

A1) \[ E_{AF1} = E + \frac{(F - 2.27)(E - E)}{1.82} \]

A2) \[ E_{AF2} = E + \frac{(F - 2.27)(E - E)}{1.82} \]

A3) \[ E_{AY1} = E + \frac{(Y)(E - E)}{2.25} \]

A4) \[ E_{AY2} = E + \frac{(Y)(E - E)}{2.25} \]

A5) \[ E_{AF} = E + \frac{(Y)(E - E)}{2.25} \]

A6) \[ E_{AY} = E + \frac{(F - 2.27)(E - E)}{1.82} \]

A7) \[ E = \frac{E + E}{AF - 2} \]

Before we proceed to FACES B, C, D, F, G, H, I, J, K, L (in a similar manner), we repeat the process for the standard deviations (SD's).
The boundary conditions for the three dimensional space can also be the twelve standard deviations (SD₁ to SD₁₂) of the mean endurance times described previously. This is shown in Fig. 13 as a system of SD's (S.D. Y, X, F). The same eleven face elements (AA to LL) are present as with the endurance times. Each element face is described by the same set of seven equations. Face AA is shown in Fig. 14.

Face AA equations are:

AA1) \[ SD = SD + \frac{(F - 2.27)(SD - SD)}{1.82} \]

AA2) \[ SD = SD + \frac{(F - 2.27)(SD - SD)}{1.82} \]

AA3) \[ SD = SD + \frac{(Y)(SD - SD)}{2.25} \]

AA4) \[ SD = SD + \frac{(Y)(SD - SD)}{2.25} \]

AA5) \[ SD = SD + \frac{(Y)(SD - SD)}{2.25} \]

AA6) \[ SD = SD + \frac{(F - 2.27)(SD - SD)}{1.82} \]

A6.7) \[ SD = SD + SD \]

We now proceed to FACES B through L, but now computing an SD for each face (i.e., replace E with SD). Results are given in Appendix A.

For any load \( F \) between 2.27 kg. and 4.09 kg., a particular endurance time \( E \) can be interpolated using equations M1 to M4 as shown in Figure 15.

For any load \( F \) between 1.45 kg's. and 2.26 kg's., a particular endurance time \( E \) can be interpolated using equations M5 to M8 as shown in Figure 16.

Also recall since we have computed the SD's for each of the 11 faces:

M6.1) \[ SD = SD + \frac{(X)(SD - SD)}{4.75} \]

M6.2) \[ SD = SD + \frac{(X)(SD - SD)}{2.25} \]
The other half of the model utilizes a three-dimensional space defined by the -X, Y, and F axes (see Figure 17). The -X axis (or the W-axis) defines the location of the C.G. backward from the system origin to 2.25 cm rearward. The Y-axis and F-axis are as previously defined. The boundary conditions of the three-dimensional space are the four previous endurance times (E1, E3, E4, and E6) and eight more endurance times (E13 to E18).

The three-dimensional system consists of eleven element faces (A and B previously, as well as W to V) as shown at the bottom of Figure 17. Each element face requires the same seven equations to describe the coordinate (E, endurance) point for that face. Note that Faces A and B were previously defined. Equations for Faces W to V are given in Appendix B. A system of SD's (SDy,w,f) can also be defined for face elements (Ww to Vv).

For any load (F) between 2.27 kg. and 4.09 kg., a particular endurance time E can be interpolated using equations W1 to W4 as shown in Figure 18.

For any load (F) between 1.45 kg. and 2.26 kg., a particular endurance time E can be interpolated using equations W5 to W8 as shown in Fig. 19.

Also recall since we have computed the SD's for each of the 11 faces:

WW1) SD = SD + (W) (SD - SD)
     AP A 2.75 P A

WW2) SD = SD + (Y) (SD - SD)
     RN R 2.75 N R

WW3) SD = SD + (F - 2.27) (SD - SD)
     UT U 1.82 T U
We now modify the model to account for specific endurance times associated with forward or lateral contractions. Suppose for E1 through E18, these are the endurance times for forward contractions. Then define:

\[ E = EF \]

and substitute this term in all the preceding equations, i.e., A1 through W8. Suppose now that E1 through E18 represent the respective endurance times for lateral contractions. Then define:

\[ E = EL \]

and substitute in all equations (A1 through W8).

Consequently, all equations (A1 through W8) must be written twice. For example, regarding forward contractions:

A1) \[ EF = EF + (F - 2.27) (EF - EF \) \] to . . .

W8) \[ EF = EF + EF + EF \]

For example, regarding lateral contractions:

A1) \[ EL = EL + (F - 2.27) (EL + EL \) \] to . . .

W8) \[ EL = EL + EL + EL \]
The process can be easily repeated for the respective equations that solve for the standard deviation (SD).

For forward contractions, define:

\[ SD = SF \]

and substitute this term in all the parallel equations (AA1 through WW8).

For lateral contractions, define:

\[ SD = SL \]

and substitute this term in all the parallel equations (AA1 through WW8).

The computer program must be directed to solve for E and SD in one of four quadrants as shown in Figure 20.

This can be done by BASIC statements "IF...THEN..." which process the input data and direct the computer to the correct quadrant (i.e., sets of equations).

**INPUT DATA (Range of Values):**

F (Load): 1.45 kg to 4.09 kg
X (X-Axis): -2.25 cm to 4.75 cm
YIN (Y-Axis): -2.25 cm to 2.25 cm

**DATA PREPROCESSING:**

1. **INPUT DATA** (Range of Values):
   - F (Load): 1.45 kg to 4.09 kg
   - X (X-Axis): -2.25 cm to 4.75 cm
   - YIN (Y-Axis): -2.25 cm to 2.25 cm

2. **DATA ROUTING**
   - This is a series of tests to partition the data in the appropriate quadrant.
   - 100 IF F < 2.27 THEN 300
   - 105 IF X < 0 THEN 500
   - 110 REM: Equations for Quadrant A:
     - A1 - A7, C1 - C7, F1 - F7, H1 - H7,
     - J1 - J7, K1 - K7, M1 - M4;
   - 184 AA1 - AA7, CC1 - CC7, FF1 - FF7,
   - Equations HH1 - HH7, JKL - JKL, KK1 - KK7,
   - MM1 - MM4; (Equations written for EF, EL, SF, SL).
   - 290 GOTO 900
   - 300 IF X < 0 THEN 700
   - 305 REM: Equations for Quadrant B:
     - B1 - B7, D1 - D7, G1 - G7, I1 - I7,
   - 184 K1 - K7, L1 - L7, M5 - M8;
RESULTS

The results are summarized into four categories: the endurance times (and their standard deviations) which represent the boundary conditions, the vertical endurance time, the horizontal endurance time, and the final computer model.

ENDURANCE TIME (BOUNDARY CONDITIONS)

The mean endurance times (and standard deviations) which were experimentally determined and used as the boundary conditions for the mathematical model are presented in Table 5. The stored constants used in the computer program (top of Figure 21), EF1 to EF18 and SF1 to SF18, are those values presented in Table 5A. The other stored constants, EL1 to EL18 and SL1 to SL18, are those values shown in Table 5B. This is summarized in Table 6.

ENDURANCE TIME (VERTICAL)

The endurance times (and standard deviations) for helmet weights of 1.45 kg., 2.27 kg. and 4.09 kg. when the C.G. was center-high (CH) compared to center-low (CL) are presented for forward isometric neck muscle contractions in Table 7A.

The endurance times (and standard deviations) for the same three helmet weights and same two C.G.'s are presented for lateral isometric neck muscle contractions in Table 7B.

For both tables, paired T-tests between the two C.G. locations (for each of the three helmet weights) showed no statistically significant difference.
ENDURANCE TIME (LATERAL)

The endurance times (and standard deviations) for helmet weights of 1.45 kg., 2.27 kg. and 4.07 kg. when the C.G. was left-lateral-low (LLL) compared to right-lateral-low (RLL) are presented for forward isometric neck muscle contractions in Table 8A.

The endurance times (and standard deviations) for the same three helmet weights and same two C.G.'s are presented for lateral isometric neck muscle contractions in Table 8B.

For both tables, paired T-tests between the two C.G. locations were not significantly different at 1.45 kg. and 2.27 kg. of helmet weight. The two C.G. locations were significantly different (p ≤ .05) at the 4.09 kg. helmet weight.

COMPUTER MODEL

The final computer model was constructed utilizing the stored constants EF1 - EF18, SF1 - SF18, EL1 - EL18 and SL1 - SL18 (as per Table 6). EF1 - EF18 were substituted into Eqs. A1 to W8 and EL1 - EL18 were also substituted in Eqs. A1 to W8 as per the Mathematical Methods (see METHODS AND MATERIALS section). SF1 - SF18 and SL1 - SL18 were substituted into Eqs. A1 to WW8. The program is user interactive and a complete listing is given in Appendix III.

The user enters the helmet weight (in kilograms), the X-axis coordinate of the C.G. and the Y-axis coordinate of the C.G. (in centimeters).

The program will then print out:
(a) the mean endurance time of a forward isometric neck muscle contraction (sustained at 70% of the MVC) in seconds;
(b) the standard deviation of (a);
(c) the mean endurance time of a lateral isometric neck muscle contraction (sustained at 70% of the MVC) in seconds;
(d) the standard deviation of (c).

A special significance test program has also been written and is listed in Appendix IV. If a second helmet weight and C.G. combination is also evaluated, the significance test program will test as to whether the first helmet weight and C.G. loading combination is significantly different from the second helmet weight and C.G. loading combination with respect to neck muscle endurance times.

