TR-01-476

RESEARCH DIVISION
COLLEGE OF ENGINEERING
NEW YORK UNIVERSITY

2894

2894

AD0.641319

INVESTIGATIONS WITH RESPECT TO THE DESIGN CONSTRUCTION AND EVALUATION OF PROSTHETIC DEVICES

Vol. I

Prepared for Office of Naval Research
Special Devices Center
Sands Point, L. I., New York
Project No. 80—Report No. 80.10
Contract N6 ONR-279

NEW YORK UNIVERSITY
COLLEGE OF ENGINEERING
UNIVERSITY HEIGHTS, NEW YORK 53, N.Y.

RESEARCH DIVISION

TELEPHONE: LUdlow 3-6310

AD-641319

June 1, 1949

Commanding Officer
Special Devices Center
Office of Naval Research
Sands Point, Port Washington
Long Island, New York

Dear Sir:

It is a pleasure to transmit to you herewith our report "Investigations with Respect to the Design, Construction and Evaluation of Prosthetic Devices", prepared in accordance with Task Order No. 1 Amended of Contract N6-onr-279 between your center and New York University.

In transmitting this report, we should like to invite your attention to the fact that this report represents in part a summary of the findings reported previously in interim reports, along with findings not previously reported. Together with Reports 80.11 "The Personality Characteristics of Forty-Eight Above-the-Knee Amputees", and Report 80.12 "Problems in the Fitting and Servicing of Prosthetic Devices for Above-the-Knee Amputees" previously submitted, this report fulfills in part the arrangements of the contract.

It is interesting to note that these findings confirm and elaborate findings in similar areas of research which have been conducted elsewhere. It is of further interest that as a result of this work the research group at New York University was invited to participate in a similar program of research being conducted under the guidance of the Advisory Committee on Artificial Limbs of the National Research Council. The New York University group was invited because it was fitted to conduct research in areas which had not been considered previously.

That the New York University group was so fitted can be attributed in great measure to the guidance of the Project Officers assigned by the Special Devices Center to direct this work for them.

Very sincerely yours,

Harold K Work

HAROLD K.. WORK
Director of Research

HKW:lac

AD-641319

TECHNICAL REPORT - SDC 2 79-1-10

INVESTIGATIONS WITH RESPECT TO THE DESIGN, CONSTRUCTION, AND EVALUATION OF PROSTHETIC DEVICES

(Aeromedical Research)

VOL. I.

Research Division, College of Engineering, New York University.
Project No. 80.

Contract N6ONR-279,T.O.I, Amend.2
Project Designation NR-900-002
SDC Project 9-D-1

Prepared by Renato Contini

Renato Contini,
Project Director,
New York University

Approved by Harold K Work

Harold K. Work,
Director of Research,
New York University

FOR THE SPECIAL DEVICES CENTER:

Reviewed by

Lynn S. Beals, ~~Jr.~~
Commander, MC, USN,
Research & Dev. Division,
Special Devices Center

Reviewed by C. P. Seitz

C. P. Seitz, Ph.D.,
Head, Research Section,
Human Engineering Branch,
Special Devices Center

Submitted:

H. C. Knutson

H. C. Knutson
Technical Director

Approved:

J. R. Ruhsenberger

J. R. Ruhsenberger, Captain, USN
Commanding Officer and Director

CONTENTS

VOLUME I.

SECTION 1 - Acknowledgements and Foreword

SECTION 2 - Summary of Results, Conclusions

SECTION 3 - Force Plate Studies

SECTION 4 - Variable Knee Studies

SECTION 5 - Rotary Hydraulic Damper

VOLUME II.

SECTION 6 - Reciprocating (Piston) Type Hydraulic Damper

SECTION 7 - Hydraulic Leg

SECTION 8 - Studies of Mechanical Knee Stabilizing Devices

SECTION 9 - Miscellaneous Studies

SECTION 10 - Amputee Training

SECTION 11 - Appendices

SECTION 1

ACKNOWLEDGMENTS AND FOREWORD

SECTION 1 ACKNOWLEDGMENTS AND FOREWORD

I. SPONSORSHIP

1. The Research Project has been sponsored by the Special Devices Center, Office of Naval Research, under Task Order I of contract N6-ORI-II, and continued under Task Order I of contract N6-ONR-279.

2. Grateful acknowledgment of the project personnel is made to Captain D. L. Hibbard, U.S.N., under whose direction the project was initiated; and Lieutenant Commander E. J. Kupjack, who served as Project Engineer for the Special Devices Center during the early stages of these contracts.

3. Acknowledgment is made also to Commander Lynn S. Beals, Jr., M.C., U.S.N., and to Doctor Clifford P. Seitz, both of whom served as Project Engineers for the Special Devices Center in the latter stages of the project. Both Doctor Seitz and Doctor Beals have given generously of their aid and counsel. They were instrumental in channeling the course of this work, and assisted in integrating this project with similar work being done under the sponsorship of the Advisory Committee on Artificial Limbs of the National Research Council.

II. RESEARCH DIVISION, COLLEGE OF ENGINEERING, NEW YORK UNIVERSITY

1. The project staff expresses special thanks to Professor A. F. Spilhaus, Director of the Research Division, and to Professor E. N. Kemler, Acting Director of the Research Division for their aid in the furthering of the work in the project in important stages in its development.

III. PERSONNEL RELATED TO THE RESEARCH

1. The following persons in one way or another have made contributions to the research study, and thanks are expressed to each of them:

Engineering Division:

Joseph Adiletta
Leon Bennett
Renato Contini, Project Director
John Hayford
Frederick Polnauer
Rotha Sawyer
Harry Slater

Physio-Therapist:

Signe Brunnstrom

Psychology Division:

Lawrence Edwin Abt, Assistant Project Director
Sidney Fishman
Allan Katcher
Sidney Levy
Walter Lifton
Aaron Stern
Adassa Whitman

Secretarial Staff:

Helen Bronski
Edith Hilbert

Subjects - Amputees:

Haywood Johnsen
Herbert Kramer
Albert Yatkauskas

Veterans Administration cooperating personnel:

James Ferris
Edward Ford
Morris Kransdorf
Gabriel Rosenkranz, M.D.
William Rummler
Walter Slote

Department of Neurology, College of Medicine:

Morris Bender
Howard Krieger
H. L. Teuber

Consultants:

Leopold Bellak -- N.Y. Medical College, Associate in Psychiatry

Jean Davis -- Negelski and Company, Statistical Assistant

Herbert Elftman -- Associate Professor of Anatomy, College of Physicians & Surgeons, Columbia University

Kurt Goldstein -- College of City of New York, Neurologist

Bruno Klopfer -- Department of Psychology, University of California Los Angeles

David Porter -- Professor of Industrial Engineering, New York University, College of Engineering

Mandell Shimberg, M.D. -- Veterans Administration

Fred K. Teichmann -- Professor of Aeronautical Engineering, New York University, College of Engineering

IV. FOREWORD

1. In the early part of 1946, discussions were entered into between Captain D. L. Hibbard of the Special Devices Center of the Office of Naval Research and members of the Research Division of the College of Engineering, New York University, leading to the possibility of a project for the development of a bio-mechanical knee. As a result of this conference Contract N6-ORI-11 was entered into between the Office of Naval Research and the Research Division for work to be done and reports to be furnished with respect to the design and construction of a bio-mechanical knee. This study was to include motivation from supplemental power sources. The contract was later amended to include similar studies in leg braces. The specific requirements of the task together with the subsequent amendment and new contract entered into later have been included in Section XI of this report.

2. Upon receipt of the contract a staff of engineers was recruited and investigations were started in three phases:

A. FIRST, a program of familiarization with the problem was initiated. The participants in the research made a survey and a review of the available literature and patents. Contacts were established with the Veterans Administration in New York; with the New York University Rehabilitation Institute and the Institute for the Crippled and Disabled. Available advice on the problems of the above-knee amputee and suggestions as to possible improvements in the above-knee prosthesis were made both by the surgeons and limb fitters in these institutions. A number of amputees were contacted to obtain from them their recommendations as to direction of the research.

B. SECOND, a study of the principles of locomotion was sta Dr. Herbert Elftman was retained as a consultant at this stage because of his extensive pioneer efforts in the study of human locomotion. The design of equipment and the development of techniques for the study of locomotion was initiated at this stage.

C. THIRD, a design program was outlined. This design program provided for the later studies and development of various knee stabilizing devices which initially appeared to have promise in the solution of the task. The very first design studies were concentrated around the design of mechanical types of braking devices applied externally to the knee box.

3. The work accomplished in these early stages of the project has been reported in Reports 80.01, 80.02, and 80.03. Certain of the information contained in these and subsequent reports has been abstracted and included in this report.

4. With the amendment of the contract to include the study of leg braces, it became apparent that the time allowed for this research was entirely inadequate. Negotiations for the extension of the contract were started in May 1946.

5. Early experience indicated that there were conflicting opinions as to the needs of the amputee and how those needs could be satisfied. It became apparent at a very early stage that the development and stabilizing devices to be incorporated in a prosthesis could not be evaluated on the basis of the physical requirements of the device alone. It was realized that the acceptance or rejection of the device by the amputee might very well be a reflection of his problems and his adjustment to the amputation and to his physical and social environment as well as to his prosthesis.

6. Contract N6-ONR-279 Task Order II resulted from these considerations and discussions and contained provisions for research in these related areas. In January 1947, the project staff was expanded to include psychologists along with engineers and consultants who already were associated with the project. The psychologists had the task of studying the needs of the amputee, interpreting these needs to the engineer in terms of specifications for the design of devices and, in a later stage, of developing methods for evaluating the acceptance or rejection of the device by the amputee.

7. Concurrently there had been in progress a similar but much broader program of research sponsored by the National Research Council and administered by the Advisory Committee on Artificial Limbs. It was inevitable that much of the work being done in the two research programs would result in a duplication of efforts. A review of the work done by the participants in the National Research Council program indicated that many of the engineering phases were similar in nature. Similar equipment had been established for the study of locomotion, and the engineering thinking in the knee stabilizing devices evaluated partially lies in both programs. However, it was only in the New York University research program that any intensive effort was being spent in the study of the amputee and the influence of his attitudes on his acceptance of a device. It appeared desirable, therefore, to subordinate some of the engineering work that was in progress and to expand the work which dealt with the amputee as an individual.

8. The value of this decision was realized in October 1947. At that time, representatives of the Advisory Committee on Artificial Limbs of the National Research Council met with the representatives of the Special Devices Center, Office of Naval Research, and representatives of the

Research Division to discuss the possible participation of the New York University group in the overall program of the National Research Council. In December 1947, the Special Devices Center extended their contract with the Research Division until June 1948 by Amendment No. 2 to Task Order I. This amendment defined the extent of the cooperation of the New York University group in the National Research Council program. The New York University group was charged with the responsibility of evaluating devices which were then resulting from the program under the direction of the Advisory Committee on Artificial Limbs. For this work it was necessary to add to the staff training specialists and "professional" amputees.

9. In order to be able to prosecute this work thoroughly, it was necessary to have the cooperation of a number of veteran amputees. Because of this, the major portion of the work was transferred to the Prosthetic Testing and Development Laboratory of the Veterans Administration. With their cooperation the services of amputees for the study of evaluation of devices was recruited. The program was expanded at this stage to include studies not only with above-knee devices but also with devices for all amputees, above and below knee and above and below elbow.

10. This work is not finished. It is continuing under the direction of the Advisory Committee on Artificial Limbs of the National Research Council. Reports as to the progress of the work have been issued from time to time during the life of these contracts.

80.01 Preliminary Investigation With Respect To A Bio-Mechanical Knee

80.02 Preliminary Investigation With Respect To A Bio-Mechanical Knee

80.03 Preliminary Investigation With Respect To A Bio-Mechanical Knee - Final Report

80.04 Preliminary Investigation With Respect To Leg Braces

80.05 Preliminary Investigations In Psychological Research On Above-the-Knee Amputees

80.06 Experimental Design For The Service Test Of Prosthetic Devices For Above-the-Knee Amputees

80.07 Report Of Questionnaire Survey Of 128 Above-the-Knee Amputees

80.08 Report Of Questionnaire Survey of 68 Orthopedic Surgeons

80.09 Report Of Questionnaire Study of 69 Limb Makers and Limb Fitters

11. The present report, Report 80.11, The Personality Characteristics of 48 Above-the-Knee Amputees, and Report 80.12, Problems in the Fitting and Servicing of Prosthetic Devices for Above-the-Knee Amputees, constitute the final report to the Office of Naval Research together with the reports indicated above. They are submitted in partial fulfillment of the arrangements of the contract.

SECTION 2

SUMMARY OF RESULTS, CONCLUSIONS

Section 2. SUMMARY OF RESULTS, CONCLUSIONS

I. Force Plates:

1. Force plates as designed and fabricated by the Research Division have been generally satisfactory. The experiences obtained in taking force plate readings indicate to the satisfaction of this group that the present force plates are entirely adequate for the purpose intended. In order to obtain accuracies of a higher order than those available with the force plates built here, it appears necessary to modify existing equipment or introduce additional equipment and add greatly to the expense.

2. It is possible to measure the total vertical component of ground reactions to an accuracy of + 5 or -5 pounds. It is possible to measure the total horizontal fore and aft component to an accuracy of +2 or -2 pounds, and it is possible to measure the horizontal lateral component to an accuracy of +2 or -2 pounds. It is believed these variations are negligible, since within the limits of our present experience, they are well within the variations that may normally be expected in the course of the different test runs, even on the same subject.

3. It is believed that the results obtained will prove of value in the furtherance of this project, and other related projects.

II. Force Plate Data:

1. Work has progressed far enough in the accumulation of force plate data to indicate what information usefully may be gained.

2. Major differences in gait between normal and abnormal locomotion may readily be interpreted. Variations between two types of abnormal locomotion may be discerned although at times an exact definition of the variation is more difficult that in the case between normal and abnormal locomotion. Variations in the gait between two samples of normal locomotion appear most difficult to define and interpret. This may be due in

part to the fact that many more runs have been made using amputee subjects than have been made using normal subjects, and that, therefore, not enough data are available to permit proper interpretation of what causes variations between normals.

3. It is possible from these force plate data taken on amputee subjects to discern significant changes that occur in the walking pattern due to the introduction of devices in the prosthesis. It is possible, also, although to a more limited degree, with our present knowledge to indicate the general requirements of an amputee for better gait. In Section 3 a more complete discussion of gait analysis is included. There are presented also, a number of sample runs made on amputee subjects, and the data accumulated from these runs. These data are part of those obtained from testing seventy-two right and left A/K amputees over an extended period.

4. A composite chart indicating the average force plate pattern, and also indicating the average force vectors both for right as well as left A/K amputees, is included in this Section.

III. Variable Knee Studies:

1. These studies were conducted to determine, if possible, the most adequate position of the knee bolt in an A/K prosthesis. The devices and the procedures are discussed in detail in Section 4. Because of the number of tests necessary, they were conducted on one subject and, therefore, the results are only preliminary. Seventy-two basic knee bolt positions were tested with a subject walking on level ground, and a more limited number of positions were tested with the subject walking up and down ramps, and up and down steps. At the time of this report, some of these data have been interpreted for level walking positions of this one subject. It appears from these studies as well as in the opinion of the amputee, that for the best walking on level ground, the knee bolt should be in a trigger

position. By this is meant a position of the knee bolt on a vertical line joining the center of gravity of the man and the ankle bolt. This confirms other previous experience. It indicates also the need for knee stabilization. With the knee bolt in trigger position, the amputee has little or no stability on the prosthesis, except by conscious effort through his stump. A combination of the knee bolt in trigger position with a suitable knee-stabilizing device appears to be a satisfactory solution.

IV. Rotary Dampers:

1. Based on existing knowledge and experience, and from the opinions available from a number of amputees, it was decided to investigate a device or devices which assure knee stability.

2. Because of many considerations, it appeared most desirable to have the knee stabilizing device at the knee, and it appeared most logical that such a device should be of a rotary type. Consideration of locomotion studies available during the initial stages of this program indicated that maximum stability of the knee joint was required at the time of full extension; when the subject is standing; and maximum damping was desired at the time of maximum flexion, and at the time of maximum extension during the swing phase of the walking cycle. It appeared desirable also that the resistance to motion should be a minimum between maximum flexion and maximum extension during the swing phase, and that it should be variable with the speed of locomotion.

3. The original concept of a rotary damper is shown in Section 5, Fig. 5-17, a copy of the figure shown in the original report No. 80.01. This shows a cross-section and a longitudinal-section of the damper. It consists of a housing with two fixed vanes in which are mounted two vanes rotating on a shaft. The cross-section of the shaft on which the rotating vanes are attached is profiled so that the clearance between the stationary vanes

and the shaft changes as a shaft rotates. With the change in clearance, the change in damping was anticipated. The chamber was to be filled with an hydraulic fluid of proper viscosity and of suitable viscosity gradient.

4. In order to determine the proper orifice sizes, tests on a basic type of rotary damper were initiated. The clearance between the stationary vanes and the rotating shaft could be varied. The purpose of the test was to determine the amount of damping available with variable sizes of orifice.

5. In order to obtain the high moment or torque at the knee required for stability, the clearances between the vane and the shaft must be on the order of a few ten-thousandths of an inch. With a minimum clearance obtained in the test, the moment developed was in an order of three to five per cent of the moment desired. The moment varies inversely as the cube of the clearance between the vanes and the housing so that by more precise machine methods if the clearance can be reduced further, there could be a definite increase in the resisting moment or torque. However, with our present machining tolerances, and production methods, and with the available hydraulic fluids such a damper will not be a practical commercial item.

6. Similar attempts in a damper rotary vane were made by other researchers. In these attempts, the high moment required was obtained by valving the orifice and closing it at the time of ground contact. The results in these cases also were not satisfactory since the build up of pressure within the chamber permitted leakage around the vanes. When attempts to reduce this leakage were made by the introduction of seals or wipers, the static friction of the unit is increased so that the dynamic friction during the swing phase of walking cannot be predicted.

V. Reciprocating Dampers:

1. Together with a rotary type of damper, another obvious line of

approach in obtaining stability at the knee is the reciprocating type of damper. This approach has been tried not only by this group, but by other researchers in the program sponsored by the Committee on Artificial Limbs. The reciprocating or piston type of damper lends itself more readily to production methods and production control. The variations between these attempts is not in principle, but in detail design, and method of control. The design attempted here controls the rate of flow by a slot in the piston in the main unit so that the damping is established for a certain pattern of locomotion; preferably the normal gait of the amputees. Stability is achieved by control from a heel-contact device.

2. This design was not put into fabrication in time to obtain any data. Experiences with other designs leads one to believe, however, that nothing unusual will be achieved by this device. In fact, experience with other devices using heel control indicate that this type of control has limitations. Other devices presented are more complex in design, and may afford the amputee a greater degree of security. None of these devices has been accepted as completely adequate.

3. One disadvantage of the reciprocating or piston type damper is that the damper requires a considerable amount of space for installation, and must of necessity be located in the shin of an A/K prosthesis. This results in added weight at an undesirable location in the prosthesis.

4. In general, it may be said further research is indicated before a satisfactory reciprocating type of hydraulic damper can be developed.

VI. Mechanical Knee Locks:

1. Hydraulic devices of all kinds, because of the machine tolerances, and the number of parts are of necessity expensive . It was decided, therefore, that the possibilities of mechanical types of knee locks or knee brakes should not be overlooked. In the early stages of this research

program, contact with orthopedic surgeons and with members of the limb industry indicated that the most generally useful type of brake would be one external to the knee box, and one that could be adapted to existing prostheses. The development, therefore, was directed along these lines.

2. The surface of the knee box was designed as a brake drum with a braking mechanism contained within the shin, and actuated by heel and toe contact. Preliminary tests on the model off the amputee were encouraging. Multiplication of the ground contact force was obtainable through toggle action. The application of such a device to an actual prosthesis on an amputee was not satisfactory. To obtain adequate stabilizing moment at the knee required such small clearances that unlocking was not always assured. Variations in the type of prostheses, variation in the strain on the component parts of the prosthesis, under load, variations with temperature, and variations in the contact surfaces due to weather changes cannot all be controlled; so that the brake which works satisfactorily at one time, will not work satisfactorily at another.

3. Mechanical brake devices of the disc type, clutch type, and band type have been tried, or are being currently experimented with, with indifferent success. In all these instances, however, other than the one tried at New York University, the brake is introduced inside the knee box with consequent limitations as to the number of amputees on which it could be applied.

4. Because of the difficulties discussed above, it was not believed that continuing research on mechanical brakes was desirable.

VII. Miscellaneous Studies - Braces, Plastic Shins, and Power Motivation:

1. A study of the fabrication of shins in plastic materials was started. Tests were made of several representative shin shapes in compression

and bending. The general indication is that shins may be made from laminated fabrics and laminated glass fabrics which are equal to or superior in strength, and less in weight than comparable shins in wood. There was no indication at the time, however, that production could be materially increased, and production costs substantially reduced by the use of these materials, unless the shapes of the shins were standardized to a few sizes. Psychological factors in amputee acceptance of these devices are important. There appears to be, from studies made by this group, evidence that the cosmetic appearance of the prosthetic device is of as great importance in the mind of the amputee as adequate function.

2. Since the University of California and other institutions have been conducting parallel research of a more extensive nature, this project was abandoned after a few samples had been tested.

3. A number of miscellaneous studies were conducted under these task orders. The study for improvement of braces was limited to an investigation of the present practices in brace making, and the requirements for braces. Report No. 80.04, outlines in detail the investigations made. The conclusion arrived at that time was that improvements in braces can come only from improvements in methods of fabrication; typical of these are changes from hand forging to machine forging, or at least to forging under controlled conditions, the manufacture of standard joints and component parts, and the organization of some related practices between different brace makers. The adaptation of braces to production methods, however, does not seem possible. The brace must in most instances conform to the limb, and to the body structure which necessitates as many variations in braces as there are variations in people to whom they are applied.

4. In Report 80.03, Appendix B, Page 34, there was given an extensive discussion of the problem of power motivation. It was indicated in that

Report that the sources of power available at this stage of knowledge would be inadequate for use in prosthetic devices. Of the various sources available - mechanical, electrical, and hydraulic, the hydraulic source or hydraulic means of storing energy and restoring it seemed to be the most feasible; but even that had very definite limitations. This appeared to be the most complicated of the problems in the program, and consequently it was postponed until progress could be made in the development of suitable stabilizing means at the knee.

VIII. Amputee Training.

1. If the relative merits of different kinds of prostheses are to be evaluated and if amputee subjects are to be fully accommodated to their prosthetic devices it is important to provide them with training in the use of the several experimental devices. Such training is an essential ingredient in any program of service testing of prosthetic devices for above knee amputees.

2. Training on the conventional pelvic band prosthesis is needed for most amputees prior to the collection of base line data for use in making comparisons of the performance of subjects on experimental prosthetic devices. Repair, re-alignment and adjustments of the prosthesis is of equal importance during this initial step of service testing.

3. Evaluation of the gait of the amputee from the standpoint of appearance, whether by the use of motion pictures or by other means, is of questionable value unless such evaluation be given when the gait is automatic,i.e., at a time when the amputee does not know that he is being observed.

4. The proper utilization of the suction socket appears to be dependent not only upon the fit but also upon the training of the amputee. As the pelvic band is eliminated special training for development of hip control is indicated. A relatively long period of adjustment to the suction socket is

to be expected during which time socket adjustment and training need to go hand in hand.

5. The amount of training which is needed on an experimental prosthesis depends upon to which extent old patterns have to be broken down and new ones established. For proper evaluation of the amputee's performance on a new device it is recommended that, whenever possible, only one new feature be introduced at a time.

IX. Summary of Psychological Findings:

1. The original hypothesis that psychological factors play an important role in the efficient or inefficient use of a prosthesis by an above-the-knee amputee seems to have been sustained.

2. Positively oriented attitudes appear more often among the efficient users of A/K prostheses, and we may assume the possibility of some sort of causative relationship.

3. Phantom limb sensations are exceptionally common among A/K amputees, although phantom pain is much less common.

4. Training in the operation and maintenance of a prosthetic device for above-the-knee amputees appear of vital importance, and it is likely that the role of training is greatly increased as the artificial limb becomes mechanically more complex and its operation and maintenance offer greater difficulties to the amputee.

5. It appears important, in terms of its effect upon increasing efficiency in the use of a prosthesis, to fit the above-the-knee amputee with his artificial limb as soon as he can physically accommodate it, and is psychologically prepared to accept it.

SECTION 3

FORCE PLATE STUDIES

Prepared by: John Hayford

Rotha Sawyer

Leon Bennett

I. PURPOSE

1. The development of a pair of dynamic force plates for measuring the ground reactions of a person, normal or amputee, was viewed as essential for the satisfactory design of any new prosthetic device. The mechanical force plates, developed and used by Dr. Herbert Elftman of Columbia University; and the electromechanical plates developed and in use at the University of California have made available a great deal of data in the locomotion of the human.

2. The development of the dynamic force plates under this contract was undertaken because of the inherent disadvantages of using data procured from other isolated investigators.

3. This report summarizes previous reports and work and presents the calibration data of the finished force plates.

II. INTRODUCTION

1. The design of the dynamic force plates has been covered in Report 80-03 and following reports. The basic principles are repeated here for convenience and continuity.

2. "The platform is flexible in its application, permitting the use of the same pair of force plates and their recording apparatus with the subject walking either across the field of the camera or towards the camera. The plates are triangular in shape, mounted together on a common base. The triangular conformation eliminates the need of shifting the plates as the subject changes the direction of walk as well as eliminating any adjustments that might be required due to the difference in gait between any two individuals. The subject cannot avoid walking across both force plates in sequence, one step after the other."

3. "Each force plate is restrained from motion in the horizontal, lateral and vertical directions at six points. Any one restraint will measure forces in one direction only and permit free motion in the other two. Thus, three horizontal restraints measure the vertical forces, two vertical restraints the fore-and-aft forces, and a third vertical restraint the lateral forces. A combination of the three vertical restraints measures the torque reactions." See Figure No.10-A.

4. "The restraints are simple bending beams, mounted rigidly to the base plate and linked to the force plate through ball-bearing, tie-ended tie-rods. The tie-rods restrict the application of the loads to one direction. Each bending beam is cut away at a convenient point to localize and intensify the stresses. Strain gages

are mounted at these points to indicate the stresses. These gages are temperature-compensated and record both compressive and tensile stresses."

5. The deflection of the bending beams causes a change in the resistance of the strain-gage mounted thereon. The change in the resistance of the strain gage unbalances a Wheatsone bridge circuit. The unbalance in the bridge circuit is magnified by a two-stage electronic amplifier, the amplified signal being led into a Westinghouse string oscillograph. A permanent record is reproduced photographically.

6. This report covers the design of the electronic system, the response of the oscillograph, the control circuits, and the calibration of the force plates.

III. ELECTRONIC SYSTEM

The electronic system is composed of three parts; (1) the line voltage supply and regulation, (2) the power supply, and (3) the amplifier. Fig. 1, is a schematic layout of the system.

1. The line voltage supply and regulation.

The power is supplied through the Consolidated Edison Corporation commercial system at 110 volts, 60 cycles. A voltage regulator was installed to stabilize the voltage supply, being capable of producing 110 volts output at line input voltage fluctuations from 95 to 115 volts. This regulator caused objectionable interference and produced an unsatisfactory wave shape and was replaced with a manually operated variable transformer. It was found that during any one run the voltage variation was not of sufficient magnitude to cause a detectable change in the amplifier output signal, and this method has been retained.

2. Power Supply.

Three power supply packs and filters were built to feed the six amplifiers, one pack for two amplifiers. The power supply is well filtered to reduce wave shape deformation to a minimum. Fig. 2 is the wiring diagram of the power supply.

3. Amplifier.

The amplifier is a two-stage type, incorporating inverse feed-back for added stability. In the initial design, bridge unbalance was accomplished through use of a 100,000 ohm potentiometer in the bridge circuit. Drift in the amplifier from day to day, and the sensitivity of the bridge balance proving objectionable, these potentiometers were replaced with fixed resistances. The bridge unbalance was set through the fixed resistance to produce an initial unbalance in the output signal of approximately one inch in each channel. The exact magnitude of the unbalance was determined by tests for each channel separately.

Fig. 3 is a wiring diagram of the electronic amplifier.

IV. CONTROL SYSTEM

1. An electrical control system has been installed so that a proper sequencing of events will take place between the battery of photographic lights, the camera synchronous drive, the oscillograph recording drive, and the timing device to synchronize the camera and oscillograph records.

2. The control system is in two parts. A push button controls a pair of power relays that supply the 11,000 watts in the battery of photographic lights. These relays also energize the second part of the system. The second part of the system is controlled through another push button, which starts the camera and the oscillograph record drives simultaneously. At the same time it starts a delay timer, which, after a predetermined period used to allow the camera and oscillograph drives to come up to speed, operates a neon bulb in the field of view of the camera and the seventh channel of the string oscillograph.

3. The oscillograph record, a 60 cycle sine wave, is in phase with the camera, so that every peak of the oscillograph record represents one frame of the 16 mm. movie film. Through this means it is possible to locate the space position.of the subject's leg for any reading of the force plate data. The wiring diagram of the control system is presented in Fig. 4.

V. CALIBRATION

1. The design of the force plates was such that the ground reactions of the foot are to be measured with a minimum of error. Each restraint was to measure a force in one plane and direction only. This would be possible on a purely theoretical basis. In actual practice deflection of both upper and lower plates, friction in the ball-bearing tie-rods and even in initial alignment all introduce a certain amount of interaction between the different restraints. That is, a restraint to measure fore-and-aft forces would be influenced by a vertical load. A calibration of the force plates was necessary to measure the extent of this interaction.

2. The calibration was a point-by-point procedure. All points of application of the vertical load were calibrated for all combinations of loads in the fore-and-aft and lateral directions. The records could then be analyzed to determine the interactions among the different restraints.

A. Initial Calibration.

1. The initial calibration indicated the existence of undesirable interactions between vertical loads and the horizontal restraints. It also indicated that the interaction was not only a function of the magnitude of the vertical load but also of the position, or point of application. Further investigations showed several factors that were responsible for the interaction; (a) deflection in the upper pressure plates, (b) deflection of the lower mounting plate, (c) alignment of the tie-rods to the horizontal restraints, and (d) the alignment between the upper and lower plates. Fig. 5 shows the initial calibration curves.

2. It is seen that interaction exists in all directions; i.e.

a load in one plane will create a load in a perpendicular plane. In the lowest group of curves, Beam A, a vertical beam, suffers the greatest effect from a horizontal load. The middle group of curves indicate that Beam C, another vertical beam, realizes a 7 lb. positive load when 25 pounds are laterally loaded in a negative direction. The top curve group indicates a strong vertical-to-horizontal interaction as well as a large magnitude vertical-to-lateral interaction.

B. Second Calibration.

1. The deflection of the lower mounting plate was eliminated by seating the plate on a bed of concrete. Floor deflection was taken up by shoring. The deflection in the upper plate was reduced by bolting it to a 3/8" steel plate.

2. This reduced the interaction effects as indicated in the calibration curves in Fig.6. A study of this series of curves will show no interaction trend on the vertical beams arising from either horizontal (fore-and-aft) or lateral loading. However, one of the horizontal members (Beam E) is strongly affected by vertical loading indicating the presence of some interaction in a vertical-to-horizontal direction. This indicated that further investigation was necessary regarding the alignment of the restraints and their link-rods. The electronic amplication system did not give consistent results. The indications were that it was non-linear; that is, the output signal was not only dependent on the initial bridge unbalance, but also on the degree of amplification.

C. Individual Beam Calibrations

1. The platform was disassembled for realignment. The individual beams were calibrated. At the same time, the amplifiers

were modified. Fixed resistances were incorporated in the bridge circuit to eliminate the unbalance potentiometer and fix the bridge unbalance at a known value. The gain controls were replaced with higher quality potentiometers. This eliminated the tendency of the amplifiers to drift, or vary, from day to day. With the fixed resistances, it was possible to keep the bridge circuit close enough to balance to produce linear results in the output circuit.

2. Fig. 7 shows the curves of the individual beam calibrations. It is to be noted that the individual calibrations of the beams yield linearity greatly superior to that obtained with the beams in place. This lack of linearity resulted from lack of proper alignment as well as the previously mentioned electronic difficulties.

D. Final Calibration.

1. The platform was reassembled, correctly aligned. Fig. 8 shows the final calibration curves. These curves are typical of those obtained in actual test work. The loads are those assumed when the plate is loaded in a number of marked locations on the plate. The corresponding deflection is in the projected or magnified units employed in evaluating data.

2. Not all the interaction could be eliminated. What interaction remained was in a vertical-to-horizontal direction. The vertical loading of the plate in a number of chosen locations allowed the plotting of contour graphs which indicated the regions offering interaction difficulties. See Fig. No. 9. More work on alignment quickly removed these regions. The little that remained was distributed over the force plate in no set pattern and being in the neighborhood of plus or minus two pounds, was ignored.

VI. TEST PROCEDURE.

1. The force plate is located centrally in a walkway of twenty-five feet. A walkway of forty to fifty feet is more desirable but available facilities limited the run to twenty-five feet. This allows the subject to walk at a normal gait at the time he steps on the force plate.

2. The walkway can be replaced by a ramp with an angle of inclination of ten degrees or by a portable stairway with average riser and treads.

3. At each evaluation period as described in the basic experimental design, photographic and force plate readings are taken of the subject walking on the level in two directions, walking up and down the ramp, and walking up and down the stairs.