DISCUSSION AND CONCLUSIONS

A computer model of neck muscle endurance and fatigue as a function of helmet loading has been developed. The final model consists of over 700 equations and has been formatted to run on an Apple II+ and/or Apple IIe microcomputer with at least 48K of memory.

Our objective has been to make the model "definitive," but the final model deviates from this desired objective in several respects. An appreciation of those limitations will allow the user to more reasonably interpret results he/she may obtain from the model.
First, the model is valid only over a limited range of weight and C.G. locations. Specifically, helmet weight must be between 1.45 kg (3.2 lbs) and 4.09 kg (9.0 lbs), the X-axis displacement must be between -2.25 cm and 4.75 cm and the Y-axis displacement must be between -2.25 cm and +2.25 cm. Any conditions outside these limits will cause the program to print a "DATA OUT OF BOUNDS" statement.

Second, the model has been defined for a three-dimensional space based upon defined boundary conditions (see Methods and Materials, Mathematical Methods). It assumes that any helmet weight and C.G. location that falls within the three-dimensional space can be linearly interpolated between the various boundary conditions. In reality, the model is "piece-wise linear" between helmet weights of 1.45 kg to 2.26 kg and 2.27 kg to 4.09 kg. It is also "piece-wise" linear for X-axis displacements between -2.25 cm to 0 cm and 0 cm to 4.75 cm. Finally, it is "piece-wise" linear for Y-axis displacements between -2.25 cm to 0 cm and 0 cm to +2.25 cm.

Third, the assumption of insensitivity to vertical loading has been established, but only for the 0,0 X-Y coordinate. This assumption was not tested at any of the other boundary conditions. Furthermore, flight situations in which all G forces are not vertical, GZ (i.e., where there is some lateral loading such as Gx or GY forces) may make the vertical insensitivity assumption invalid.

Fourth, the assumption of axi-symmetry (i.e., data acquired for right sided head loading is also valid for left sided head loading) has only been partially validated. The assumption appears valid for light-to-moderate helmet weights (i.e., 1.45 kg to 2.27 kg) but again was only tested at the 0,0 X-Y coordinate system. This assumption was not tested at any other boundary condition. Furthermore, for heavy helmet weights (4.09 kg) the assumption was not validated. Results predicted by the model for heavier weight helmets with left sided C.G. locations must be viewed with discretion.

Fifth and finally, laboratory based studies which predict isometric neck muscle endurance times (either forward or lateral) as a function of headgear loading cannot be extrapolated to predict "operational mission endurance times" (OMET). OMET's are a complex function of operator workload, heat, noise, vibration, etc.

Therefore, OMET's are multi-factorial problems which do not easily lend themselves to mathematical analysis. It was the inability of our group to translate our laboratory based isometric endurance times into meaningful OMET's that was a major factor in not pursuing this project further. We remain open to suggestions and would be pleased to submit a proposal in this area if warranted.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs.)</th>
<th>Height (cm)</th>
<th>Weight (kg.)</th>
<th>Neck Cir. (cm)</th>
</tr>
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<tbody>
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<td>77</td>
<td>37</td>
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<td>2</td>
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<tr>
<td>5</td>
<td>20</td>
<td>185</td>
<td>70</td>
<td>36</td>
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<tr>
<td>6</td>
<td>19</td>
<td>168</td>
<td>61</td>
<td>36</td>
</tr>
</tbody>
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**TABLE 1. GENERAL CHARACTERISTICS OF THE SUBJECTS**
<table>
<thead>
<tr>
<th>C.G. Location</th>
<th>Description*</th>
<th>Displacement (cm)**</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Central</td>
<td>Maximum Height</td>
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</tr>
<tr>
<td></td>
<td>Medium Height</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Low Height</td>
<td>5.0</td>
</tr>
<tr>
<td>Aftward</td>
<td>Maximum Height</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td>Medium Height</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td>Low Height</td>
<td>-2.5</td>
</tr>
<tr>
<td>Central</td>
<td>Left, Maximum Height</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Left, Medium Height</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Left, Low Height</td>
<td>0</td>
</tr>
<tr>
<td>Central</td>
<td>Right, Maximum Height</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Right, Medium Height</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Right, Low Height</td>
<td>0</td>
</tr>
<tr>
<td>Forward</td>
<td>Left, Maximum Height</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Left, Medium Height</td>
<td>4.3</td>
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<tr>
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<td>Left, Low Height</td>
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</tr>
<tr>
<td>Forward</td>
<td>Right, Maximum Height</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Right, Medium Height</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Right, Low Height</td>
<td>4.3</td>
</tr>
</tbody>
</table>

* C.G. locations for total weights of less than 1.8 kg. may differ from values shown in this table.

** Displacement from head and neck c.g. (axis directions as defined in Figure 1).

TABLE 2. SPECIFIC C.G. LOCATIONS FOR WHICH THE HELMET SIMULATOR IS CALIBRATED
<table>
<thead>
<tr>
<th>C.G.-Weight Description</th>
<th>Weight (kgs)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>(cm)*</th>
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<tbody>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Center-Low-5</td>
<td>2.27</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Center-Low-9</td>
<td>4.09</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>CH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center-High-3</td>
<td>1.45</td>
<td>0</td>
<td>0</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Center-High-5</td>
<td>2.27</td>
<td>0</td>
<td>0</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Center-High-9</td>
<td>4.09</td>
<td>0</td>
<td>0</td>
<td>8.0</td>
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</tr>
<tr>
<td><strong>FL</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Forward-Low-5</td>
<td>2.27</td>
<td>5.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Forward-Low-9</td>
<td>4.09</td>
<td>5.0</td>
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<td></td>
<td></td>
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<td>Lat-Right-Low-3</td>
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<td>-2.5</td>
<td>0</td>
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<tr>
<td>Lat-Right-Low-5</td>
<td>2.27</td>
<td>0</td>
<td>-2.5</td>
<td>0</td>
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</tr>
<tr>
<td>Lat-Right-Low-9</td>
<td>4.09</td>
<td>0</td>
<td>-2.5</td>
<td>0</td>
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</tr>
<tr>
<td><strong>AL</strong></td>
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<tr>
<td>Afterward-Low-3</td>
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<td>Afterward-Low-5</td>
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<tr>
<td>Afterward-Low-9</td>
<td>4.09</td>
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</table>

* Displacement from the head/neck center-of-gravity: axis directions as per Fig. 1, and displacement distances as per Table 2.

**TABLE 3. FIFTEEN HEADGEAR COMBINATIONS ORIGINALLY EVALUATED**
TABLE 4. NINE ADDITIONAL HEADGEAR COMBINATIONS EVALUATED

<table>
<thead>
<tr>
<th></th>
<th>C.G.-Weight</th>
<th>Weight (kgs)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>(cm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FRL</strong></td>
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<tr>
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<tr>
<td>For-Right-Low-5</td>
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<td>4.3</td>
<td>-1.8</td>
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<tr>
<td>For-Right-Low-9</td>
<td>4.09</td>
<td>4.3</td>
<td>-1.8</td>
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</tr>
<tr>
<td><strong>ARL</strong></td>
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</tr>
<tr>
<td>Aft-Right-Low-3</td>
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* Same as footnote (Table 3.)
### A. Forward Contractions

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<tbody>
<tr>
<td></td>
<td>1.45 kg</td>
<td>2.27 kg</td>
<td>4.09 kg</td>
</tr>
<tr>
<td>*C.G.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRL</td>
<td>49 ± 19</td>
<td>37 ± 10</td>
<td>41 ± 9</td>
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<tr>
<td>FL</td>
<td>86 ± 49</td>
<td>65 ± 26</td>
<td>56 ± 24</td>
</tr>
<tr>
<td>LRL</td>
<td>75 ± 57</td>
<td>66 ± 21</td>
<td>96 ± 61</td>
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<tr>
<td>CL</td>
<td>98 ± 34</td>
<td>74 ± 43</td>
<td>68 ± 34</td>
</tr>
<tr>
<td>ARL</td>
<td>43 ± 12</td>
<td>46 ± 16</td>
<td>45 ± 13</td>
</tr>
<tr>
<td>AL</td>
<td>86 ± 34</td>
<td>64 ± 19</td>
<td>83 ± 20</td>
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### B. Lateral Contractions

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<tr>
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<td>1.45 kg</td>
<td>2.27 kg</td>
<td>4.09 kg</td>
</tr>
<tr>
<td>*C.G.</td>
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<tr>
<td>FRL</td>
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<td>72 ± 40</td>
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<td>106 ± 88</td>
<td>83 ± 33</td>
<td>86 ± 38</td>
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<tr>
<td>ARL</td>
<td>82 ± 31</td>
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<tr>
<td>AL</td>
<td>91 ± 38</td>
<td>73 ± 47</td>
<td>129 ± 69</td>
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* See "CC-Weight Description" Column (Table 3).

**TABLE 5. ENDURANCE TIME: BOUNDARY CONDITIONS (Secs)**
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<th>VALUE</th>
<th>CONSTANT</th>
<th>VALUE</th>
<th>CONSTANT</th>
<th>VALUE</th>
<th>CONSTANT</th>
<th>VALUE</th>
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</thead>
<tbody>
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<td>SF₁</td>
<td>34</td>
<td>EL₁</td>
<td>106</td>
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<td>SF₂</td>
<td>43</td>
<td>EL₂</td>
<td>83</td>
<td>SL₂</td>
<td>33</td>
</tr>
<tr>
<td>EF₃</td>
<td>68</td>
<td>SF₃</td>
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**TABLE 6. IDENTIFICATION OF STORED CONSTANTS**
### A. Forward Contractions

<table>
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<tr>
<th>Wt.</th>
<th>1.45 kg.</th>
<th>2.27 kg.</th>
<th>4.09 kg.</th>
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<td><em>C.G.</em></td>
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<td></td>
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<tr>
<td>CH</td>
<td>71 ± 49</td>
<td>82 ± 59</td>
<td>71 ± 55</td>
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<tr>
<td>CL</td>
<td>98 ± 34</td>
<td>74 ± 43</td>
<td>68 ± 34</td>
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</tbody>
</table>

p-level | N.S. | N.S. | N.S. |

* See footnote (Table 5).

### B. Lateral Contractions

<table>
<thead>
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<th>1.45 kg.</th>
<th>2.27 kg.</th>
<th>4.09 kg.</th>
</tr>
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<td><em>C.G.</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>82 ± 56</td>
<td>72 ± 35</td>
<td>61 ± 39</td>
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<tr>
<td>CL</td>
<td>106 ± 88</td>
<td>83 ± 33</td>
<td>86 ± 38</td>
</tr>
</tbody>
</table>

p-level | N.S. | N.S. | N.S. |

* See footnote (Table 5).
## A. Forward Contractions

<table>
<thead>
<tr>
<th>Wt.</th>
<th>1.45 kg</th>
<th>2.27 kg</th>
<th>4.09 kg</th>
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<td>*C.G.</td>
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<tr>
<td>LLL</td>
<td>46 ± 18</td>
<td>47 ± 19</td>
<td>43 ± 10</td>
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<tr>
<td>RLL</td>
<td>75 ± 57</td>
<td>66 ± 21</td>
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<td>N.S.</td>
<td>p ≤ .05</td>
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## B. Lateral Contractions

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<th>4.09 kg</th>
</tr>
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<tr>
<td>LLL</td>
<td>108 ± 50</td>
<td>110 ± 27</td>
<td>116 ± 35</td>
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<tr>
<td>RLL</td>
<td>156 ± 59</td>
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<td>72 ± 40</td>
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<td>p-level</td>
<td>N.S.</td>
<td>N.S.</td>
<td>p ≤ .05</td>
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</tbody>
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* See footnote (Table 7).

### Table 8. Endurance Time: Lateral (Secs)

29
FIGURE 1. THE EIGHT C.G. LOCATIONS EVALUATED AT EACH OF THREE WEIGHTS
FIGURE 2. SCHEMATIC DIAGRAM OF THE HDRD DYNAMOMETER
FIGURE 3. SUBJECT USING THE HEAD DYNAMOMETER: FRONTAL VIEW
FIGURE 4. SUBJECT USING THE HEAD DYNAMOMETER: LATERAL VIEW
FIGURE 5. COORDINATE SYSTEM FOR THE HELMET SIMULATOR
FIGURE 6. HELMET SIMULATOR: LATERAL VIEW
FIGURE 7. HELMET SIMULATOR: OBLIQUE VIEW
FIGURE 8. SUBJECT USING THE HELMET SIMULATOR: FRONTAL VIEW
New Coordinate System
(See Fig. 10)

T = Cross-Hatched Area
FIGURE 10. THE SIMPLIFIED HELMET SIMULATOR COORDINATE SYSTEM
Three Dimensional System: \((E_y, x, f)\)

Simplified: (see also SD's)

FIGURE 11. THE THREE DIMENSIONAL SPACE SYSTEM \((E_y, x, f)\)
FIGURE 12. FACE "A" ELEMENT

Face A:

```
EAF1
E2
E3
EAY1

EAY2
EAF2
E6
E5
```
Three Dimensional System (SD's): $SD_{y,x,f}$

FIGURE 13. THE THREE DIMENSIONAL SPACE SYSTEM ($SD_{y,x,f}$)
FIGURE 14. FACE "AA" ELEMENT
For $F = 2.27$ to $4.09$ Kg

\[ M1) \quad E_{AF} = E_A + \left( \frac{x}{4.75} \right) (E_F - E_A) \]

\[ M2) \quad E_{CH} = E_C + \left( \frac{y}{2.25} \right) (E_H - E_C) \]

\[ M3) \quad E_{KJ} = E_K + \left( \frac{F - 2.27}{1.82} \right) (E_J - E_K) \]

\[ M4) \quad E = \frac{E_{AF} + E_{CH} + E_{KJ}}{3} \]
For $F = 1.45$ to $2.26$ Kg

\[ M5) \quad E_{BG} = E_B + \left( \frac{x}{4.75} \right) (E_G - E_B) \]

\[ M6) \quad E_{DL} = E_D + \left( \frac{y}{2.25} \right) (E_I - E_D) \]

\[ M7) \quad E_{LK} = E_L + \left( \frac{F - 1.45}{0.82} \right) (E_K - E_L) \]

\[ M8) \quad E = \frac{E_{BG} + E_{DL} + E_{LK}}{3} \]

**FIGURE 16. QUADRANT 'B' SPACE SYSTEM AND EQUATIONS**
Three Dimensional System: (E_y,w,f)

In this system  \( w = -x \)

Simplified:

FIGURE 17. THE THREE DIMENSIONAL SPACE SYSTEM (E_y,w,f)
For $F = 2.27$ to $4.09$ Kg

\[ W1) \quad E_{AP} = E_A + \left( \frac{W}{2.25} \right) (E_P - E_A) \]

\[ W2) \quad E_{RN} = E_R + \left( \frac{y}{2.25} \right) (E_N - E_R) \]

\[ W3) \quad E_{UT} = E_U + \left( \frac{F}{1.82} \right) (E_T - E_U) \]

\[ W4) \quad E = \frac{E_{AP} + E_{RN} + E_{UT}}{3} \]

FIGURE 18. QUADRANT 'C' SPACE SYSTEM AND EQUATIONS
For $F=1.45$ to $2.26$ Kg

\[ W5) \quad E_{BQ} = E_B + \left( \frac{W}{2.25} \right) (E_Q - E_B) \]

\[ W6) \quad E_{SO} = E_S + \left( \frac{y}{2.25} \right) (E_O - E_S) \]

\[ W7) \quad E_{VU} = E_V + \left( \frac{F-1.45}{0.82} \right) (E_U - E_V) \]

\[ W8) \quad E = \frac{E_{BQ} + E_{SO} + E_{VU}}{3} \]

**FIGURE 19. QUADRANT 'D' SPACE SYSTEM AND EQUATIONS**
FIGURE 20. SUMMARY OF THE FOUR QUADRANT SYSTEM
FIGURE 21. FLOW DIAGRAM OF THE COMPUTER PROGRAM
REFERENCES CITED


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APPENDIX A

SUBSIDIARY EQUATIONS (FACE ELEMENTS B-L)

Face B:

\[ E_{B1} = E + \left( F - 1.45 \right) \left( E - E_{BF1} \right) \]
\[ E_{B2} = E + \left( F - 1.45 \right) \left( E - E_{BF2} \right) \]
\[ E_{BY1} = E + \left( \frac{Y}{2.25} \right) \left( E - E_{BY1} \right) \]
\[ E_{BY2} = E + \left( \frac{Y}{2.25} \right) \left( E - E_{BY2} \right) \]
\[ E_{BF} = \frac{E}{BF} + \left( \frac{Y}{7.25} \right) \left( E - E_{BF1} \right) \]
\[ E_{BY} = \frac{E}{BY} + \left( \frac{F - 1.45}{0.82} \right) \left( E - E_{BY1} \right) \]
\[ E_{B} = \frac{E}{B} + \frac{E}{BF} \]

A-1
C1) \( E_{CF1} = \frac{E}{2} + \left( \frac{F - 2.27}{1.82} \right) (E - E_3) \)

C2) \( E_{CF2} = E_{11} + \left( \frac{F - 2.27}{1.82} \right) (E - E_{12}) \)

C3) \( E_{CX1} = E + \left( \frac{X}{4.75} \right) (E - E_{11}) \)

C4) \( E_{CX2} = E + \left( \frac{Y}{4.75} \right) (E - E_{12}) \)

C5) \( E_{CF} = \frac{E_{CF1}}{4.75} + \left( \frac{X}{4.75} \right) (E_{CF2} - E_{CF1}) \)

C6) \( E_{CX} = E_{CX1} + \left( \frac{F - 2.27}{1.82} \right) (E_{CX2} - E_{CX1}) \)

C7) \( E = \frac{E + E_{CF}}{2} \)
Face D:

\[
\begin{align*}
D1) \quad E_{DF1} &= E_1 \left[ 1 + \frac{F - 1.45}{0.82} \right] (E_2 - E_1) \\
D2) \quad E_{DF2} &= E_1 \left[ 10 + \frac{F - 1.45}{0.82} \right] (E_11 - E_10) \\
D3) \quad E_{DX1} &= E_1 \left[ 1 + \frac{F}{4.75} \right] (E_10 - E_1) \\
D4) \quad E_{DX2} &= E_2 \left[ 1 + \frac{F}{4.75} \right] (E_11 - E_2) \\
D5) \quad E_{DF} &= E_{DF1} \left[ 1 + \frac{F}{4.75} \right] (E_{DF2} - E_{DF1}) \\
D6) \quad E_{DX} &= E_{DX1} \left[ 1 + \frac{F - 1.45}{0.82} \right] (E_{DX2} - E_{DX1}) \\
D7) \quad E_{D} &= E_{DF} + E_{DX}
\end{align*}
\]
Face F:

\[
\begin{align*}
F1) \quad E_{FF1} &= E_{11} + \frac{(F - 2.27)}{1.82} (E_{12} - E_{11}) \\
F2) \quad E_{FF2} &= E_{8} + \frac{(F - 2.27)}{1.82} (E_{9} - E_{8}) \\
F3) \quad E_{FY1} &= E_{11} + \frac{(Y_{11})}{2.25} (E_{12} - E_{11}) \\
F4) \quad E_{FY2} &= E_{12} + \frac{(Y_{12})}{2.25} (E_{9} - E_{12}) \\
F5) \quad E_{FF} &= E_{FF1} + \frac{(Y_{FF1})}{2.25} (E_{FF2} - E_{FF1}) \\
F6) \quad E_{FY} &= E_{FY1} + \frac{(F - 2.27)}{1.82} (E_{FY2} - E_{FY1}) \\
F7) \quad E_{FF} &= E_{FF} + \frac{E_{FF}}{2} E_{FY}
\end{align*}
\]
Face G:

G1) \[ E \times GF1 \times 10 \times 0.82 \times (E + E) \]

G2) \[ E \times GF2 \times 7 \times 0.82 \times (E + E) \]

G3) \[ E \times GY1 \times 1C \times 2.25 \times (E + E) \]

G4) \[ E \times GY2 \times 11 \times 2.25 \times (E + E) \]

G5) \[ E \times GF \times GF1 \times 2.25 \times GF2 \times GF1 \]

G6) \[ E \times GY \times GY1 \times 0.82 \times GY2 \times GY1 \]

G7) \[ E \times GF \times GY \times 2 \times GY \]

A-5
H1) $E_{HF1} = E + (E - 2.27) \times (E_{HF1} - E_{HF2})$

H2) $E_{HF2} = E + (E - 2.27) \times (E_{HF2} - E_{HF1})$

H3) $E_{HX1} = E + (E - 2.27) \times (E_{HX1} - E_{HX2})$

H4) $E_{HX2} = E + (E - 2.27) \times (E_{HX2} - E_{HX1})$

H5) $E_{HF} = E + (E - 2.27) \times (E_{HF} - E_{HF1})$

H6) $E_{HX} = E + (E - 2.27) \times (E_{HX} - E_{HX1})$

H7) $E_{HF} = E + E_{HF1}$
Face 1:

I1) $E_{IF1} = E + \left( \frac{F + 1.45}{0.82} \right) (E - E_{5})$

I2) $E_{IF2} = E + \left( \frac{F + 1.45}{0.82} \right) (E - E_{7})$

I3) $E_{IX1} = E + \left( \frac{K}{4.75} \right) (E - E_{7})$

I4) $E_{IX2} = E + \left( \frac{K}{4.75} \right) (E - E_{8})$

I5) $E_{IF} = E_{IF1} + \left( \frac{K}{4.75} \right) (E_{IF2} - E_{IF1})$

I6) $E_{IX} = E_{IX1} + \left( \frac{F + 1.45}{0.82} \right) (E_{IX2} - E_{IX1})$

I7) $E_{I} = E + E_{IF} + E_{IX}$
Face J:

\[ E_{JY1} = E_{3} \cdot \frac{X}{2.25} \cdot (E - E_{6}) \]

\[ E_{JY2} = E_{12} \cdot \frac{X}{2.25} \cdot (E - E_{9}) \]

\[ E_{JX1} = E_{3} \cdot \frac{X}{4.75} \cdot (E - E_{12}) \]

\[ E_{JX2} = E_{6} \cdot \frac{X}{4.75} \cdot (E - E_{9}) \]

\[ E_{Y} = E_{JY1} + E_{JY2} \]

\[ E_{X} = E_{JX1} + E_{JX2} \]

\[ J = \frac{E_{Y} + E_{X}}{2} \]
Face K:

K1) \[ E_{KY1} = E + \left( \frac{y}{2.25} \right) (E - E) \]

K2) \[ E_{KY2} = E + \left( \frac{y}{2.25} \right) (E - E) \]

K3) \[ E_{KX1} = E + \left( \frac{x}{4.75} \right) (E - E) \]

K4) \[ E_{KX2} = E + \left( \frac{x}{4.75} \right) (E - E) \]

K5) \[ E_{KY} = E + \left( \frac{x}{4.75} \right) (E_{KY1} - E) \]

K6) \[ E_{KX} = E + \left( \frac{x}{2.25} \right) (E_{KX1} - E) \]

K7) \[ E_{K} = E + E \]
Face L:

\[ L_1 \) \( E_{LY1} = E_1 + \left( \frac{Y_{LY1}}{2.25} \right) (E - E_1) \]

\[ L_2 \) \( E_{LY2} = E_{10} + \left( \frac{Y_{LY2}}{7} \right) \left( E - E_{10} \right) \]

\[ L_3 \) \( E_{LX1} = E_1 + \left( \frac{X_{LX1}}{4.75} \right) \left( E - E_1 \right) \]

\[ L_4 \) \( E_{LX2} = E_{4} + \left( \frac{X_{LX2}}{7} \right) \left( E - E_{4} \right) \]

\[ L_5 \) \( E_{LY} = E_{LY1} + \left( \frac{X_{LY1}}{4.75} \right) \left( E_{LY2} - E_{LY1} \right) \]

\[ L_6 \) \( E_{LX} = E_{LX1} + \left( \frac{X_{LX1}}{2.25} \right) \left( E_{LX2} - E_{LX1} \right) \]

\[ L_7 \) \( E_L = E_{LY} + \frac{E_{LX}}{2} \]
APPENDIX B

SUBSIDIARY EQUATIONS (FACE ELEMENTS N-V)

Face N:

\[ E_6 = E_1 + (F - 2.27) (E - E_{NW2}) \]
\[ \text{W1) } E_{NF1} \]
\[ E_5 = E_1 + (F - 2.27) (E - E_{NW1}) \]
\[ \text{W2) } E_{NF2} \]
\[ E_{NW1} = E_1 + (W_{NW1}) (E - E_{NW2}) \]
\[ \text{W3) } E_{NW2} \]
\[ E_{NW1} = E_1 + (W_{NW1}) (E - E_{NW2}) \]
\[ \text{W4) } E_{NW2} \]
\[ E_{NW1} = E_1 + (W_{NW1}) (E - E_{NW2}) \]
\[ \text{W5) } E_{NW2} \]
\[ E = E_1 + (F - 2.27) (E - E_{NW1}) \]
\[ \text{W6) } E_{NW2} \]
\[ E = E_1 + (W_{NW1}) (E - E_{NW2}) \]
\[ \text{W7) } E_{NW2} \]
Face O:

01) \[ E_{OF1} = E + \frac{(F - 1.45)}{0.82} (E - \bar{E}) \]

02) \[ E_{OF2} = E + \frac{(F - 1.45)}{0.82} (E - \bar{E}) \]

03) \[ E_{OW1} = E + \frac{(W)}{2.25} (E - \bar{E}) \]

04) \[ E_{OW2} = E + \frac{(W)}{2.25} (E - \bar{E}) \]

05) \[ E = \frac{(W)}{2.25} (E_{OF1} - \bar{E}) \]

06) \[ E = \frac{(W)}{2.25} (E_{OF2} - \bar{E}) \]

07) \[ E = \frac{(W)}{2.25} (E_{OW1} - \bar{E}) \]

08) \[ E = \frac{(W)}{2.25} (E_{OW2} - \bar{E}) \]

E - 2
Face P:
P1) \[ E_{PF1} = E_{17} + \frac{(F - 2.27)}{1.82} (E_{18} - E_{17}) \]
P2) \[ E_{PF2} = E_{14} + \frac{(F - 2.27)}{1.82} (E_{15} - E_{14}) \]
P3) \[ E_{PY1} = E_{17} + \frac{(Y - 2)}{2.25} (E_{18} - E_{17}) \]
P4) \[ E_{PY2} = E_{18} + \frac{(Y - 2)}{2.25} (E_{16} - E_{18}) \]
P5) \[ E_{PF} = E_{PF1} + \frac{(Y - 2)}{2.25} (E_{PF2} - E_{PF1}) \]
P6) \[ E_{PY} = E_{PY1} + \frac{(F - 2.27)}{1.82} (E_{PY2} - E_{PY1}) \]
P7) \[ E_P = \frac{E_{PF} + E_{PY}}{2} \]
Face Q:

Q1) \[ E_{QF1} = E + (F - 1.45) \left( \frac{E_{17} - E_{16}}{0.82} \right) \]

Q2) \[ E_{QF2} = E + (F - 1.45) \left( \frac{E_{14} - E_{13}}{0.82} \right) \]

Q3) \[ E_{QY1} = E + \left( \frac{Y}{2.25} \right) \left( E_{16} - E_{13} \right) \]

Q4) \[ E_{QY2} = E + \left( \frac{Y}{2.25} \right) \left( E_{14} - E_{17} \right) \]

Q5) \[ E = E_{QF1} + \left( \frac{Y}{2.25} \right) \left( E_{QF2} - E_{QF1} \right) \]

Q6) \[ E = E_{QY1} + (F - 1.45) \left( \frac{E_{QY2} - E_{QY1}}{0.82} \right) \]

Q7) \[ E = E_{QF2} + E_{QY} \]
Face R:

\[ R1) E_{RF1} = E + \left( \frac{F - 2.27}{1.82} \right) \left( \frac{E_3 - E_2}{3} \right) \]

\[ R2) E_{RF2} = E + \left( \frac{F - 2.27}{1.82} \right) \left( \frac{E_{18} - E_{17}}{18} \right) \]

\[ R3) E_{RW1} = E + \left( \frac{W}{2.25} \right) \left( \frac{E_{17} - E_2}{17} \right) \]

\[ R4) E_{RW2} = E + \left( \frac{W}{2.25} \right) \left( \frac{E_{18} - E_3}{18} \right) \]

\[ R5) E_{RF} = E + \frac{W_{RF1}}{2.25} \left( \frac{E_{RF2} - E_{RF1}}{RF1} \right) \]

\[ R6) E_{RW} = E + \left( \frac{F - 2.27}{1.82} \right) \left( \frac{E_{RW1} - E_{RW2}}{RW1} \right) \]

\[ R7) E = \frac{E}{2} + \frac{E_{RF}}{RW} \]
Face S:

S1) \[ E_{SF1} = E + \frac{(F - 1.45)(E - E)}{0.82} \]

S2) \[ E_{SF2} = E + \frac{(F - 1.45)(E - E)}{0.82} \]

S3) \[ E_{SW1} = E + (W)(E - E) \]

S4) \[ E_{SW2} = E + (W)(E - E) \]

S5) \[ E_{SF} = E + (W)(E - E) \]

S6) \[ E_{SW} = E + \frac{(F - 2.27)(E - E)}{1.82} \]

S7) \[ E_S = E \]

B-6
Face T:

1) \[ E_{TY1} = \frac{e}{3} + \frac{y}{2.25} \left( E - E_3 \right) \]

2) \[ E_{TY2} = \frac{e}{1} + \frac{y}{2.25} \left( E - E_18 \right) \]

3) \[ E_{TW1} = \frac{e}{3} + \frac{y}{2.25} \left( E - E_15 \right) \]

4) \[ E_{TW2} = \frac{e}{6} + \frac{y}{2.25} \left( E - E_6 \right) \]

5) \[ E_{TY} = \frac{e}{TY_{TY1}} + \frac{y}{2.25} \left( E - E_{TY1} \right) \]

6) \[ E_{TW} = \frac{e}{TW_{TW1}} + \frac{y}{2.25} \left( E - E_{TW1} \right) \]

7) \[ E_T = \frac{e}{TY_{TY2}} + \frac{y}{2.25} \left( E - E_{TW1} \right) \]

B-7
**Face U:**

1. \( E_{U1} = E_{U0} + \frac{2}{2.25} (E_{U2} - E_{U1}) \)
2. \( E_{U2} = E_{U1} + \frac{17}{2.25} (E_{U2} - E_{U2}) \)
3. \( E_{U3} = E_{U0} + \frac{17}{2.25} (E_{U3} - E_{U0}) \)
4. \( E_{U4} = E_{U0} + \frac{5}{2.25} (E_{U4} - E_{U0}) \)
5. \( E_{U5} = E_{U1} + \frac{2.25}{U_{U2} - U_{U1}} \)
6. \( E_{U6} = E_{U0} + \frac{2.25}{U_{U2} - U_{U0}} \)
7. \( E_{U7} = E_{U0} + \frac{2}{U_{U0} - U_{U0}} \)
\textbf{Face V:}

\begin{align*}
\text{V1)} & \quad E_{\text{VY1}} = E + \left( \frac{y_{\text{VY}}}{1} \right) \left( E - E_{\text{VY1}} \right) \\
\text{V2)} & \quad E_{\text{VY2}} = E + \left( \frac{y_{\text{VY}}}{16} \right) \left( E - E_{\text{VY2}} \right) \\
\text{V3)} & \quad E_{\text{VW1}} = E + \left( \frac{w_{\text{VW}}}{2.25} \right) \left( E - E_{\text{VW1}} \right) \\
\text{V4)} & \quad E_{\text{VW2}} = E + \left( \frac{w_{\text{VW}}}{4} \right) \left( E - E_{\text{VW2}} \right) \\
\text{V5)} & \quad E_{\text{VY}} = E + \left( \frac{y_{\text{VY}}}{2.25} \right) \left( E_{\text{VY1}} - E_{\text{VY2}} \right) \\
\text{V6)} & \quad E_{\text{VW}} = E + \left( \frac{w_{\text{VW}}}{2.25} \right) \left( E_{\text{VW1}} - E_{\text{VW2}} \right) \\
\text{V7)} & \quad E = E + \frac{E_{\text{VY}} + E_{\text{VW}}}{2}
\end{align*}
APPENDIX C

COMPUTER LISTING (MUSCLE FATIGUE PROGRAM)

25 HOME
30 PRINT "MATH MODEL OF NECK MUSCLE FATIGUE"
32 FOR PAUSE = 1 TO 1500: NEXT PAUSE
35 REM I.E.P. & L.A.F. 6-FEB-84
50 REM STORED CONSTANTS: ENDURANCE TIMES & STANDARD DEVIATIONS
60 REM EA-ER=FWD MEAN; XA-XR=LATERAL MEAN; YA-YR=FWD STD.; ZA-ZR=LATERAL STD.

70 EA = 98.25: EB = 74.40: EC = 67.60: ED = 75.40
75 EE = 65.60: EF = 48.80: EH = 37.40
80 EI = 41.40: EJ = 34.66: EL = 55.83
85 EM = 43.20: EN = 46.20: EP = 45.00: EF = 85.60
90 ED = 64.20: ER = 87.25: EA = 106.30: EB = 83.00
95 XC = 86.00: XD = 155.80: EX = 81.00: EF = 71.60
100 XG = 105.20: XH = 102.20: XI = 122.70: XJ = 148.64
105 XH = 89.33: XL = 61.83: XM = 81.80: XN = 98.80
110 XQ = 93.80: XP = 91.20: XR = 75.40: XA = 120.60
115 YA = 34.29: YB = 47.16: YC = 33.97: YD = 56.84
120 YE = 20.94: YF = 61.28: YG = 18.67: YH = 9.91
125 YI = 8.87: YJ = 48.64: YK = 26.29: YL = 23.84
130 YL = 11.56: YM = 15.79: YQ = 13.39: YR = 33.65
135 YQ = 19.43: YR = 20.33: YS = 88.46: YT = 35.10
140 ZC = 33.19: ZD = 58.89: ZE = 40.12: ZF = 39.63
145 ZF = 24.81: ZG = 26.41: ZH = 48.66: ZI = 52.56
150 ZI = 42.32: ZJ = 35.47: ZK = 50.77: ZL = 42.21
155 ZL = 20.79: ZM = 37.85: ZN = 46.64: ZO = 69.01
159 HOME
160 INPUT "ENTER HELMET WEIGHT FROM 1.45 TO 4.09 KG. ";F: PFINT
170 INPUT "ENTER DISPLACEMENT ON X-AXIS FROM -2.25 CM. TO 4.75 CM. ";X: PXINT

180 INPUT "ENTER DISPLACEMENT ON Y-AXIS FROM -2.25 CM. TO 2.25 CM. ";Y: PYINT
190 Y = ABS(Y)
195 REM DATA OUT-OF-BOUNDS?
200 IF F < 1.45 GOTO 4000