VII. EVALUATION OF DATA

1. Oscillograph data (see Fig. 10-E) is recorded in sine wave form — amplitudes indicating load. A line drawn through the tips of the zero-load wave establishes a base line from which measurements of deflections are made. When projected this line is made to coincide with a zero line, designated deflection "20", drawn on a large wall-mounted coordinate system. Deviations from this line, caused by instantaneous loads, are then measured. The force plate readings as projected on the grid have their deflections magnified ten times. The deflections are converted to pounds with the use of calibration curves. A calibration is taken before each day's run. The reaction as measured on the three vertical beams are totalled and give the vertical vector. Those of the two fore-and-aft beams are added algebraically to give the fore-and-aft vector. The sixth beam gives the lateral vector. By using the total vertical vectors and the loads at individual beams the reaction point is determined by nomographic means. The motion pictures are projected on coordinate paper, using every third frame. In this way the time increment is 1/20 second. Re-projection is made using the vertical plane of symmetry of the leg concerned as a base. As the physical positioning of this plane will vary, utilization of vanishing point perspective is necessary to provide proper scale factors. Control points at the hip, knee, ankle and toe joints and on the body are spotted for each projected frame. When connected, these points (for each position) result in line or stick diagrams from which the angular and linear displacement of each element per unit of time can be observed.

2. On these stick diagrams the resultant vector, which is the vector sum of the vertical and fore-and-aft forces, is plotted. This provides

a pattern of the man's walk which is analyzed and compared to the normal walk pattern and walk patterns made by the subject on various devices. From the data available, information such as the torque and moments about ankle, knee and hip may be drawn and compared.

3. To coordinate force plate-oscillograph data and stick diagram-motion picture data the following method is used. As described in Part III, pushing the master control button will start the camera and oscillograph simultaneously. After a preset time delay a neon bulb in the field of the camera, and in phase with its shutter, will light, registering on every succeeding motion picture film frame. The neon light also records on the oscillograph data as a 60-cycle sine wave, or at a rate of one pip per film frame. In practice from one to three seconds will elapse before the subject's foot strikes the force plate, as measured from the instant that the neon light draws current.

4. To coordinate records, one counts forward from the light's appearance on the film and matches the count with that on the oscillograph record until the heel strike region is reached. At an arbitrarily chosen point in this region, the stick diagram number one is assigned. Every third pip or frame from this point on is given a consecutive number.

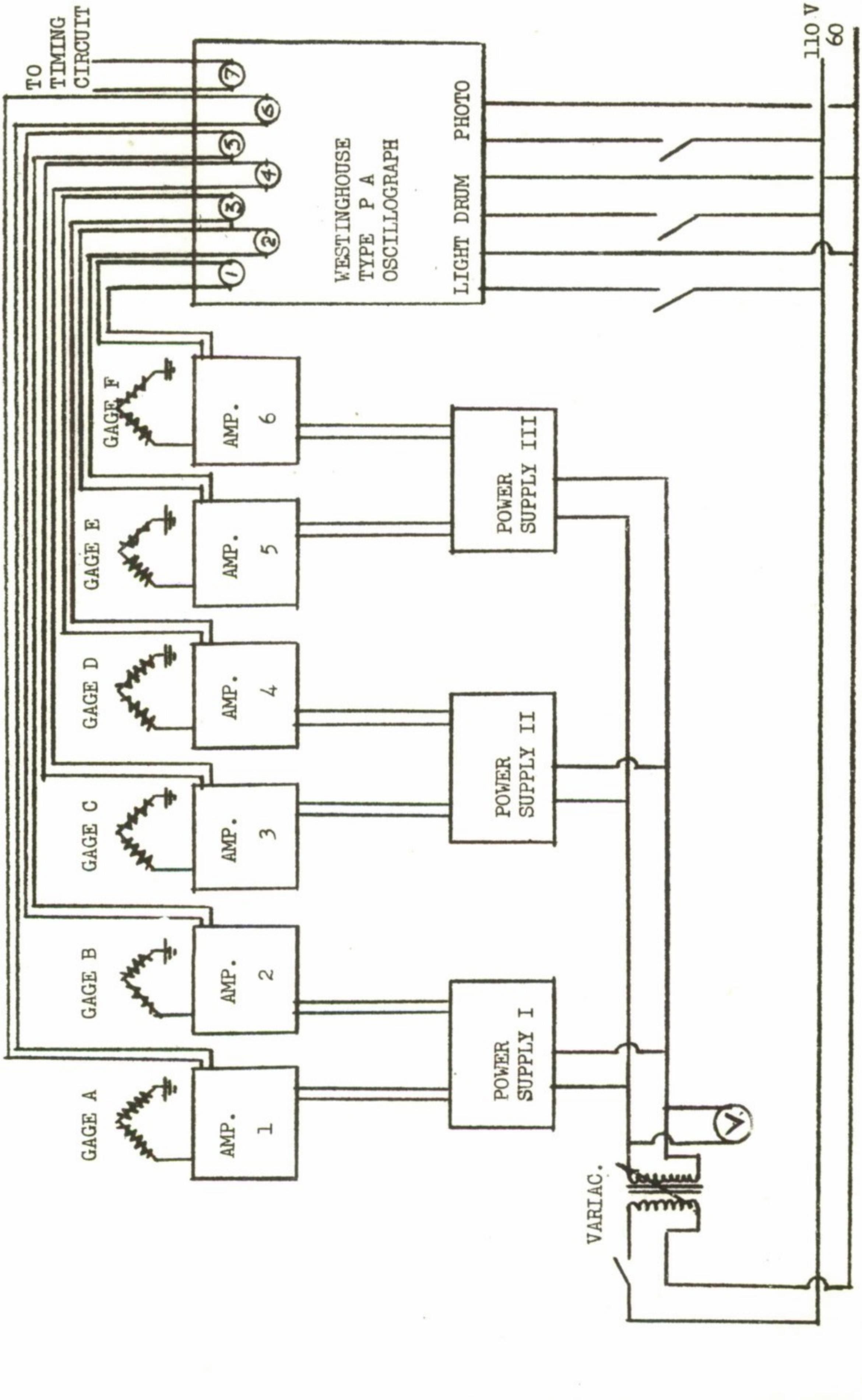


FIGURE 3-1

ELECTRONIC SYSTEM SCHEMATIC LAYOUT

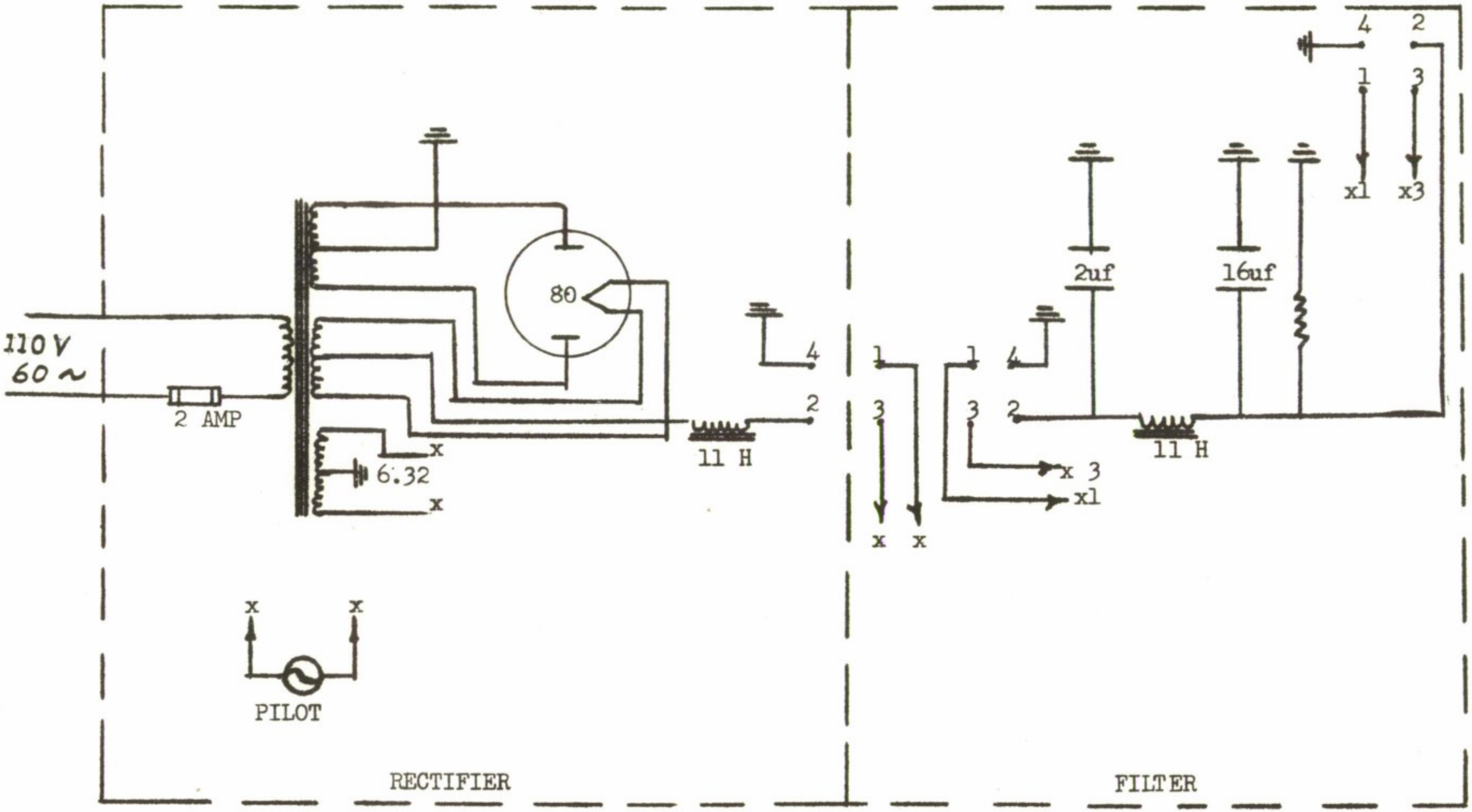


FIGURE 3-2

WIRING DIAGRAM POWER SUPPLY

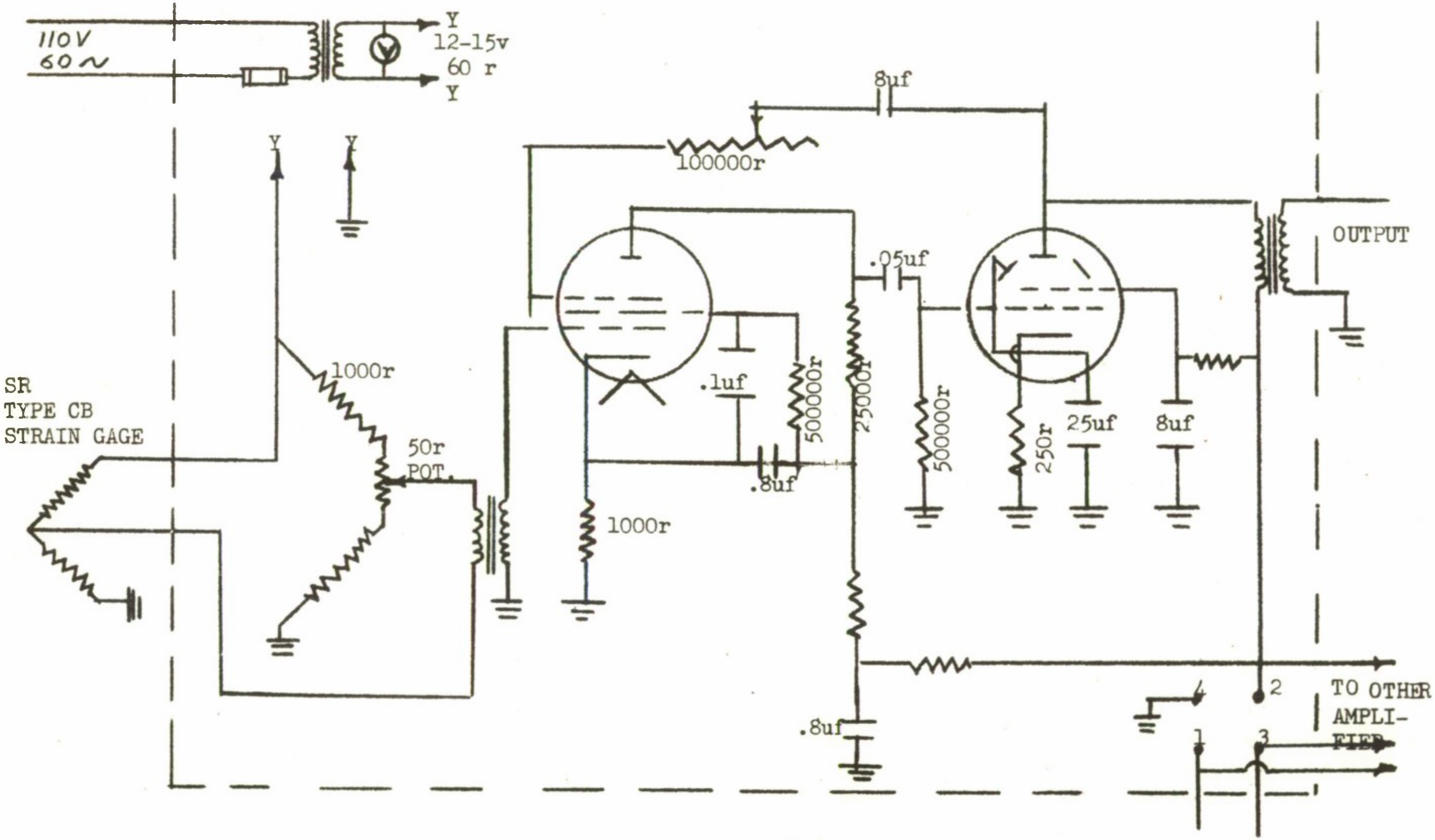


FIGURE 3-3

WIRING DIAGRAM AMPLIFIER

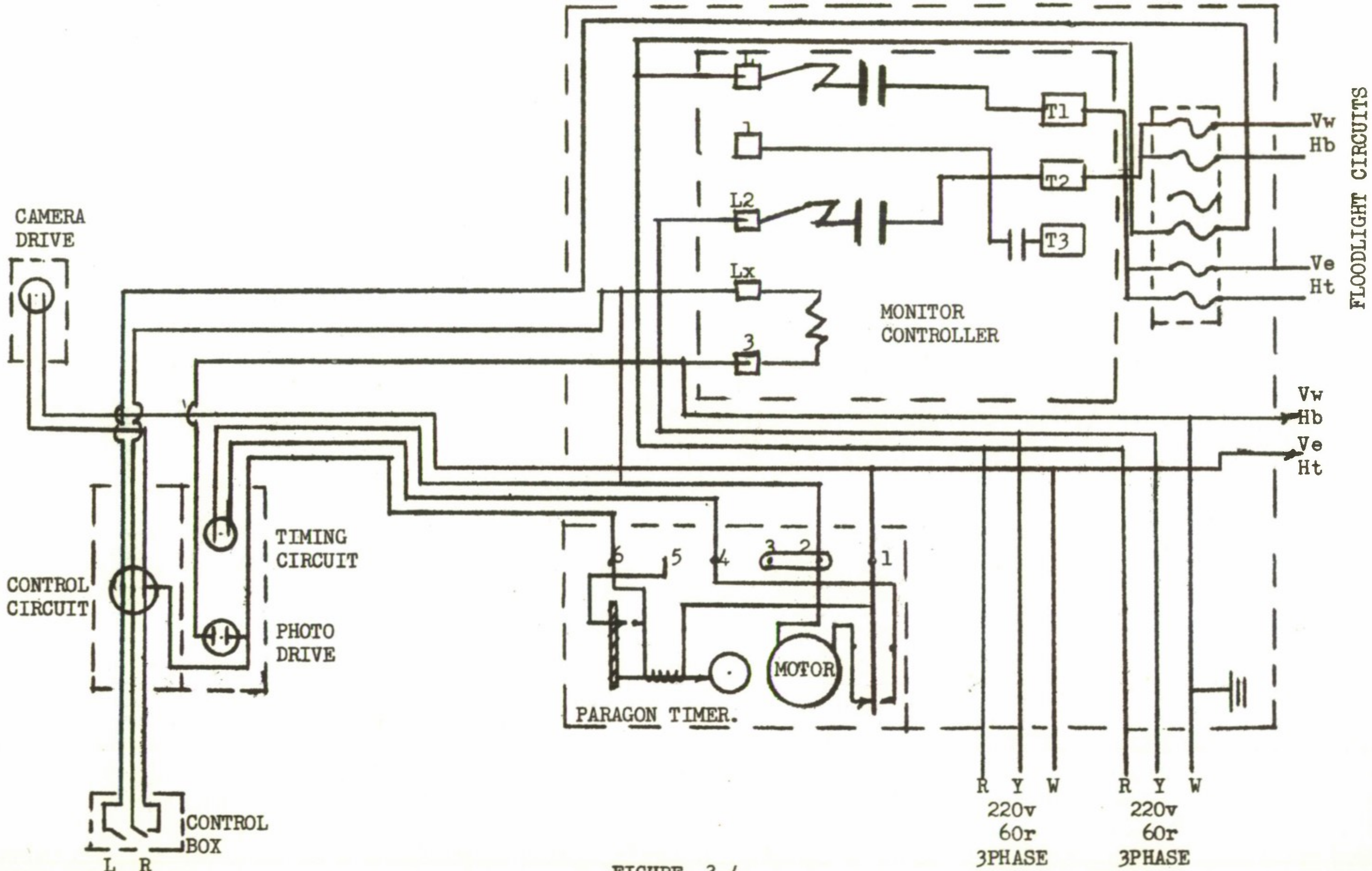
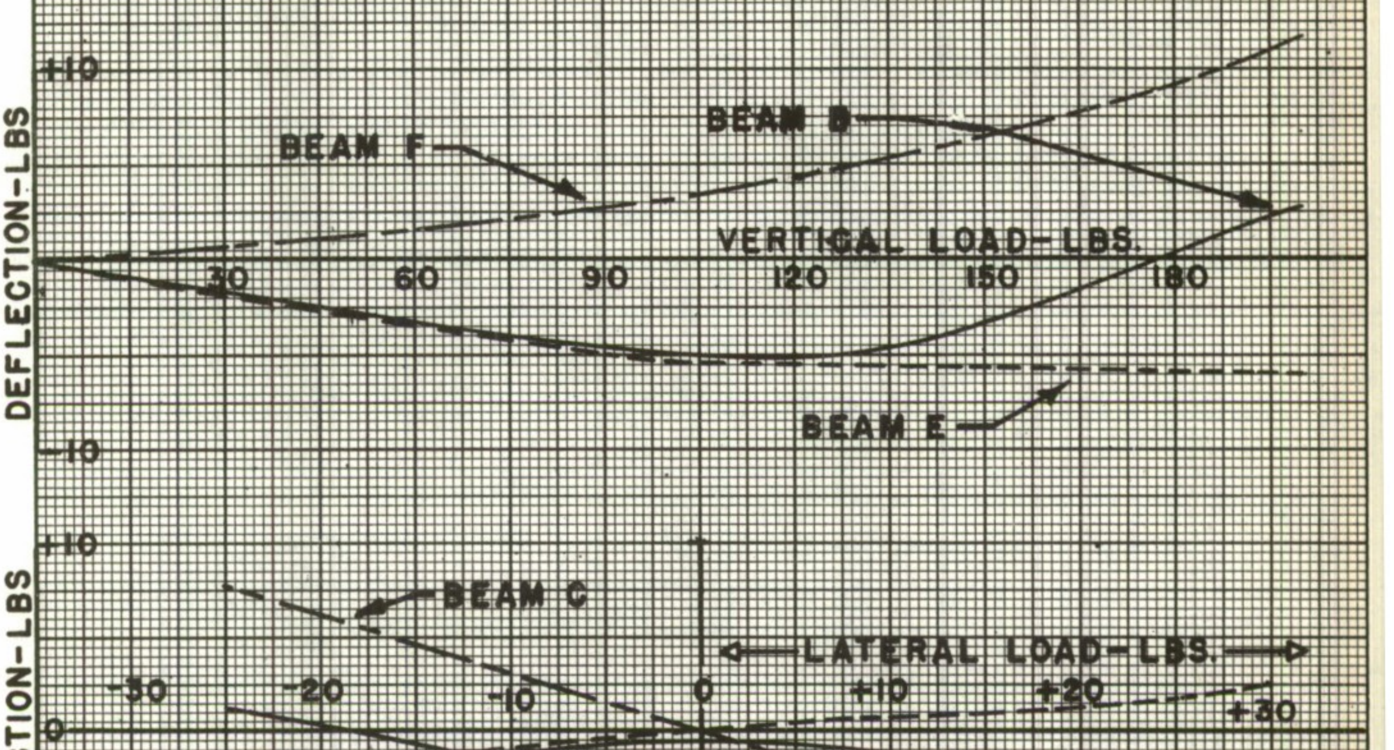


FIGURE 3-4

WIRING DIAGRAM CONTROL SYSTEM

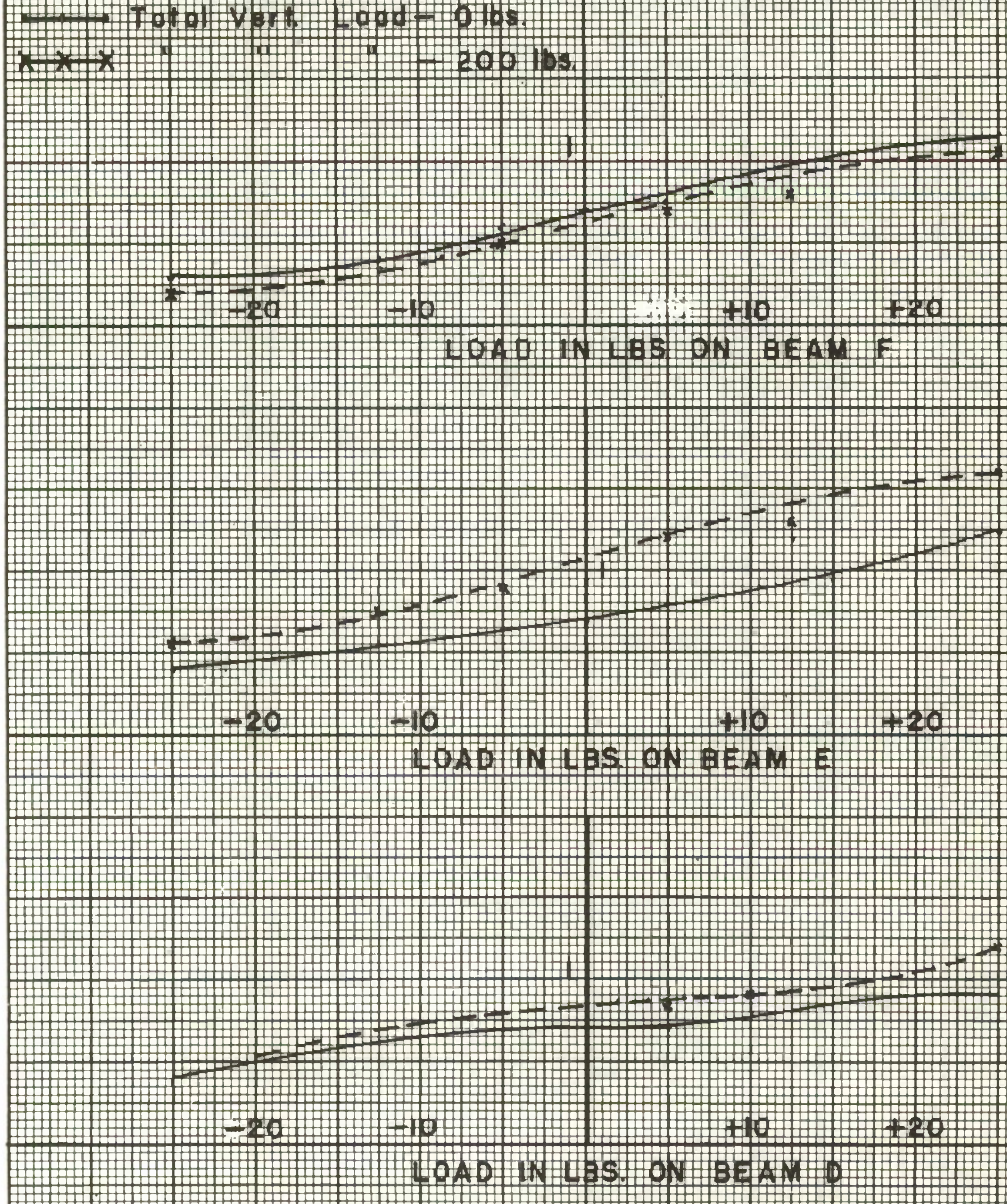


Interaction Effects Of

Various Loading Upon

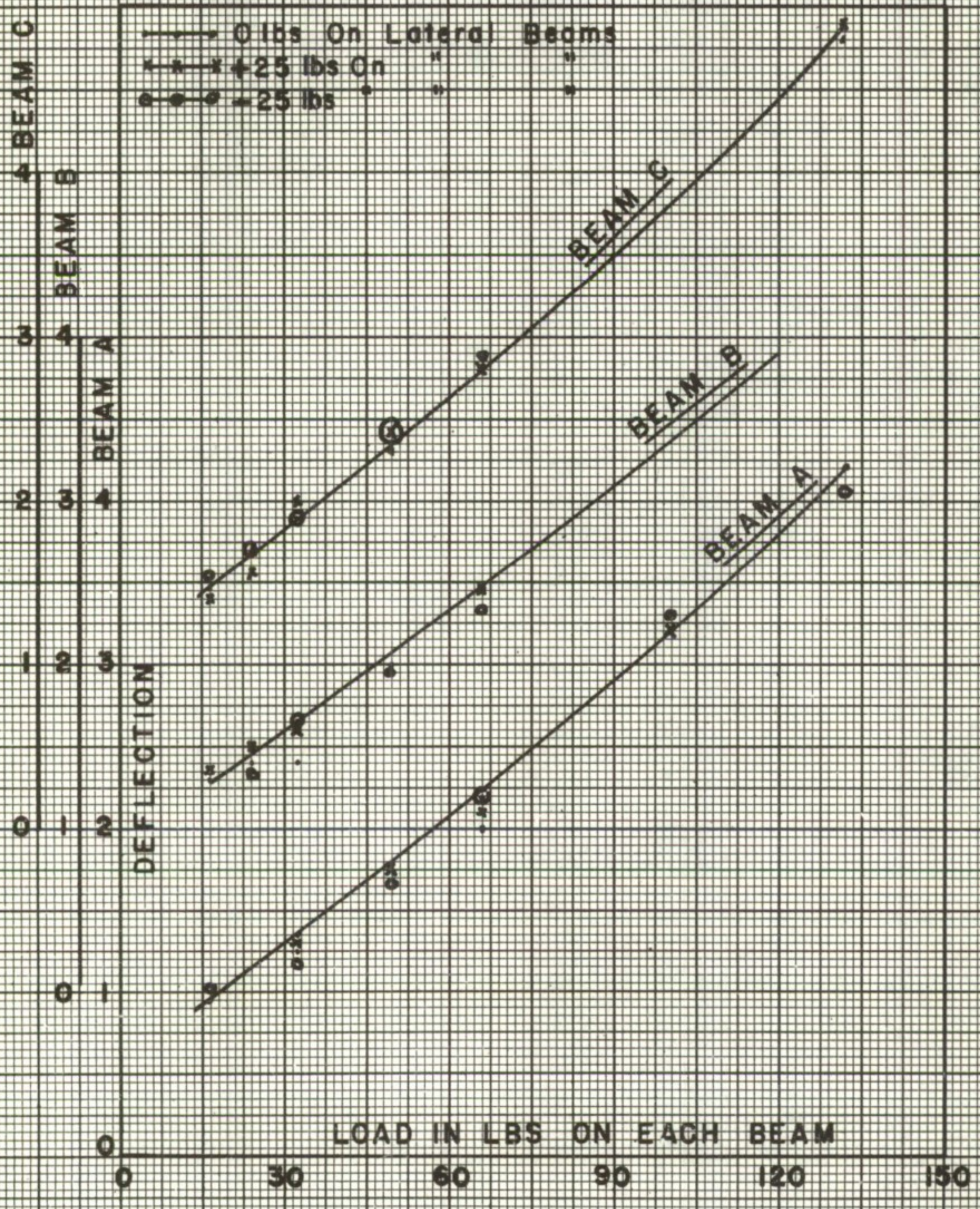
Horizontal And Vertical Beams

Fig 3-5



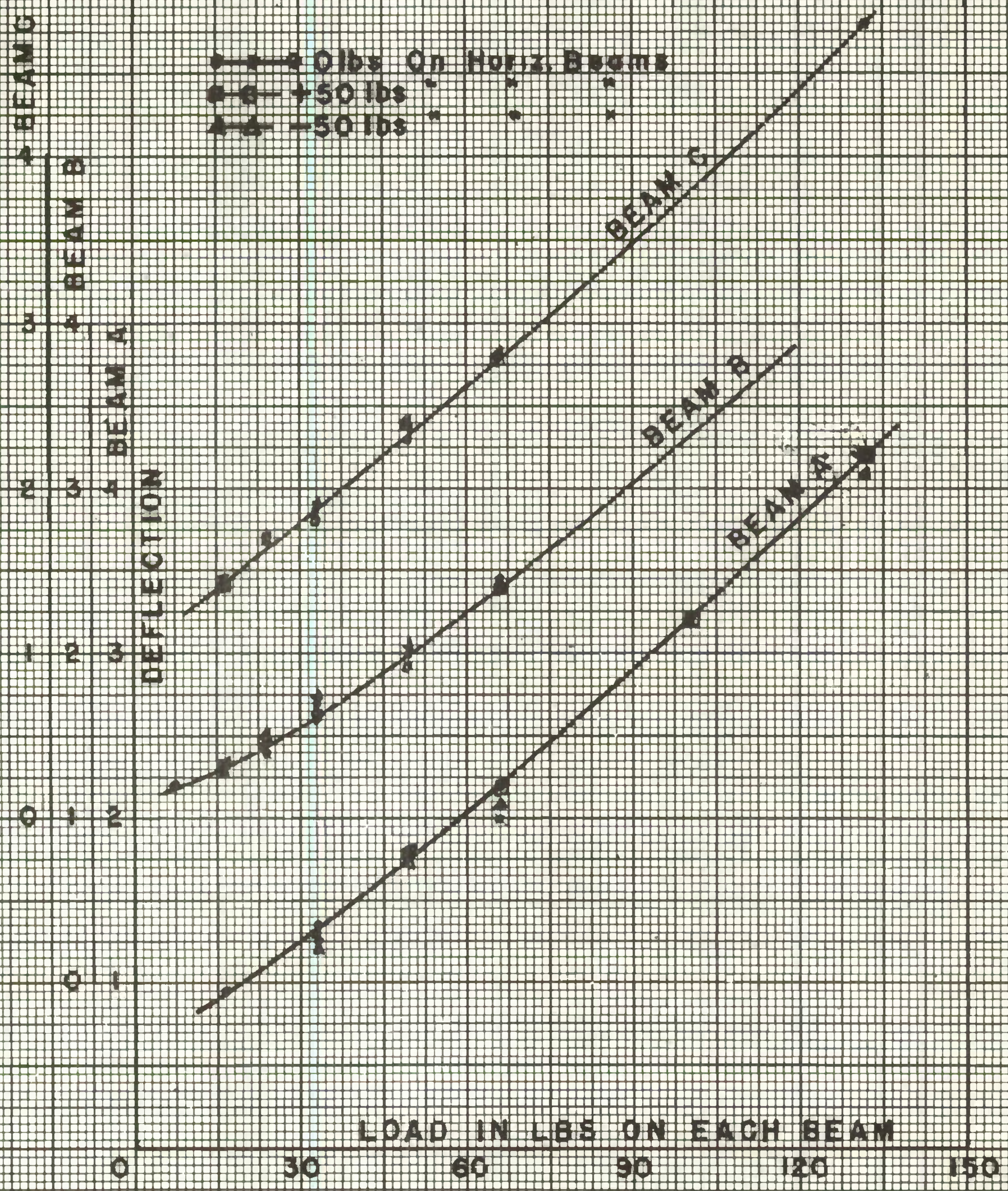
Interaction Effect of Vertical Loads on Horizontal and Lateral Beams