C-1
210 IF F ) 4.09 GOTO 4000
220 IF Y ) 2.25 GOTO 4000
230 IF X . 4.75 GOTO 4000
240 IF X < - 2.25 GOTO 4000
245 REM DATA ROUTING
250 IF F < 2.27 GOTO 2450
260 IF X < - 4.75 GOTO 245
265 REM EQUATIONS FOR QUADRANT A
270 A1 = EB + (((F - 2.27) / 1.82) * (EC - EB))
272 A2 = EE + (((F - 2.27) / 1.82) * (EF - EE))
274 A3 = EB + (((Y / 2.25) * (EE - EB))
276 A4 = EC + (((Y / 2.25) * (EF - EC))
280 A6 = A3 + (((F - 2.27) / 1.82) * (A4 - A3))
282 A7 = ((A5 + A6) / 2)
284 C1 = EB + (((F - 2.27) / 1.82) * (EC - EB))
286 C2 = EC + (((F - 2.27) / 1.82) * (EL - EC))
288 C3 = EB + (((Y / 4.75) * (EK - EB))
290 C4 = EC + (((Y / 4.75) * (EL - EC))
292 C5 = C1 + (((Y / 4.75) * (C2 - C1))
294 C6 = C3 + (((F - 2.27) / 1.82) * (C4 - C3))
296 C7 = ((C5 + C6) / 2)
298 F1 = EC + (((F - 2.27) / 1.82) * (EL - EC))
300 F2 = EH + (((F - 2.27) / 1.82) * (E1 - EH))
302 F3 = EC + (((Y / 2.25) * (EH - EC))
304 F4 = EL + (((Y / 2.25) * (EI - EL))
306 F5 = F1 + (((Y / 2.25) * (F2 - F1))
308 F6 = F3 + (((F - 2.27) / 1.82) * (F4 - F3))
310 F7 = ((F3 + F6) / 2)
312 H1 = EE + (((F - 2.27) / 1.82) * (EF - EE))
314 H2 = EH + (((F - 2.27) / 1.82) * (E1 - EH))
316 H3 = EE + (((Y / 4.75) * (EH - EE))
318 H4 = EF + (((Y / 4.75) * (EI - EF))
320 H5 = H1 + (((Y / 4.75) * (H2 - H1))
322 H6 = H3 + (((F - 2.27) / 1.82) * (H4 - H3))
324 H7 = ((H5 + H6) / 2)
326 J1 = EC + (((Y / 2.25) * (EF - EC))
328 J2 = EL + (((Y / 2.25) * (EI - EL))
330 J3 = EC + (((Y / 4.75) * (EL - EC))
332 J4 = EF + (((Y / 4.75) * (EI - EF))
334 J5 = J1 + (((Y / 4.75) * (J2 - J1))
336 J6 = J3 + (((Y / 2.25) * (J4 - J3))
338 J7 = ((J5 + J6) / 2)
340 K1 = EB + (((Y / 2.25) * (EE - EB))
342 K2 = EC + (((Y / 2.25) * (EH - EC))
344 K3 = EB + (((Y / 4.75) * (EH - EB))
346 K4 = EE + (((Y / 4.75) * (EH - EE))
348 K5 = K1 + (((Y / 4.75) * (K2 - K1))
350 K6 = K3 + (((Y / 2.25) * (K4 - K3))
352 K7 = ((K5 + K6) / 2)
354 M1 = A7 + (((Y / 4.75) * (F7 - A7))
356 M2 = C7 + (((Y / 2.25) * (H7 - C7))
358 M3 = K7 + (((Y - 2.27) / 1.82) + (J7 - K7))
360 M4 = ((M1 + M2 + M3) / 3)
362 AA = XB + (((F - 2.27) / 1.82) * (XH - XB))
364 AB = XE + (((F - 2.27) / 1.82) * (XH - XE))
366 AC = XB + (((Y / 2.25) * (XH - XB))
368 AD = XC + (((Y / 2.25) * (XH - XC))
370 AE = AA + (((Y / 2.25) * (AB - AA))
372 AF = AC + (((F - 2.27) / 1.82) * (AD - AC))
374 AG = ((AE + AF) / 2)
376 CA = XB + (((F - 2.27) / 1.82) * (XH - XB))
378 CB = XF + (((F - 2.27) / 1.82) * (XL - XF))
380 CC = XB + (((Y / 4.75) * (XL - XB))
382 CD = XC + (((Y / 4.75) * (XL - XC))
384 CE = CA + (((Y / 4.75) * (CB - CA))
<table>
<thead>
<tr>
<th>IF X &lt; 0</th>
<th>EQUATIONS FOR QUADRANT B</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 = EA + ((F - 1.45) / .82) * (EB - EA)</td>
<td></td>
</tr>
<tr>
<td>B2 = ED + ((F - 1.45) / .82) * (EE - ED)</td>
<td></td>
</tr>
<tr>
<td>B3 = EA + ((Y / 2.25) * (ED - EA))</td>
<td></td>
</tr>
<tr>
<td>B4 = EB + ((Y / 2.25) * (EE - EB))</td>
<td></td>
</tr>
<tr>
<td>B5 = B1 + ((Y / 2.25) * (B2 - B1))</td>
<td></td>
</tr>
<tr>
<td>B6 = B3 + ((F - 1.45) / .82) * (B4 - B3)</td>
<td></td>
</tr>
<tr>
<td>B7 = (B5 + B6) / 2</td>
<td></td>
</tr>
<tr>
<td>B8 = EA + ((F - 1.45) / .82) * (EB - EA)</td>
<td></td>
</tr>
<tr>
<td>D2 = EJ + ((F - 1.45) / .82) * (EK - EJ)</td>
<td></td>
</tr>
<tr>
<td>D3 = EA + ((Y / 4.75) * (EJ - EA))</td>
<td></td>
</tr>
<tr>
<td>D4 = EB + ((Y / 4.75) * (EK - EB))</td>
<td></td>
</tr>
<tr>
<td>D5 = D1 + ((Y / 4.75) * (D2 - D1))</td>
<td></td>
</tr>
<tr>
<td>D6 = D3 + ((F - 1.45) / .82) * (D4 - D3)</td>
<td></td>
</tr>
<tr>
<td>D7 = (D5 + D6) / 2</td>
<td></td>
</tr>
<tr>
<td>G1 = EJ + ((F - 1.45) / .82) * (EK - EJ)</td>
<td></td>
</tr>
<tr>
<td>G2 = EG + ((F - 1.45) / .82) * (EH - EG)</td>
<td></td>
</tr>
<tr>
<td>G3 = EJ + ((Y / 2.25) * (EG - EJ))</td>
<td></td>
</tr>
<tr>
<td>G4 = EK + ((Y / 2.25) * (EH - EK))</td>
<td></td>
</tr>
<tr>
<td>G5 = G1 + ((Y / 2.25) * (G2 - G1))</td>
<td></td>
</tr>
<tr>
<td>G6 = G3 + ((F - 1.45) / .82) * (G4 - G3)</td>
<td></td>
</tr>
<tr>
<td>G7 = (G5 + G6) / 2</td>
<td></td>
</tr>
<tr>
<td>I1 = ED + ((F - 1.45) / .82) * (EE - ED)</td>
<td></td>
</tr>
<tr>
<td>I2 = EG + ((F - 1.45) / .82) * (EH - EG)</td>
<td></td>
</tr>
<tr>
<td>I3 = ED + ((Y / 4.75) * (EG - ED))</td>
<td></td>
</tr>
<tr>
<td>I4 = EE + ((Y / 4.75) * (EH - EE))</td>
<td></td>
</tr>
<tr>
<td>I5 = I1 + ((Y / 4.75) * (I2 - I1))</td>
<td></td>
</tr>
<tr>
<td>I6 = I3 + ((F - 1.45) / .82) * (I4 - I3)</td>
<td></td>
</tr>
<tr>
<td>L1 = EB + ((Y / 2.25) * (EE - EB))</td>
<td></td>
</tr>
<tr>
<td>L2 = EJ + ((Y / 2.25) * (EG - EJ))</td>
<td></td>
</tr>
<tr>
<td>L3 = EA + ((Y / 4.75) * (ED - EA))</td>
<td></td>
</tr>
<tr>
<td>L4 = ED + ((Y / 4.75) * (EB - ED))</td>
<td></td>
</tr>
<tr>
<td>L5 = L1 + ((Y / 4.75) * (L2 - L1))</td>
<td></td>
</tr>
<tr>
<td>L6 = L3 + ((Y / 2.25) * (L4 - L3))</td>
<td></td>
</tr>
<tr>
<td>L7 = (L5 + L6) / 2</td>
<td></td>
</tr>
<tr>
<td>M5 = B7 + ((Y / 4.75) * (G7 - B7))</td>
<td></td>
</tr>
<tr>
<td>M6 = D7 + ((Y / 2.25) * (I7 - D7))</td>
<td></td>
</tr>
<tr>
<td>M7 = L7 + ((F - 1.45) / .82) * (K7 - L7)</td>
<td></td>
</tr>
<tr>
<td>M8 = (M5 + M6 + M7) / 3</td>
<td></td>
</tr>
<tr>
<td>XA = (X / 2.25) * (KA - XA)</td>
<td></td>
</tr>
<tr>
<td>XD = XD + ((Y / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>XC = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>XE = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>XB = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>KA = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>KB = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LD = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LE = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LF = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LG = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LH = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LA = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LB = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LC = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LD = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LE = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LF = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LG = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LH = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
<tr>
<td>LA = (X / 4.75) / .82) * (KE - XD))</td>
<td></td>
</tr>
</tbody>
</table>

C-5
920   LK = YD + ((X / 4.75) * (YG - YD))
922   LL = LH + ((X / 4.75) * (LI - LH))
924   LM = LJ + ((Y / 2.25) * (LK - LJ))
926   LN = ((LL + LM) / 2)
928   MM = BN + ((X / 4.75) * (GN - BN))
930   MN = DN + ((Y / 2.25) * (IN - DN))
932   MO = LN + (((F - 1.45) / .82) * (KJ - KN))
934   MF = (((MM + MN + MO) / 3)
936   BO = ZA + (((F - 1.45) / .82) * (IB - ZA))
938   BP = ZD + (((F - 1.45) / .82) * (IE - ZD))
940   BO = ZA + ((X / 2.25) * (ID - ZA))
942   BR = ZB + ((Y / 2.25) * (IE - ZB))
944   BS = BO + ((Y / 2.25) * (EP - BO))
946   BT = BO + (((F - 1.45) / .82) * (BR - BO))
948   BU = (((BS + BT / 2)
950   DD = ZA + (((F - 1.45) / .82) * (IB - ZA))
952   DP = ZJ + (((F - 1.45) / .82) * (IK - ZJ))
954   DO = ZA + ((X / 4.75) * (IJ - ZA))
956   DR = IB + ((X / 4.75) * (IK - IB))
958   DS = DO + ((X / 4.75) * (ID - DD))
960   DT = DG + (((F - 1.45) / .82) * (DR - DD))
962   DU = (((DS + DT) / 2)
964   GO = ZJ + (((F - 1.45) / .82) * (IK - ZJ))
966   GP = ZG + (((F - 1.45) / .82) * (IH - ZG))
968   GO = ZJ + ((X / 2.25) * (IY - ZJ))
970   GX = ZK + ((X / 2.25) * (IH - ZK))
972   BS = GO + ((Y / 2.25) * (BP - GO))
974   GT = GO + (((F - 1.45) / .82) * (GX - GO))
976   DU = (((DS + DT) / 2)
978   IO = ZD + (((F - 1.45) / .82) * (IE - ZD))
980   IP = ZG + (((F - 1.45) / .82) * (IH - ZG))
982   IQ = ZD + ((X / 4.75) * (IZ - ZD))
984   IR = ZE + ((X / 4.75) * (IZ - ZE))
986   IS = IO + ((X / 4.75) * (IP - IO))
988   IT = IQ + (((F - 1.45) / .82) * (IQ - IO))
990   IU = (((IS + IT) / 2)
992   KO = ZB + ((Y / 2.25) * (IE - ZB))
994   KP = ZK + ((Y / 2.25) * (IK - ZK))
996   KD = ZD + ((X / 4.75) * (IZ - ZD))
998   KR = ZE + ((X / 4.75) * (IZ - ZE))
1000  KB = KO + ((X / 4.75) * (KP - KO))
1002  KT = KD + ((Y / 2.25) * (KR - KD))
1004  KU = (((KS + KT) / 2)
1006  LO = ZA + ((Y / 2.25) * (IZ - ZA))
1008  LP = ZJ + ((Y / 2.25) * (IK - ZJ))
1010  LO = ZA + ((X / 4.75) * (IZ - ZA))
1012  LR = ZD + ((X / 4.75) * (IZ - ZD))
1014  LB = LO + ((X / 4.75) * (LF - LD))
1016  LT = LO + ((Y / 2.25) * (LA - LD))
1018  LU = (((LB + LT) / 2)
1020  MU = BU + ((X / 4.75) * (GU - BU))
1022  MV = DU + ((Y / 2.25) * (IU - DU))
1024  MW = LU + (((F - 1.45) / .82) * (HU - LU))
1026  MX = (((MU + MV + MW) / 3)
1030  GOSUB 1900
1032  INPUT "DO YOU WANT A HARDCOPY? ENTER Y(YES) OR N(NO) "; A$ 
1033  IF A$ = "N" GOTO 4005
1034  IF A$ = "Y" THEN FRM 1: GOSUB 1900
1035  PRS 0
1036  GOTO 4005
1040  W = - X
1045  REM EQUATIONS FOR QUADRANT C
1050  A1 = EB + (((F - 2.27) / 1.82) * (EC - EB))
1052  A2 = EE + (((F - 2.27) / 1.82) * (EF - EE))
1054  A3 = EB + (((F - 2.27) / 1.82) * (EE - EB))
1054  A4 = EC + (((F - 2.27) / 1.82) * (EF - EC))