Fig. 3-6a



Interaction Effect of Lateral Loads on Vertical Beams

Fig. 3-6b



Interaction Effect of Horizontal Loads on Vertical Beams

Fig 3-6c

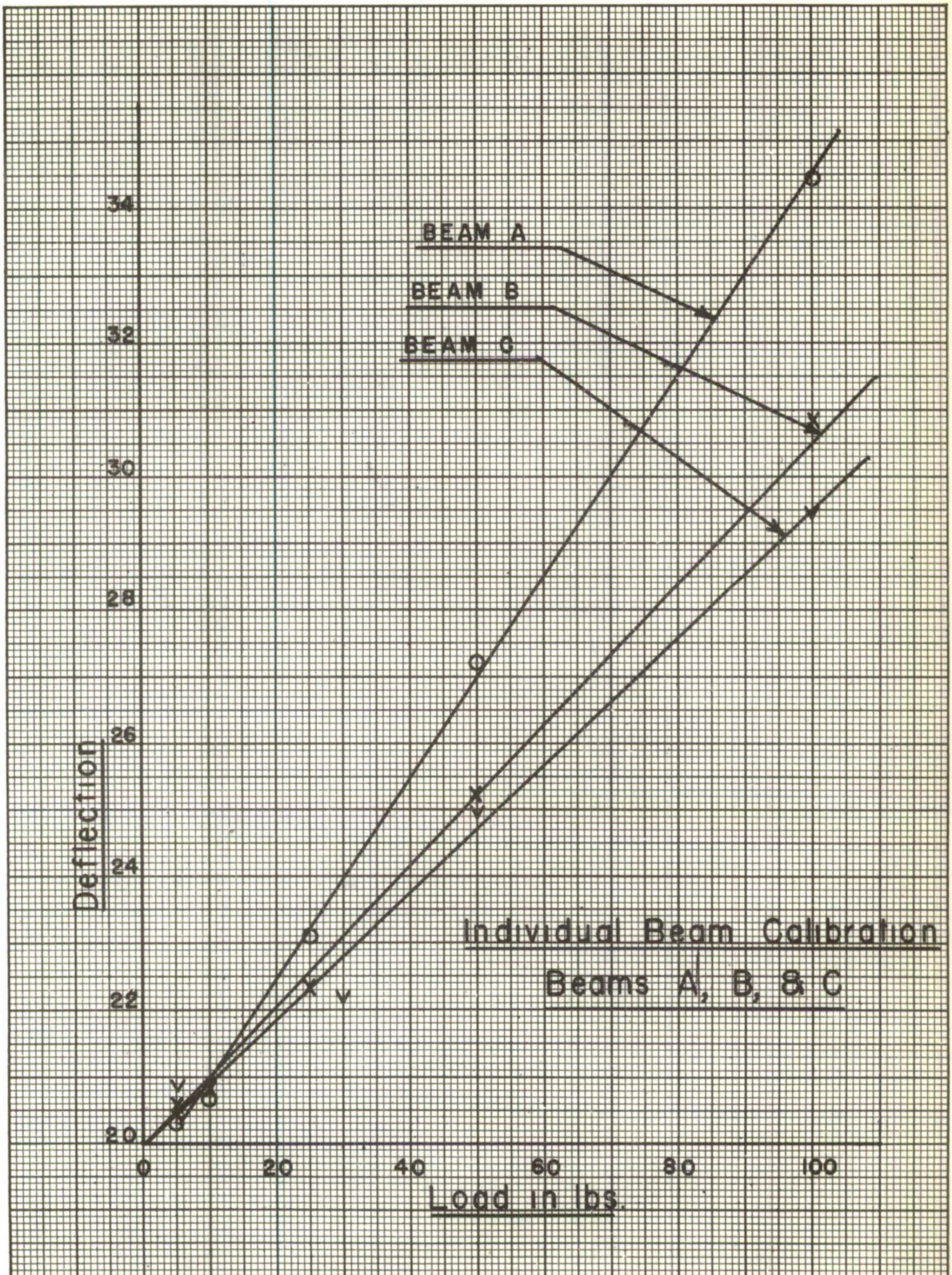

BEAM A
BEAM B
BEAM C
Deflection
20
22
24
26
28
30
32
34
0
20
40
60
80
100
Load in lbs.
Individual Beam Calibration
Beams A, B, & C

Fig. 3-7a

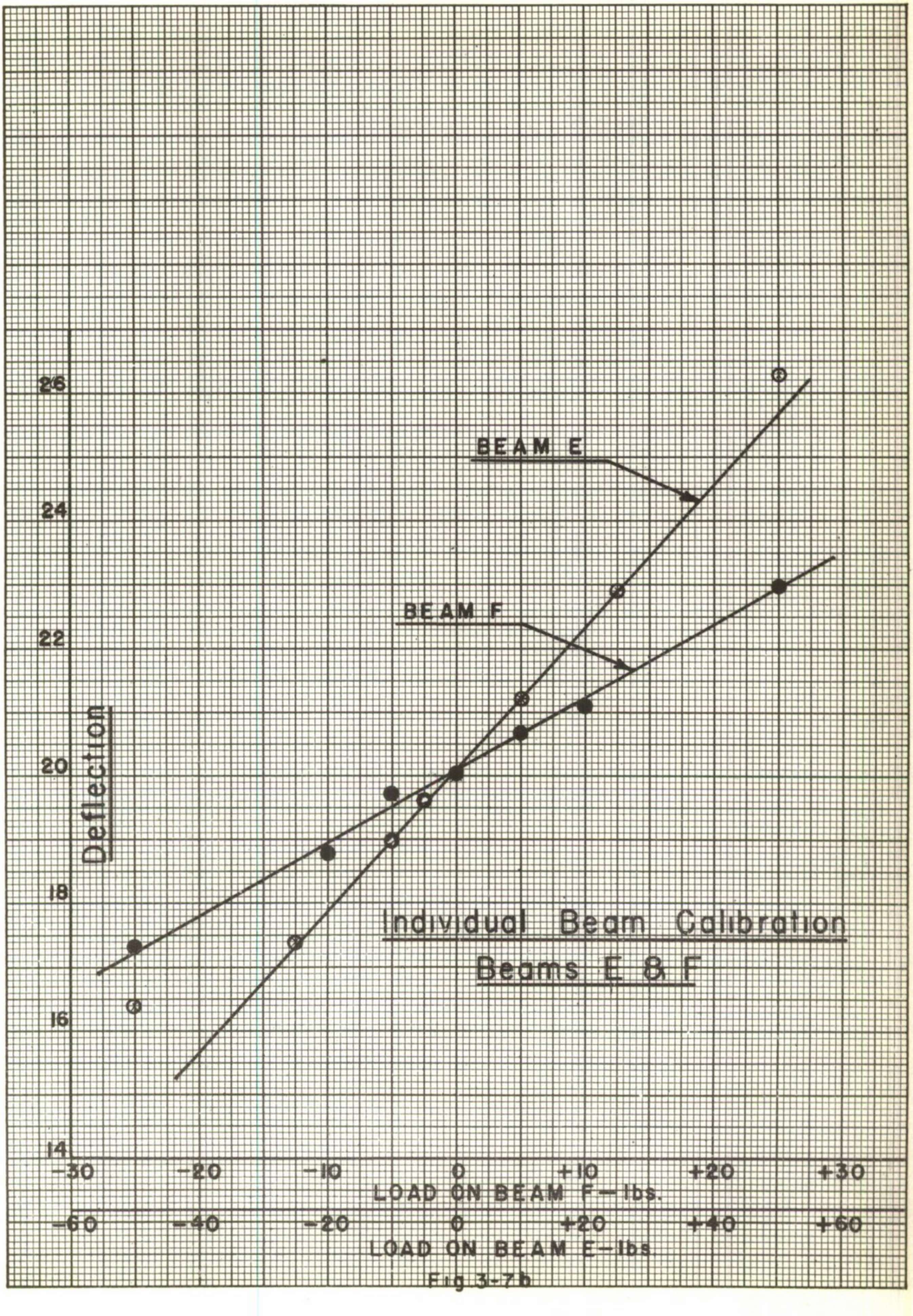

Deflection
26
24
22
20
18
16
14
BEAM E
BEAM F
Individual Beam Calibration
Beams E & F
-30
-20
-10
0
+10
+20
+30
LOAD ON BEAM F—lbs.
-60
-40
-20
0
+20
+40
+60
LOAD ON BEAM E—lbs.

Fig 3-7b

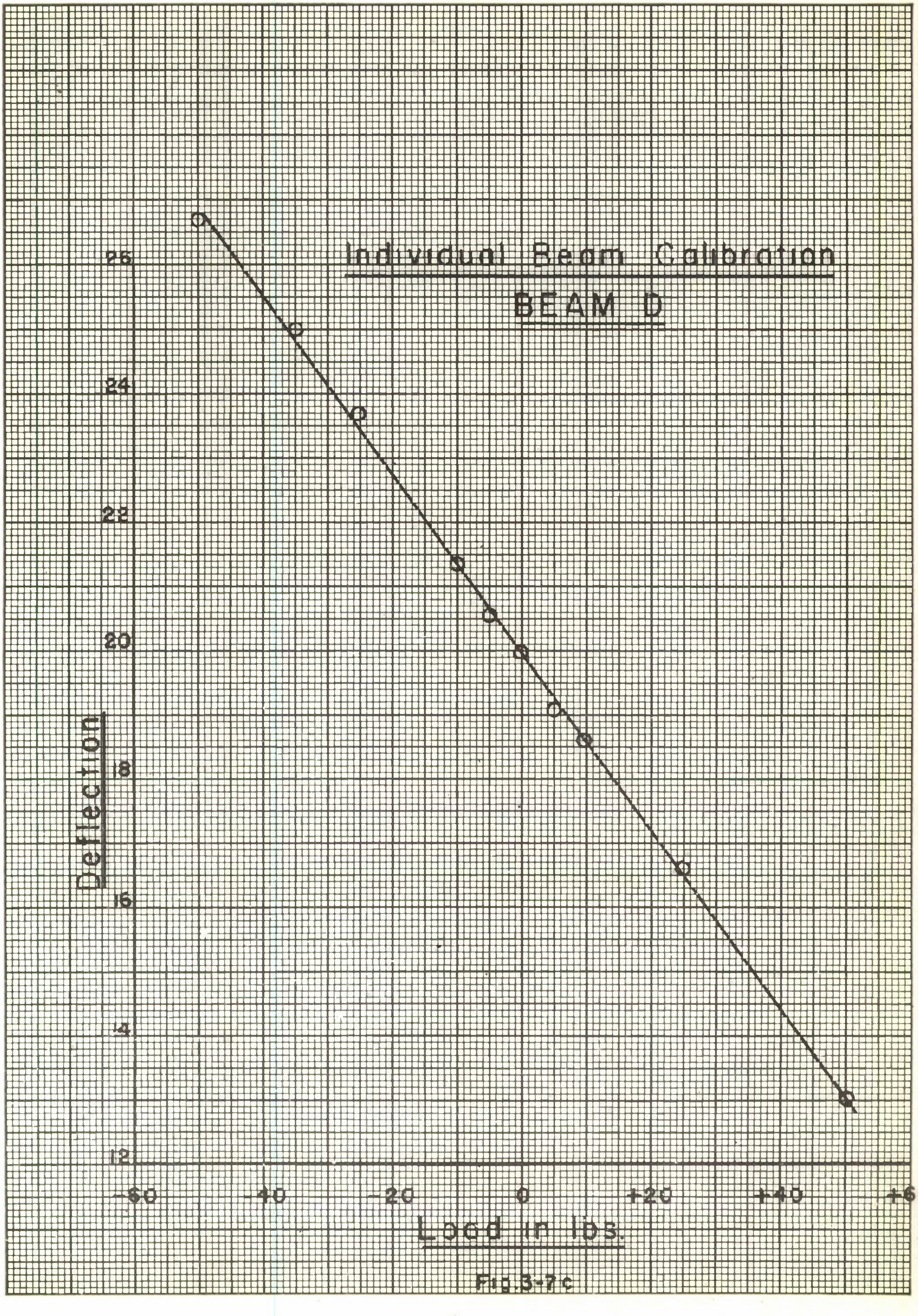

Individual Beam Calibration
BEAM D
Deflection
26
24
22
20
18
16
14
12
-60
-40
-20
0
+20
+40
+60
Load in lbs.

Fig.3-7c

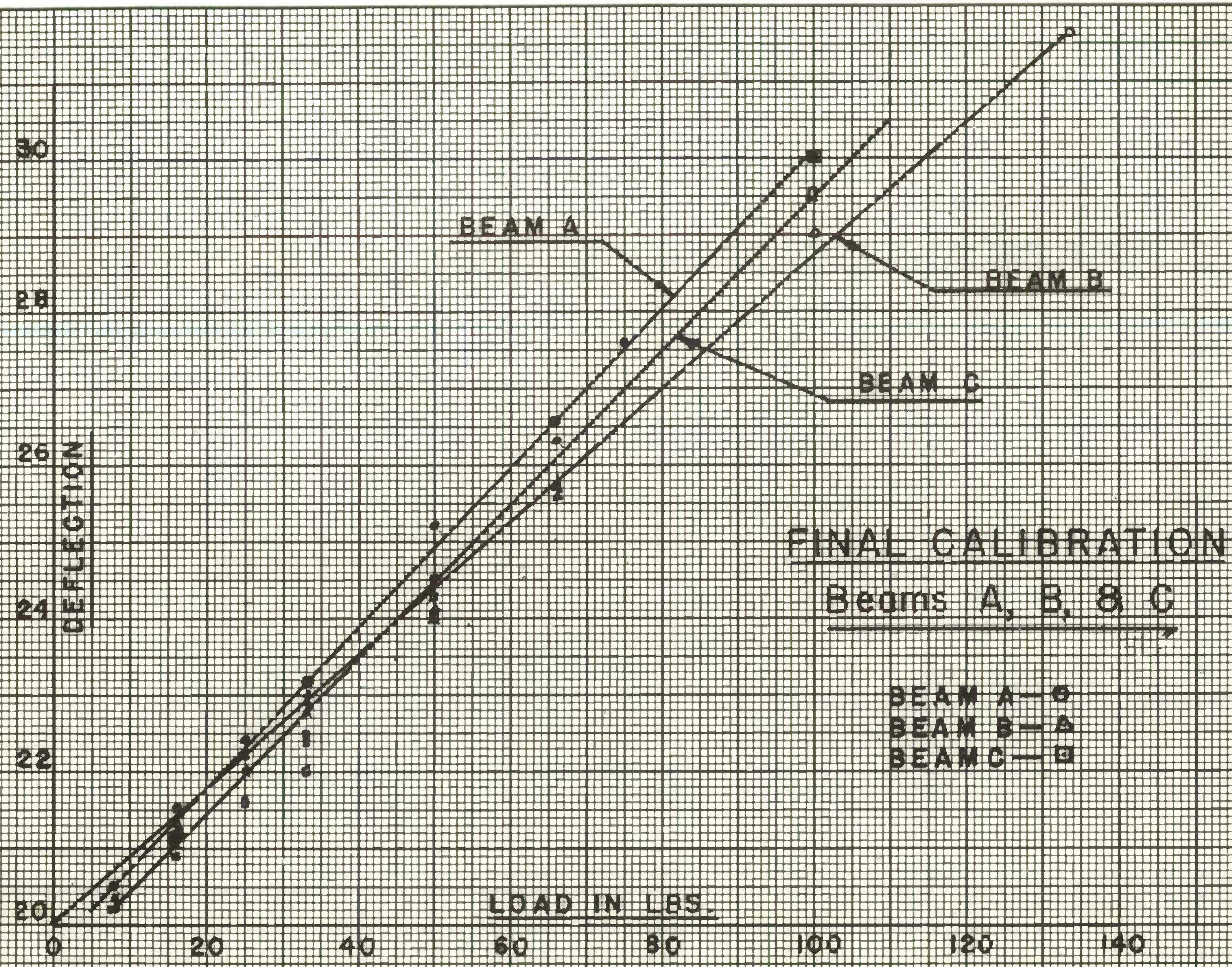

FINAL CALIBRATION
Beams A, B, & C
BEAM A — ○
BEAM B — △
BEAM C — ⊡
BEAM A
BEAM B
BEAM C
DEFLECTION
LOAD IN LBS.
20
22
24
26
28
30
0
20
40
60
80
100
120
140