C-7
1322 \( WK = UN + ((F - 2.27) / 1.82) \* (TN - UN) \)
1324 \( ML = ((W1 + W2 < WK) / 3) \)
1326 \( AQ = ZB + ((F - 2.27) / 1.82) \* (ZC - ZB) \)
1328 \( AP = ZF + ((F - 2.27) / 1.82) \* (ZF - ZE) \)
1330 \( AU = ZB + ((Y / 2.25) \* (ZE - ZB)) \)
1332 \( AP = ZC + ((Y / 2.25) \* (ZC - ZF)) \)
1334 \( AS = AO + ((Y / 2.25) \* (AP - AO)) \)
1336 \( AX = AO + ((F - 2.27) / 1.82) \* (AR - AO) \)
1338 \( AU = ((AS + AX) / 2) \)
1340 \( NO = ZE + ((F - 2.27) / 1.82) \* (ZF - ZE) \)
1342 \( NP = ZN + ((F - 2.27) / 1.82) \* (ZO - ZN) \)
1344 \( NO = ZE + ((W / 2.25) \* (ZN - ZE)) \)
1346 \( NR = ZF + ((W / 2.25) \* (ZO - ZF)) \)
1348 \( NS = NO + ((W / 2.25) \* (NP - NO)) \)
1350 \( NT = NO + ((F - 2.27) / 1.82) \* (ZR - NO) \)
1352 \( NU = ((NS + NT) / 2) \)
1354 \( PD = ZO + ((F - 2.27) / 1.82) \* (ZR - ZO) \)
1356 \( PP = ZN + ((F - 2.27) / 1.82) \* (ZD - ZN) \)
1358 \( PQ = ZO + ((Y / 2.25) \* (ZN - ZD)) \)
1360 \( PR = ZR + ((Y / 2.25) \* (ZO - ZR)) \)
1362 \( PS = PD + ((Y / 2.25) \* (PF - PQ)) \)
1364 \( PT = PD + ((F - 2.27) / 1.82) \* (FR - PQ)) \)
1366 \( PU = ((PS + PT) / 2) \)
1368 \( RD = ZB + ((F - 2.27) / 1.82) \* (ZC - ZB) \)
1370 \( RP = ZO + ((F - 2.27) / 1.82) \* (ZR - ZO) \)
1372 \( RQ = ZB + ((W / 2.25) \* (ZD - ZB)) \)
1374 \( RW = ZC + ((W / 2.25) \* (ZR - ZC)) \)
1376 \( RS = RD + ((W / 2.25) \* (RP - RD)) \)
1378 \( RT = RD + ((F - 2.27) / 1.82) \* (RR - RD)) \)
1380 \( RU = ((PS + RT) / 2) \)
1382 \( TX = ZC + ((Y / 2.25) \* (ZB - ZC)) \)
1384 \( TP = ZR + ((Y / 2.25) \* (ZR - ZR)) \)
1386 \( TQ = ZC + ((W / 2.25) \* (ZR - ZC)) \)
1388 \( TR = ZF + ((W / 2.25) \* (ZD - ZF)) \)
1390 \( TS = TX + ((W / 2.25) \* (TP - TX)) \)
1392 \( TT = TD + ((Y / 2.25) \* (TR - TD)) \)
1394 \( TU = ((TS + TT) / 2) \)
1396 \( UO = ZB + ((Y / 2.25) \* (ZE - ZB)) \)
1398 \( UP = ZG + ((Y / 2.25) \* (ZN - ZG)) \)
1400 \( UQ = ZB + ((W / 2.25) \* (ZD - ZB)) \)
1402 \( UR = ZE + ((W / 2.25) \* (ZN - ZE)) \)
1404 \( US = UO + ((W / 2.25) \* (UP - UO)) \)
1406 \( UT = UO + ((Y / 2.25) \* (UR - UO)) \)
1408 \( UU = ((US + UT) / 2) \)
1410 \( WQ = AU + ((W / 2.25) \* (FU - AU)) \)
1412 \( WR = RU + ((Y / 2.25) \* (NU - RU)) \)
1414 \( WS = OU + ((F - 2.27) / 1.82) \* (TU - OU)) \)
1416 \( WT = ((WO + WR + WS) / 3) \)
1420 \( GOSUB 1960 \)
1422 \( INPT "DO YOU WANT A HARDCOPY? ENTER Y(YES) OR N(NO) " \)
1424 \( IF A$ = "Y" THEN PR# 11: GOSUB 1965 \)
1425 \( PR# 0 \)
1426 \( GOTO 4005 \)
1430 \( W = - X \)
1435 \( REM EQUATIONS FOR QUADRANT D \)
1440 \( B1 = EA + (((F - 1.45) / 1.82) \* (EB - EA)) \)
1442 \( B2 = ED + (((F - 1.45) / 1.82) \* (FE - ED)) \)
1444 \( B3 = EA + ((Y / 2.25) \* (ED - EA)) \)
1446 \( B4 = EB + ((Y / 2.25) \* (EL - ED)) \)
1448 \( B5 = B1 + ((Y / 2.25) \* (S2 - B1)) \)
1450 \( B6 = B5 + (((F - 1.45) / 1.82) \* (B4 - B5)) \)
1452 \( B7 = ((B0 + B6) / 2) \)
1454 \( O1 = ED + (((F - 1.45) / 1.82) \* (LE - EL)) \)
1456 \( O2 = EM + (((F - 1.45) / 1.82) \* (EN - EM)) \)
1458 \( O3 = ED + ((W / 2.25) \* (EM - ED)) \)
1724 BS = BO + ((Y / 2.25) * (BP - BO))
1726 BT = BO + (((F - 1.45) / .82) * (BR - BO))
1730 BU = BS + BT / 2
1730 CO = ZD + (((F - 1.45) / .82) * (ZE - ZD))
1732 OP = ZM + (((F - 1.45) / .82) * (ZN - ZM))
1734 OQ = ZD + ((W / 2.25) * (ZM - ZD))
1736 OY = ZE + ((W / 2.25) * (ZN - ZE))
1738 OS = OO + ((W / 2.25) * (OF - OO))
1740 OT = OO + (((F - 1.45) / .82) * (OY - OO))
1742 OU = ((OS + OT) / 2)
1744 OD = ZP + (((F - 1.45) / .82) * (ZQ - ZP))
1746 OP = ZM + (((F - 1.45) / .82) * (ZN - ZM))
1748 OQ = ZP + ((Y / 2.25) * (ZM - ZP))
1750 OR = ZQ + ((Y / 2.25) * (ZN - ZQ))
1752 OS = OD + ((Y / 2.25) * (OF - OD))
1754 OT = OD + (((F - 1.45) / .82) * (OY - OD))
1756 OU = ((OS + OT) / 2)
1758 SQ = ZA + (((F - 1.45) / .82) * (ZB - ZA))
1760 SP = ZP + (((F - 1.45) / .82) * (ZQ - ZP))
1762 SQ = ZA + ((W / 2.25) * (ZB - ZA))
1764 SR = ZB + ((W / 2.25) * (ZQ - ZB))
1766 SS = SD + ((W / 2.25) * (SQ - SD))
1768 ST = SU + (((F - 1.45) / .82) * (SR - SQ))
1770 SU = ((SS + ST) / 2)
1772 UO = ZB + ((Y / 2.25) * (ZC - ZB))
1774 UP = ZC + ((Y / 2.25) * (ZN - ZC))
1774 UO = ZB + ((W / 2.25) * (ZD - ZB))
1776 UR = ZC + ((W / 2.25) * (ZN - ZC))
1780 US = UO + ((W / 2.25) * (UF - UO))
1782 UT = UO + ((Y / 2.25) * (UR - UO))
1784 UU = ((US + UT) / 2)
1786 VD = ZA + ((Y / 2.25) * (ZB - ZA))
1788 VP = ZP + ((Y / 2.25) * (ZQ - ZP))
1790 VU = ZA + ((W / 2.25) * (ZB - ZA))
1792 VR = ZC + ((W / 2.25) * (ZN - ZC))
1794 VS = VD + ((W / 2.25) * (VF - VD))
1796 VT = VQ + ((Y / 2.25) * (VR - VQ))
1798 VU = ((VS + VT) / 2)
1800 WU = BU + ((W / 2.25) * (BW - BU))
1802 WV = SU + ((Y / 2.25) * (DU - SU))
1804 WH = VU + (((F - 1.45) / .82) * (UW - VU))
1806 WX = ((WU + WV + WH) / 3)
1810 GOSUB 2025
1812 INPUT "DO YOU WANT A HARDCOPY? ENTER Y(YES) OR N(NEG): "
1812 IF #1 = "Y" THEN PRINT 1: GOSUB 2030
1815 PRINT "RESULTS FOR QUADRANT A"
1816 GOTO 4005
1820 PRINT "RESULTS FOR QUADRANT B"
1825 PRINT "RESULTS FOR QUADRANT C"
1830 PRINT "RESULTS FOR QUADRANT D"
1835 HOME
1840 PRINT "THE RESULTS FOR THE FOLLOWING INPUTS ARE:": PRINT
1845 PRINT "LOAD = "; F; PRINT
1850 PRINT "X-AXIS = "; X; PRINT
1855 PRINT "Y-AXIS = "; Y; PRINT
1860 PRINT "** RESULTS **": PRINT
1865 PRINT "ENDURANCE FORWARD = "; MA; PRINT
1870 PRINT "STANDARD DEVIATION FORWARD = "; MI; PRINT
1875 PRINT "ENDURANCE LATERAL = "; MD; PRINT
1880 PRINT "STANDARD DEVIATION LATERAL = "; MI; PRINT
1885 RETURN
1890 REM RESULTS FOR QUADRANT B
1895 HOME
1900 PRINT "THE RESULTS FOR THE FOLLOWING INPUTS ARE:": PRINT
1905 PRINT "LOAD = "; F; PRINT
1910 PRINT "X-AXIS = "; X; PRINT
1915 PRINT "Y-AXIS = "; Y; PRINT
1920 PRINT "ENDURANCE FORWARD = "; MA; PRINT
1925 PRINT "STANDARD DEVIATION FORWARD = "; MI; PRINT
1930 PRINT "ENDURANCE LATERAL = "; MD; PRINT
1935 PRINT "STANDARD DEVIATION LATERAL = "; MI; PRINT
1940 RETURN
PRINT " ** RESULTS **": PRINT
PRINT "ENDURANCE FORWARD = ";F3: PRINT
PRINT "STD. DEVIATION FORWARD = ";WP: PRINT
PRINT "ENDURANCE LATERAL = ";W3: PRINT
PRINT "STD. DEVIATION LATERAL = ";WX: PRINT
RETURN
REM RESULTS FOR QUADRANT C
HOME
PRINT "THE RESULTS FOR THE FOLLOWING INPUTS ARE": PRINT
PRINT "LOAD = ";F1: PRINT
PRINT "X-AXIS = ";X1: PRINT
PRINT "Y-AXIS = ";Y1: PRINT
PRINT " ** RESULTS **": PRINT
PRINT "ENDURANCE FORWARD = ";W4: PRINT
PRINT "STD.DEVIATION FORWARD = ";WL: PRINT
PRINT "ENDURANCE LATERAL = ";WD: PRINT
PRINT "STD.DEVIATION LATERAL = ";WT: PRINT
RETURN
REM RESULTS FOR QUADRANT D
HOME
PRINT "THE RESULTS FOR THE FOLLOWING INPUTS ARE": PRINT
PRINT "LOAD = ";F1: PRINT
PRINT "X-AXIS = ";X1: PRINT
PRINT "Y-AXIS = ";Y1: PRINT
PRINT " ** RESULTS **": PRINT
PRINT "ENDURANCE Forward = ";WF: PRINT
PRINT "STD.DEVIATION Forward = ";WF: PRINT
PRINT "ENDURANCE LATERAL = ";WH: PRINT
PRINT "STD.DEVIATION LATERAL = ";WH: PRINT
RETURN
PRINT "DATA OUT OF BOUNDS": PRINT
PRINT "TO REENTER DATA": PRINT
INPUT "TO END PROGRAM TYPE 1": Z
IF Z = 1 GOTO 15Y
IF Z = 0 GOTO 9999
END
APPENDIX D