Fig. 3-8a

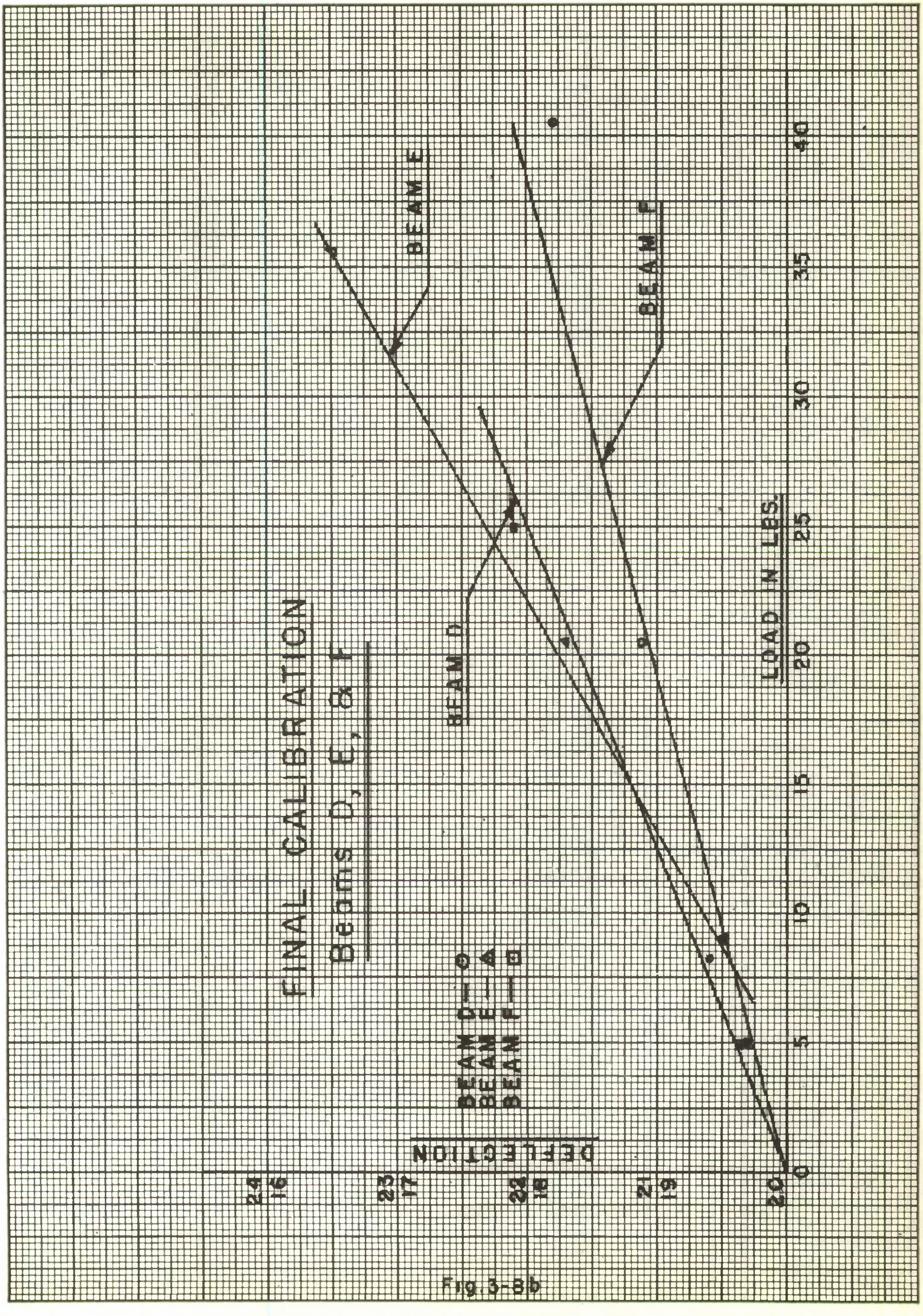
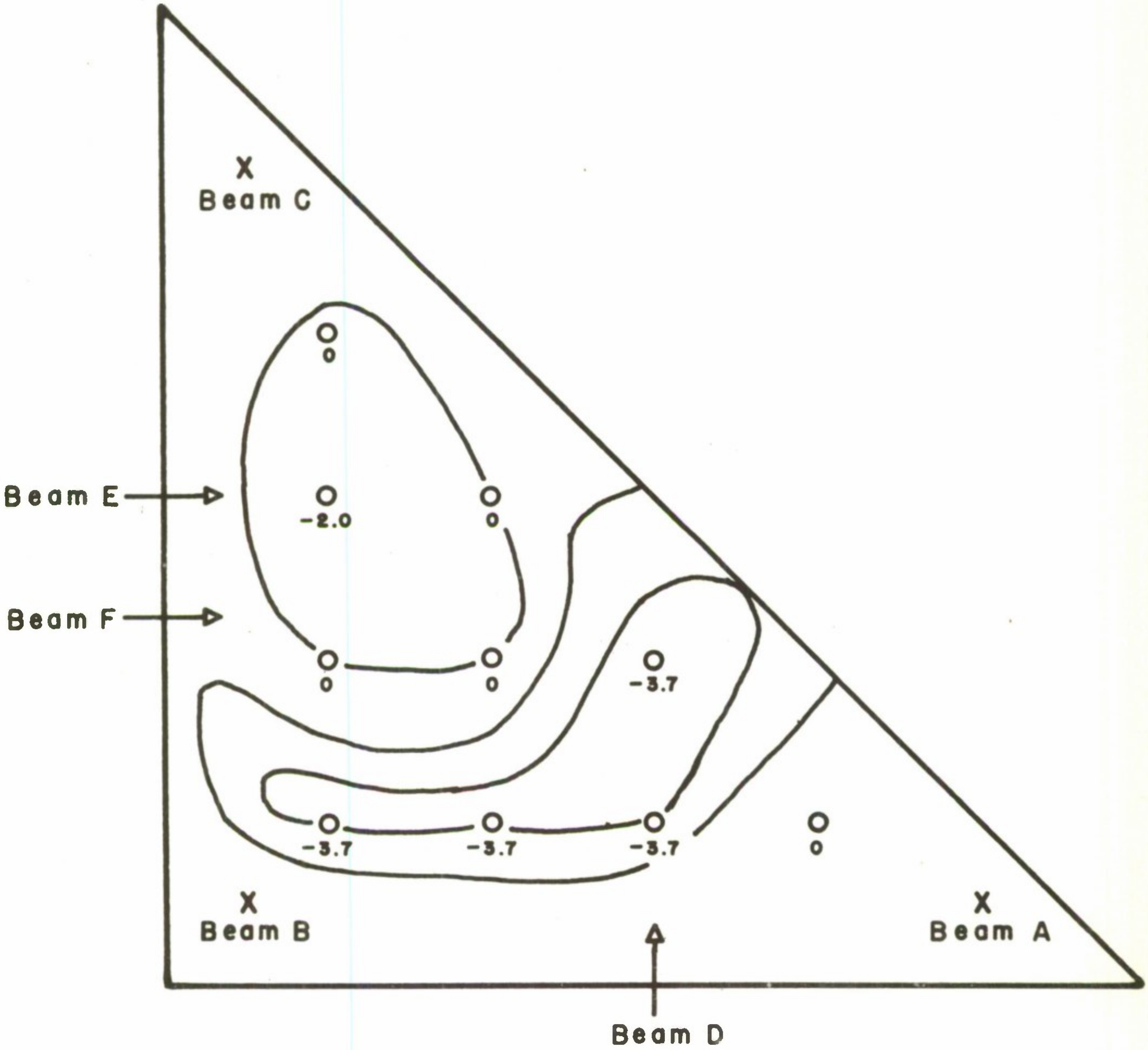

FINAL CALIBRATION
Beams D, E, & F
BEAM D—⊙
BEAM E—△
BEAM F—⊡
BEAM D
BEAM E
BEAM F
DEFLECTION
24
16
23
17
22
18
21
19
20
LOAD IN LBS.
0
5
10
15
20
25
30
35
40

Fig 3-8b



TYPICAL INTERACTION CONTOUR STUDY

150 lb. vertical load causing interaction effect on beam F.

Fig.3-9

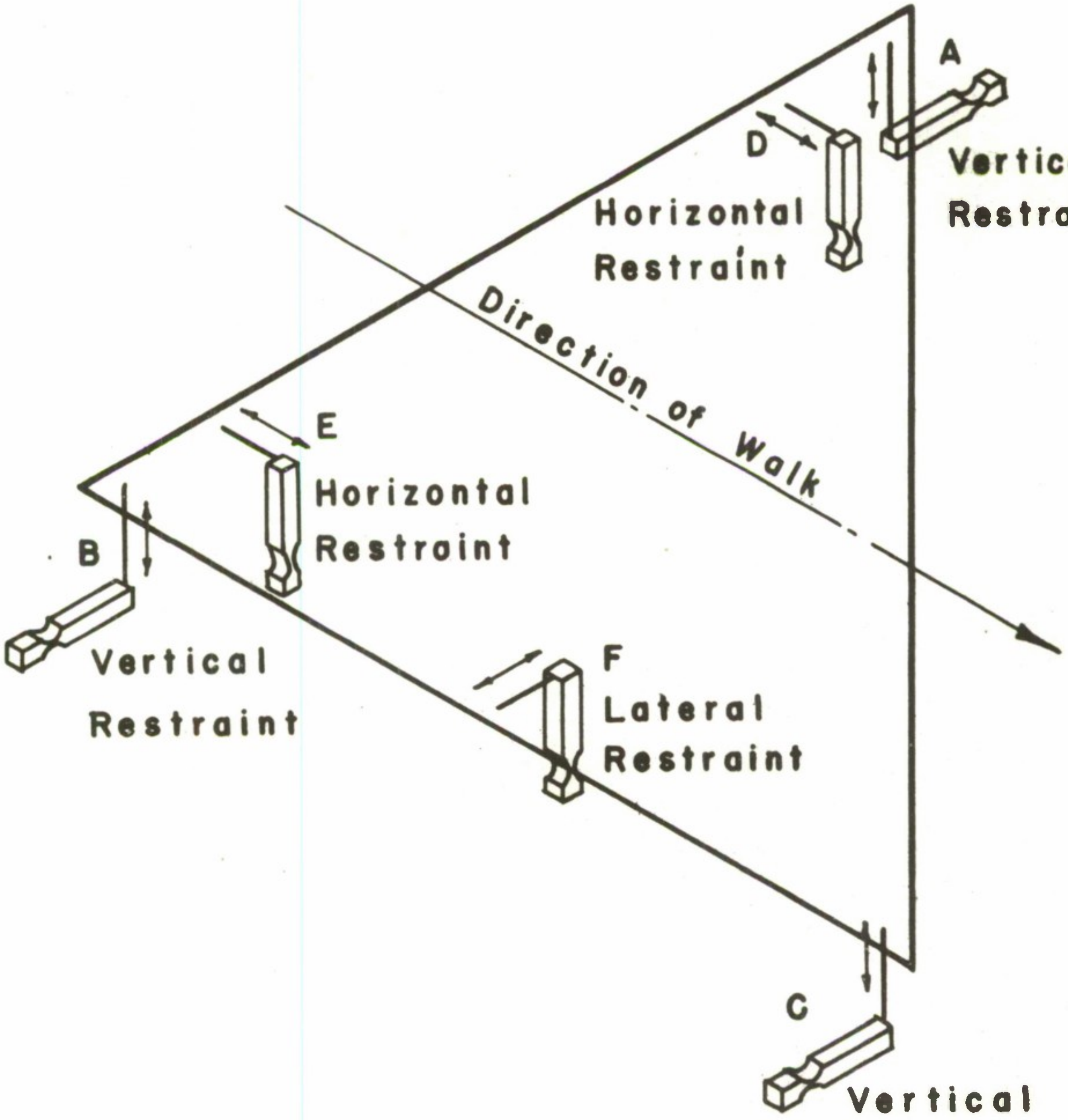
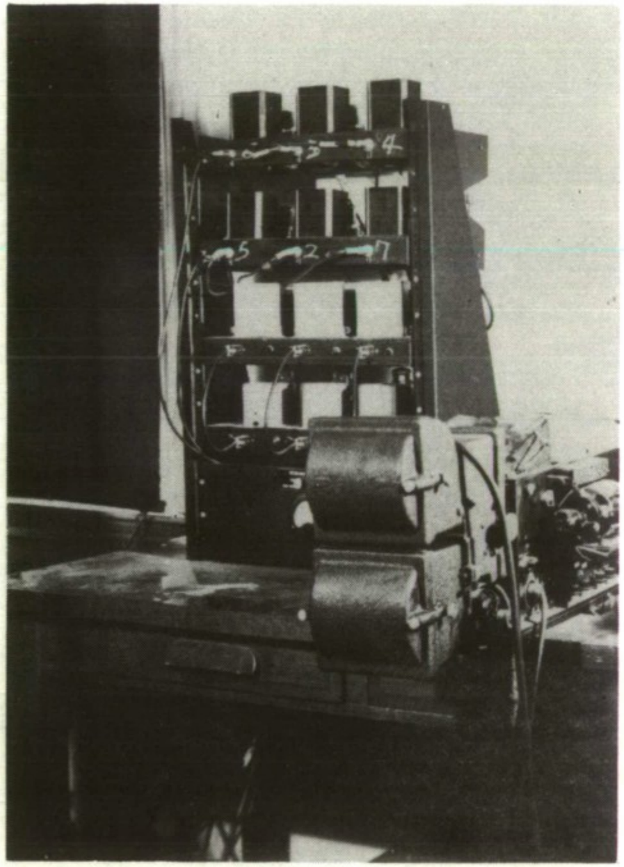