COMPUTER LISTING (THE TEST PROGRAM)

5 REM : ARMY WELCH PROGRAM
10 PRINT "ONE-TAILED WELCH TEST PROGRAM"
20 PRINT "NOTE: THIS PROGRAM TESTS FOR WHETHER A LARGER (SMALLER) ENDURANCE TIME FOR ONE HEADGEAR CONFIGURATION"
25 PRINT "IS SIGNIFICANTLY LARGER (SMALLER) COMPARED TO A SECOND HEADGEAR CONFIGURATION."
30 REM : C.A.P. 27-MAY-84.
35 PRINT
40 PRNT "WHAT IS THE MEAN VALUE OF THE FORWARD ENDURANCE TIME FOR THE FIRST HEADGEAR CONFIGURATION?";A1
42 PRINT "WHAT IS THE STANDARD DEVIATION OF THE FORWARD ENDURANCE TIME FOR THE FIRST HEADGEAR CONFIGURATION?";O1
44 V1 = O1 * O1
46 PRINT "WHAT IS THE MEAN VALUE OF THE LATERAL ENDURANCE TIME FOR THE FIRST HEADGEAR CONFIGURATION?";A3
48 PRINT "WHAT IS THE STANDARD DEVIATION OF THE LATERAL ENDURANCE TIME FOR THE FIRST HEADGEAR CONFIGURATION?";O3
51 V3 = O3 * O3
53 PRINT "WHAT IS THE MEAN VALUE OF THE FORWARD ENDURANCE TIME FOR THE SECOND HEADGEAR CONFIGURATION?";A2
55 PRINT "WHAT IS THE STANDARD DEVIATION OF THE FORWARD ENDURANCE TIME FOR THE SECOND HEADGEAR CONFIGURATION?";O2 
58 V2 = O2 * O2
60 PRINT "WHAT IS THE MEAN VALUE OF THE LATERAL ENDURANCE TIME FOR THE SECOND HEADGEAR CONFIGURATION?";A4
63 PRINT "WHAT IS THE STANDARD DEVIATION OF THE LATERAL ENDURANCE TIME FOR THE SECOND HEADGEAR CONFIGURATION?";O4
67 V4 = O4 * O4
70 W1 = V1 / b122 = V2 / b
72 W3 = V3 / b124 = V4 / b
75 W1 = (A1 - A2) / SQRT (Z1 + Z2)
77 W2 = ABS (W1)
79 W3 = (A3 - A4) / SQRT (Z3 + Z4)
81 W4 = ABS (W3)
85 PRINT "FOR THE FOLLOWING CONDITIONS:"
90 PRINT "HEADGEAR CONFIGURATION #1:
95 PRINT "FORWARD ENDURANCE TIME " (A1) " SECONDS."

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PRINT *(STD. DEV. = "1011" SECS.)."
PRINT "HEADGEAR CONFIGURATION #1:"
PRINT "FORWARD ENDURANCE TIME: "1A21" SECONDS."
PRINT *(STD. DEV. = "1021" SECS.)."
PRINT "THE CALCULATED WELCH NUMBER: "1W2

XI = W2 - 2.01
IF XI < 0 THEN GOTO 400
X2 = W2 - 2.57
IF X2 < 0 THEN GOTO 610
X3 = W2 - 4.03
IF X3 < 0 THEN GOTO 620
GOTO 650

PRINT "THIS IS NOT SIGNIFICANT (p>.05)."
GOTO 700

PRINT "THIS IS SIGNIFICANT AT THE 95% CONFIDENCE LEVEL (p<.05)."
GOTO 700

PRINT "THIS IS SIGNIFICANT AT THE 97.5% CONFIDENCE LEVEL (p<.025)."
GOTO 700

PRINT "THIS IS SIGNIFICANT AT THE 99.5% CONFIDENCE LEVEL (p<.005)."
GOTO 700

PRINT "FOR THE FOLLOWING CONDITIONS:"
PRINT "HEADGEAR CONFIGURATION #1:"
PRINT "LATERAL ENDURANCE TIME: "1A31" SECONDS."
PRINT *(STD. DEV. = "1031" SECS.)."
PRINT "HEADGEAR CONFIGURATION #2:"
PRINT "LATERAL ENDURANCE TIME: "1A41" SECONDS."
PRINT *(STD. DEV. = "1041" SECS.)."
PRINT "THE CALCULATED WELCH NUMBER: "1W4

X4 = W4 - 2.01
IF X4 < 0 THEN GOTO 800
X5 = W4 - 2.57
IF X5 < 0 THEN GOTO 810
X6 = W4 - 4.03
IF X6 < 0 THEN GOTO 820
GOTO 850

PRINT "THIS IS NOT SIGNIFICANT (p>.05)."
GOTO 890

PRINT "THIS IS SIGNIFICANT AT THE 95% CONFIDENCE LEVEL (p<.05)."
GOTO 890

PRINT "THIS IS SIGNIFICANT AT THE 97.5% CONFIDENCE LEVEL (p<.025)."
GOTO 890

PRINT "THIS IS SIGNIFICANT AT THE 99.5% CONFIDENCE LEVEL (p<.005)."
GOTO 890

PRINT "DO YOU WISH TO EVALUATE ANOTHER PAIR OF HEADGEAR CONFIGURATION?
ST TYPE '1' FOR 'YES' OR TYPE '2' FOR 'NO'."; FI

IF FI = 1 THEN GOTO 50
END
END
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DTIC