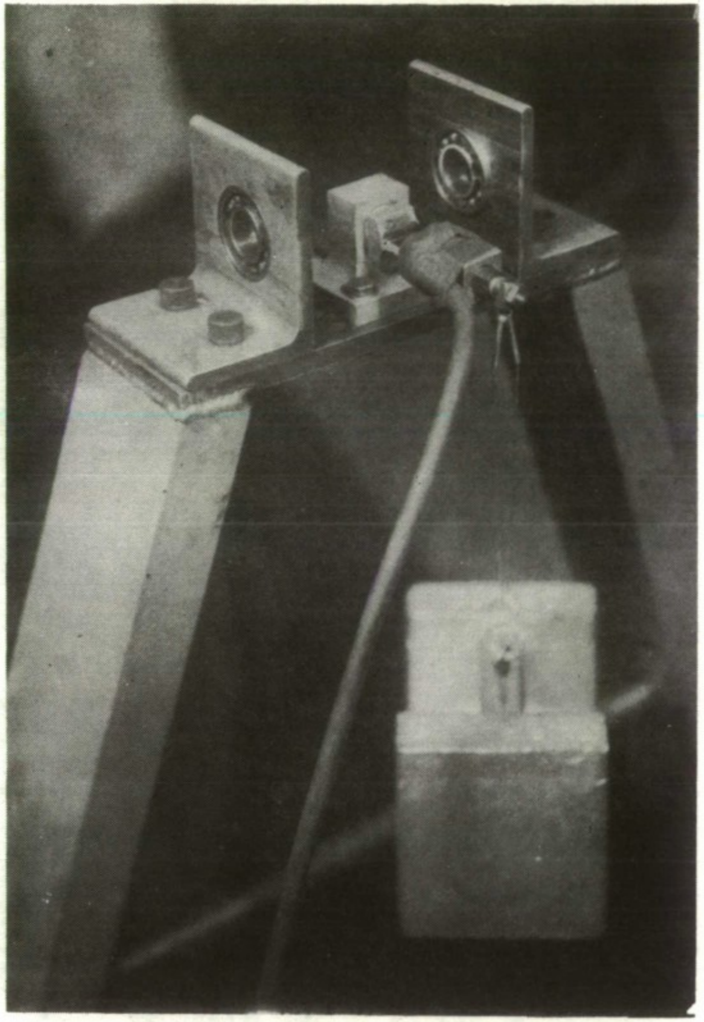
Fig.3-10a

SCHEMATIC DIAGRAM
DYNAMIC FORCE PLATE



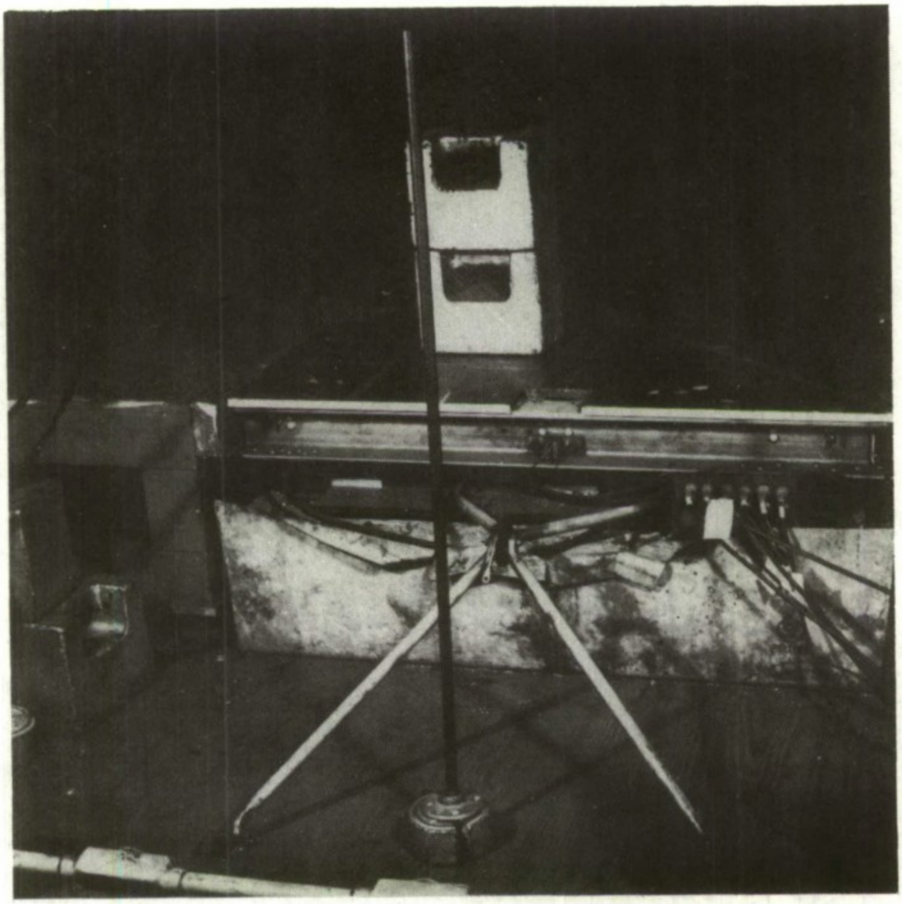
AMPLIFIER
AND
OSCILLOGRAPH

Fig. 3-10 b



INDIVIDUAL
BEAM
CALIBRATION

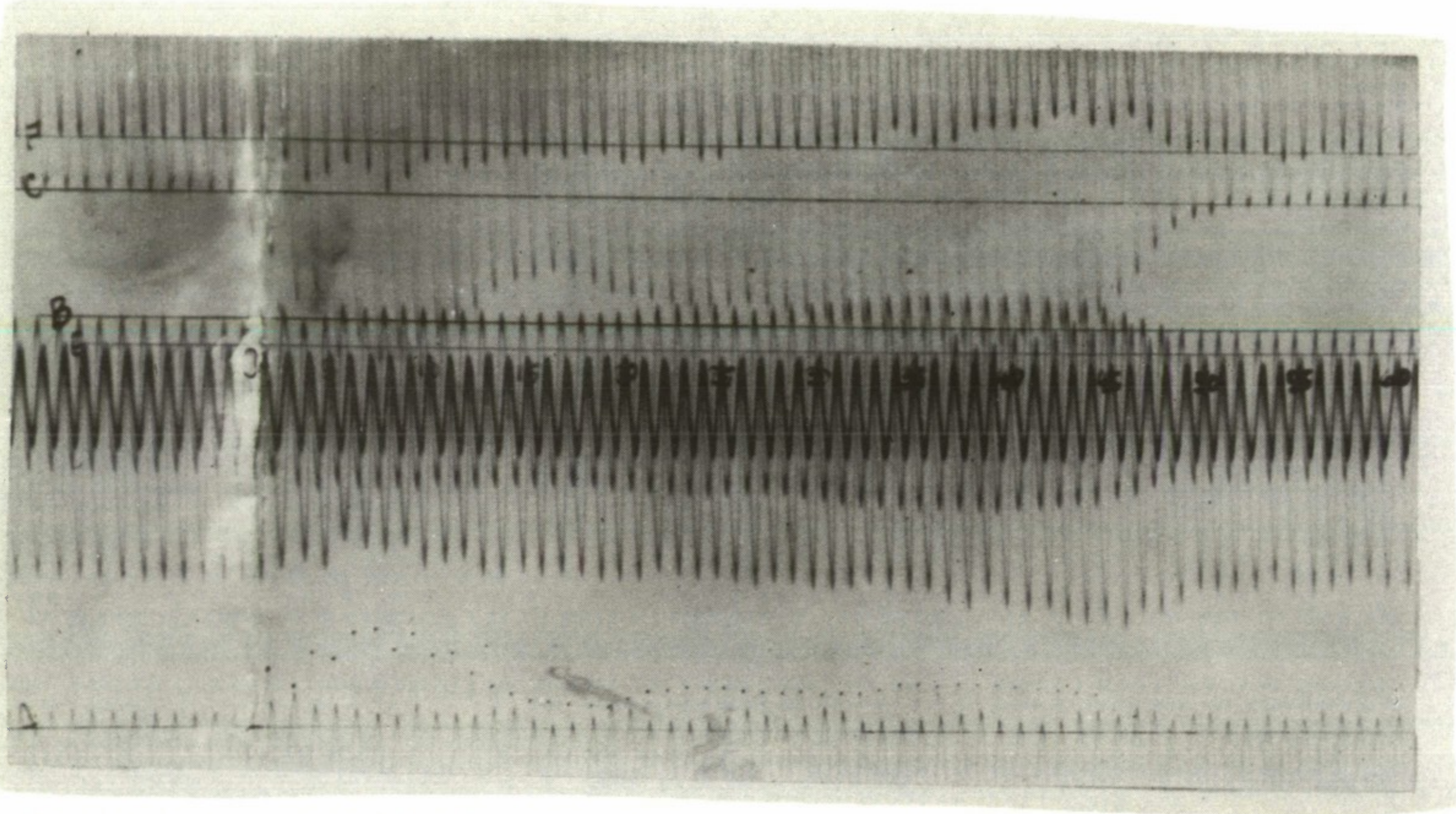
Fig. 3-10 d



CALIBRATION CHECK

The two 50 lb. weight are placed over one of the check locations on the plate face. Side loads are applied to the plate with a cable drawn over the tubing supported pulley.

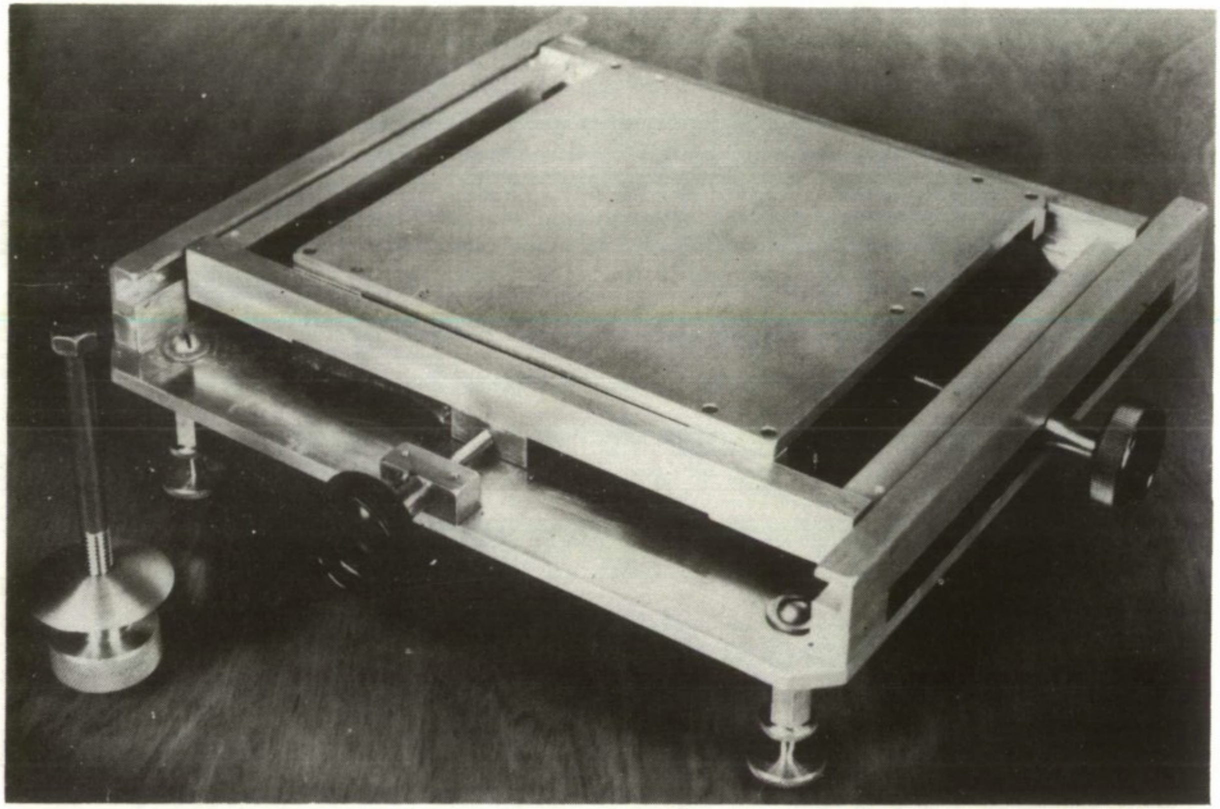
Fig. 3-10c



TYPICAL FORCE PLATE OSCILLOGRAPH RECORD

Lines drawn through zero load wave tips serve as a means of alignment.

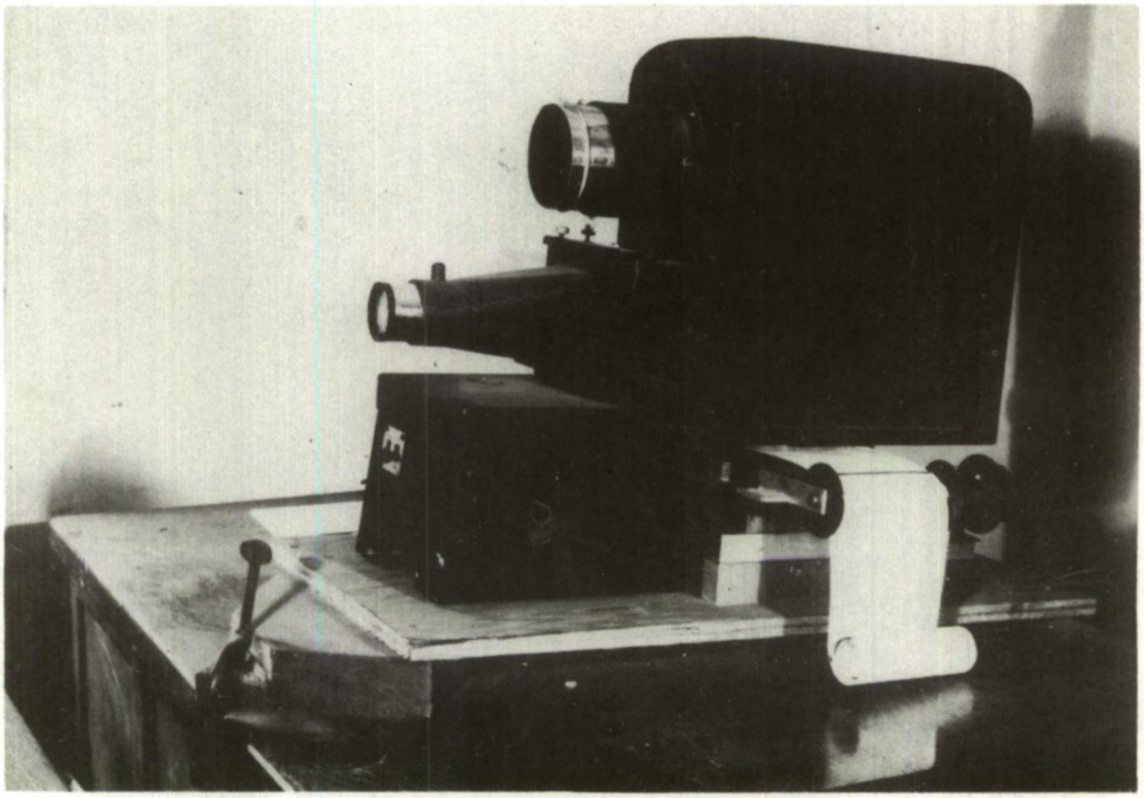
Fig.3-10e



ADJUSTABLE TABLE FOR
CAMERA AND PROJECTOR

Vernier adjustments enable precise adjustments necessary for superimposing movie frames in obtaining stick diagrams.

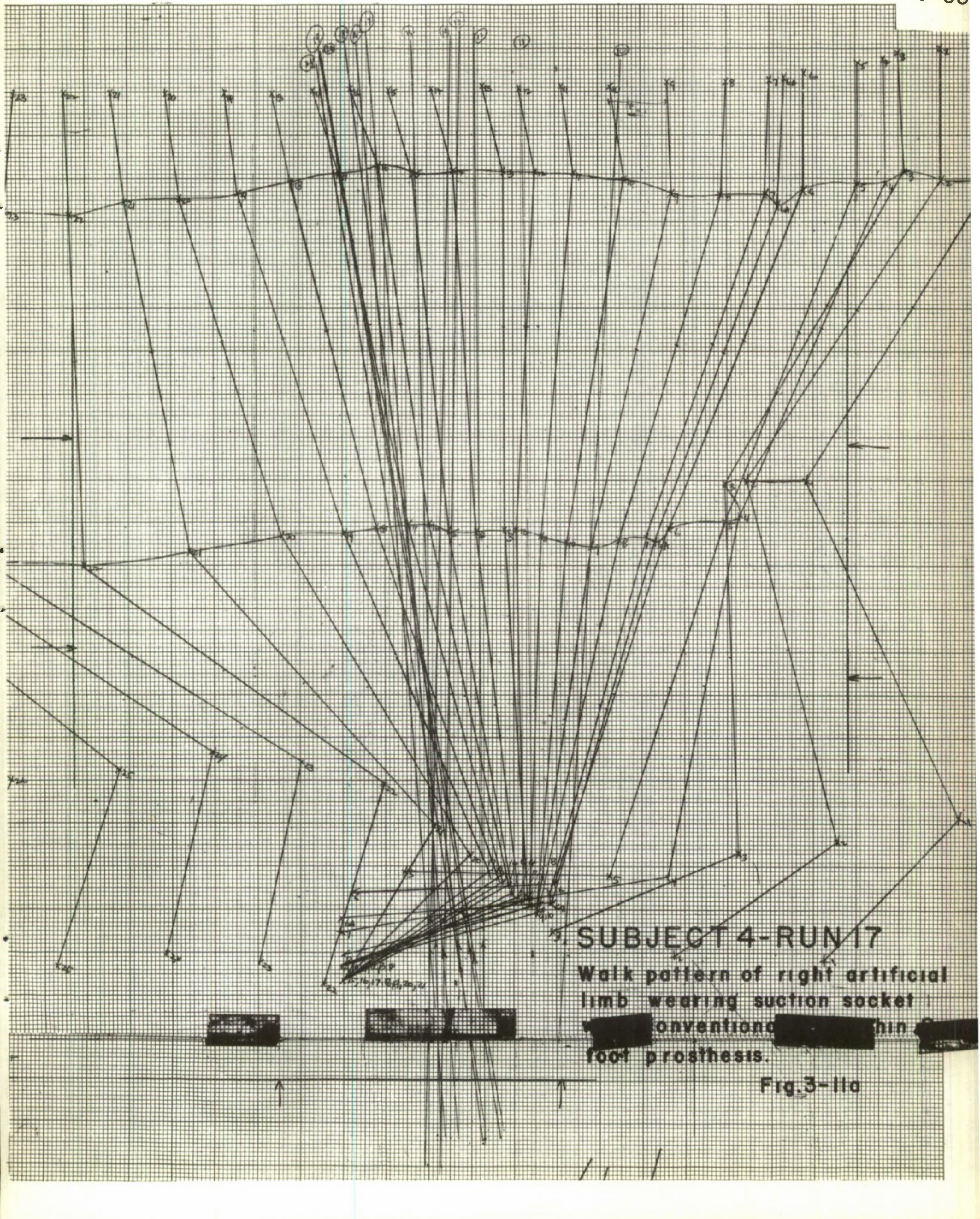
Fig.3-10f



OSCILLOGRAPH PROJECTOR

Standard opaque projector converted to handle rolls of data with provision for vernier adjustment of carrier.

Fig. 3-10g



SUBJECT 4-RUN 17

Walk pattern of right artificial limb wearing suction socket w [redacted] onventiona [redacted] hin [redacted] foot prosthesis.

Fig.3-11a

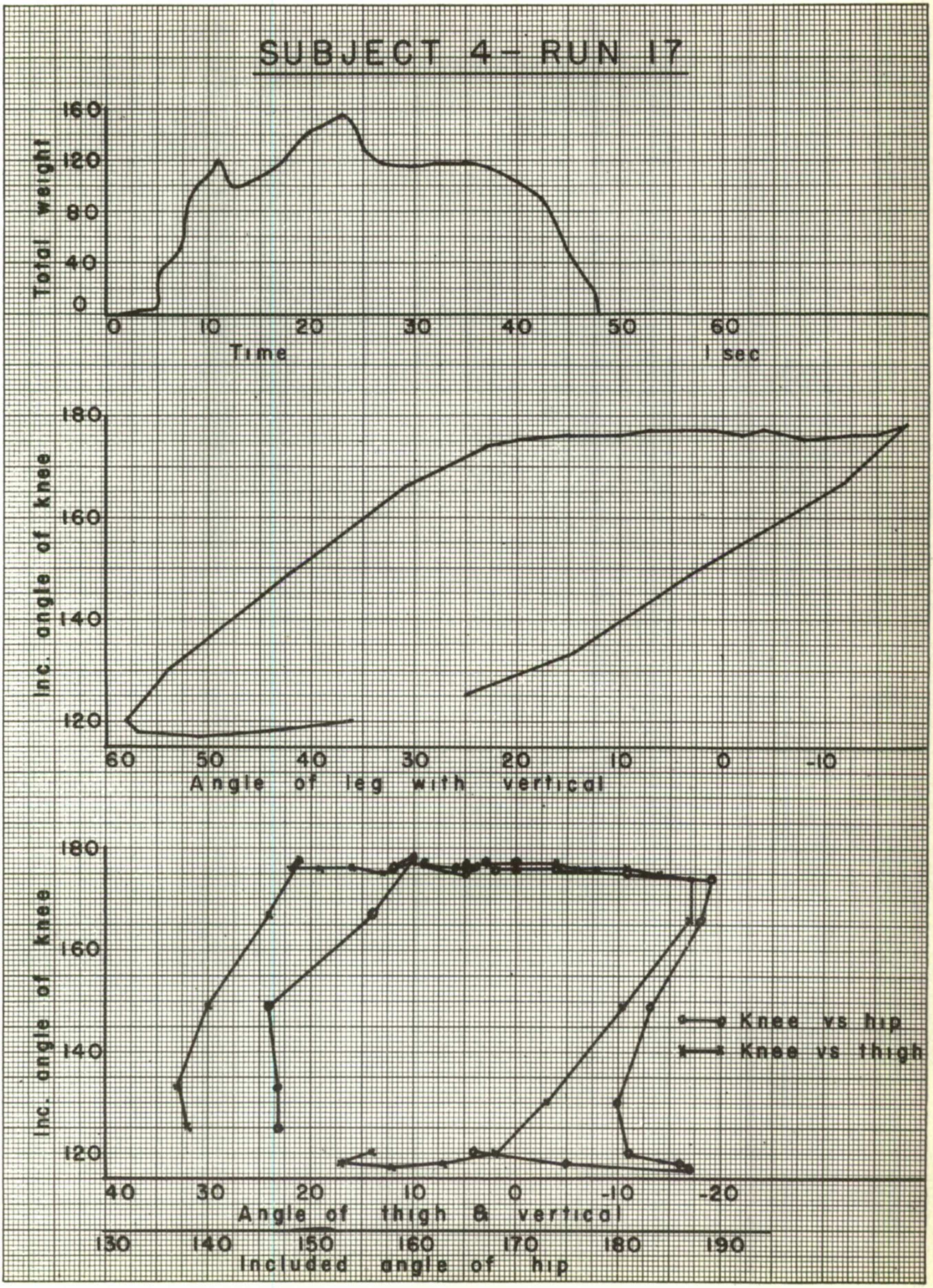
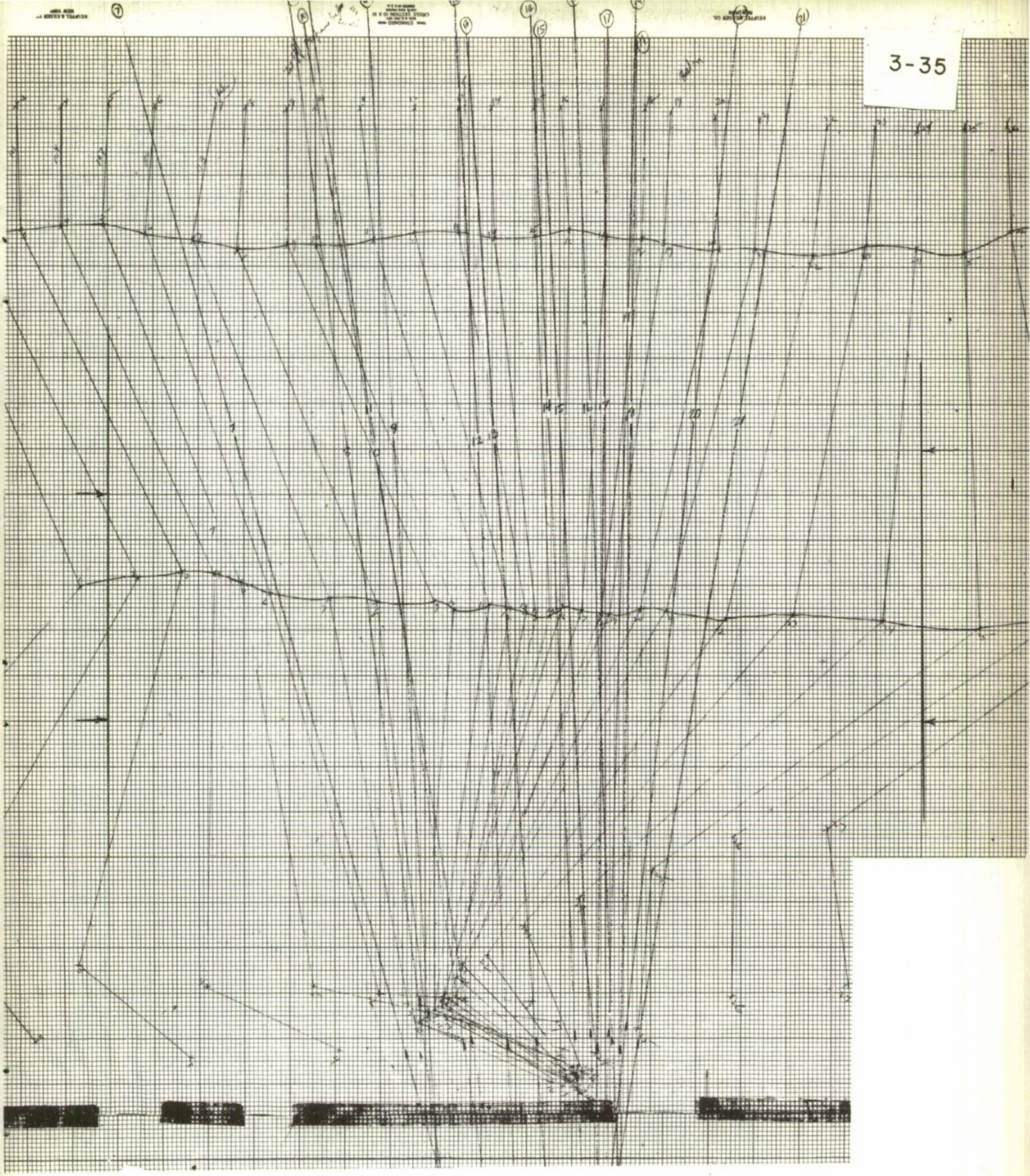

SUBJECT 4 - RUN 17
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
120
60
50
40
30
20
10
0
-10
Angle of leg with vertical
Inc. angle of knee
180
160
140
120
Knee vs hip
Knee vs thigh
40
30
20
10
0
-10
-20
Angle of thigh & vertical
130
140
150
160
170
180
190
Included angle of hip

Fig. 3-11b



SUBJECT 4 - RUN 18

Walk pattern of left normal limb wearing suction socket with conventional V.A. shin & foot prosthesis on right limb.

Fig. 3-12a

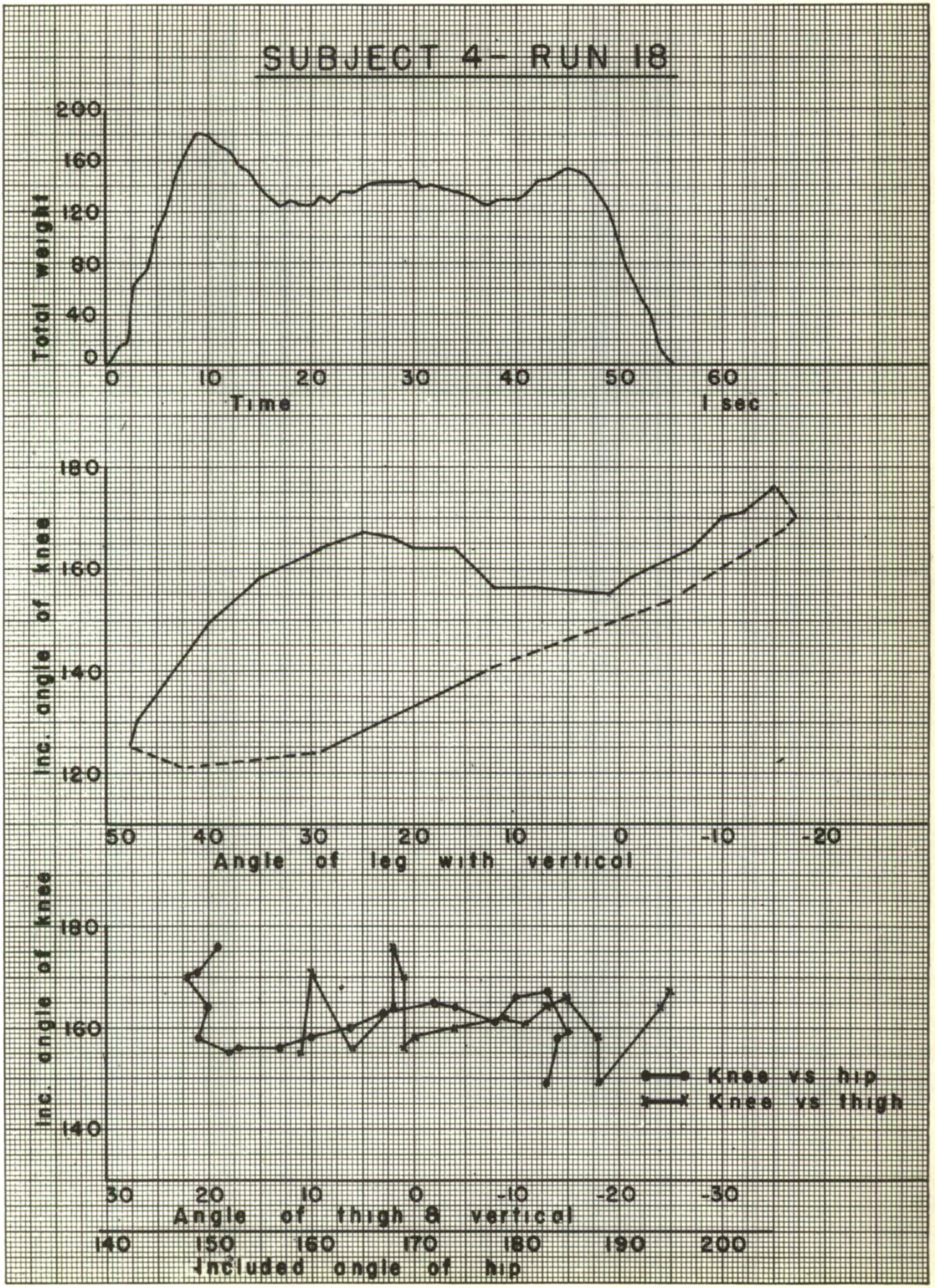
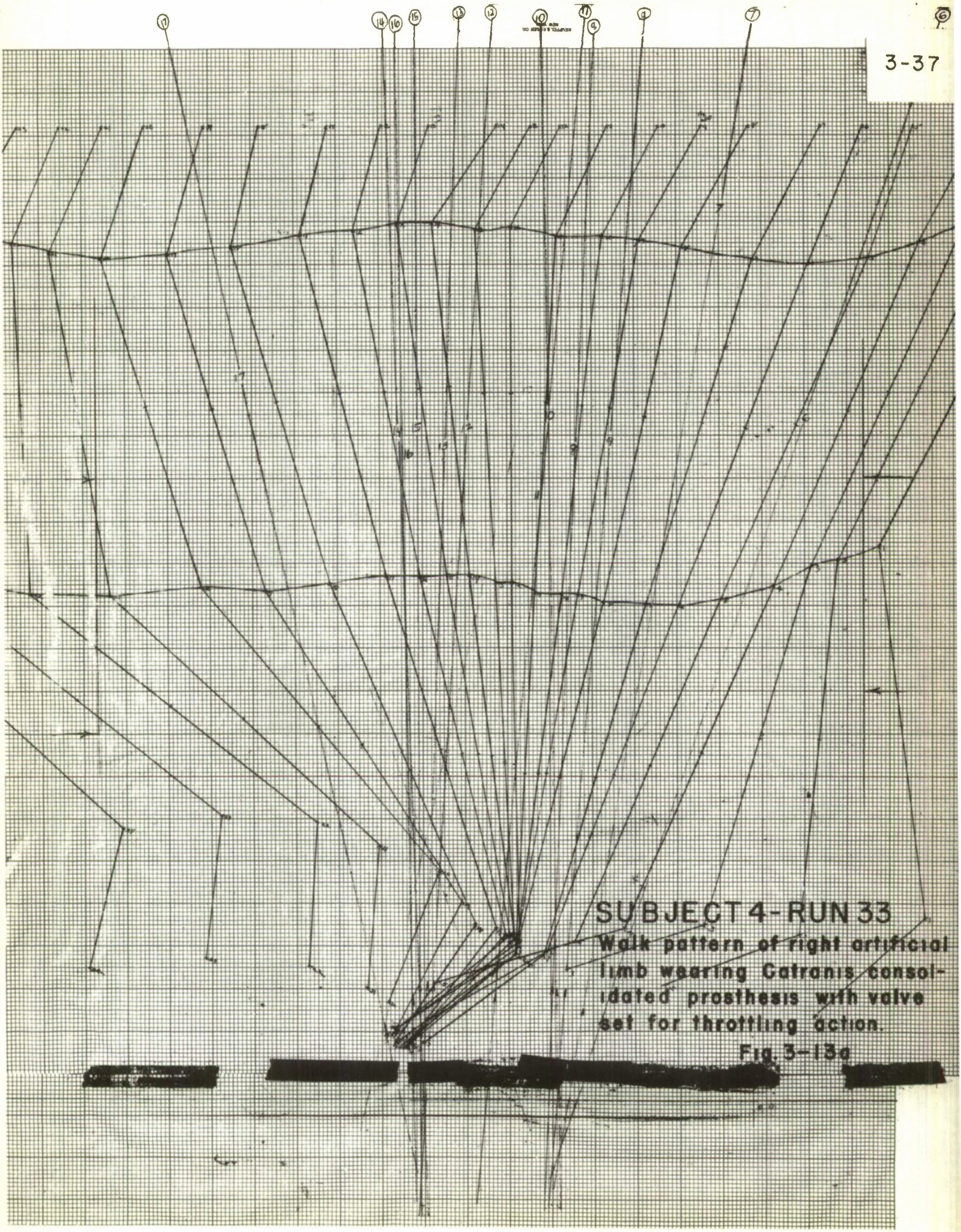

SUBJECT 4- RUN 18
Total weight
200
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
120
50
40
30
20
10
0
-10
-20
Angle of leg with vertical
Inc. angle of knee
180
160
140
Knee vs hip
Knee vs thigh
30
20
10
0
-10
-20
-30
Angle of thigh & vertical
140
150
160
170
180
190
200
Included angle of hip

Fig. 3-12 b



SUBJECT 4 - RUN 33

Walk pattern of right artificial limb wearing Catranis consolidated prosthesis with valve set for throttling action.

Fig. 3-13a

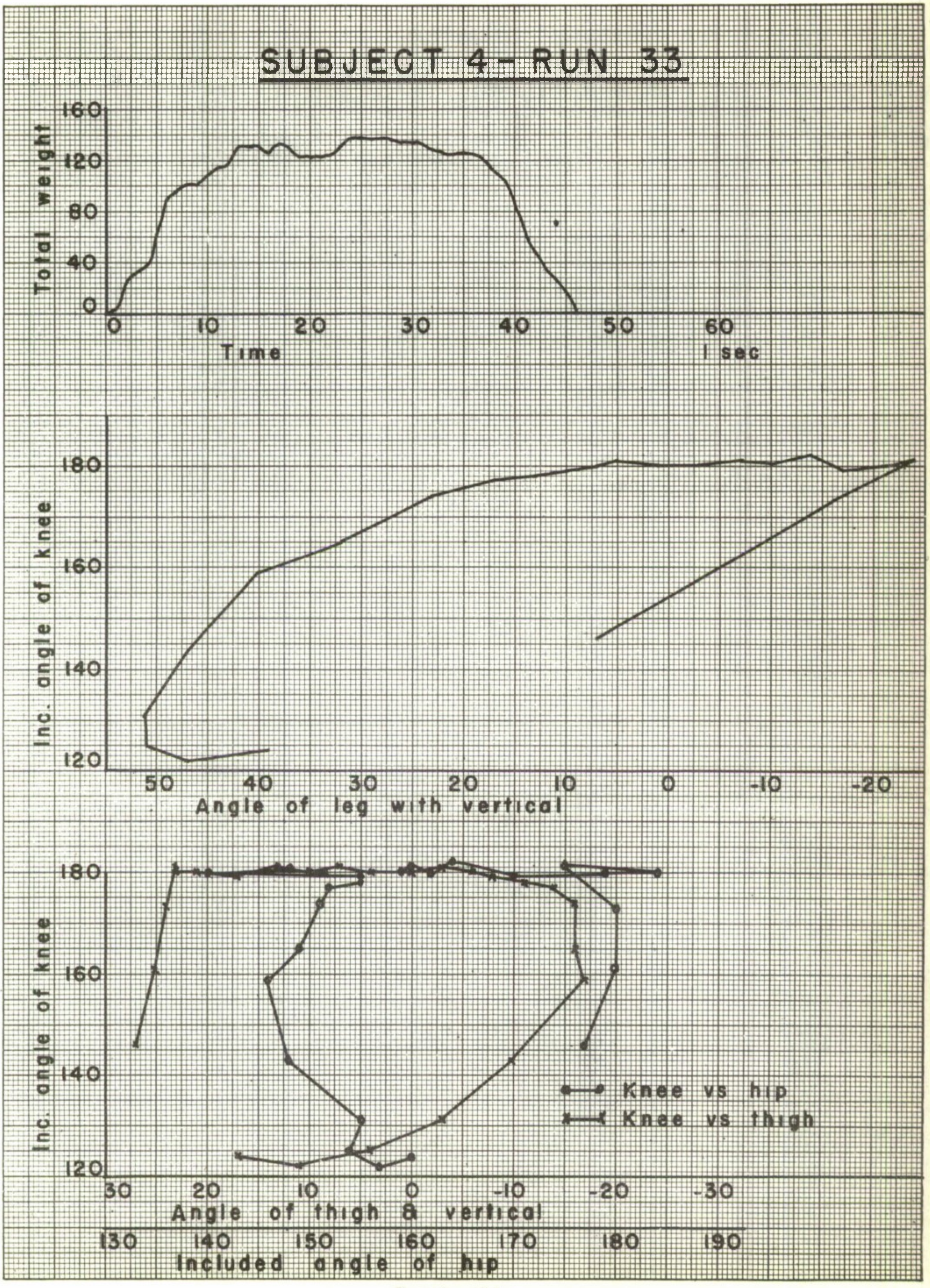
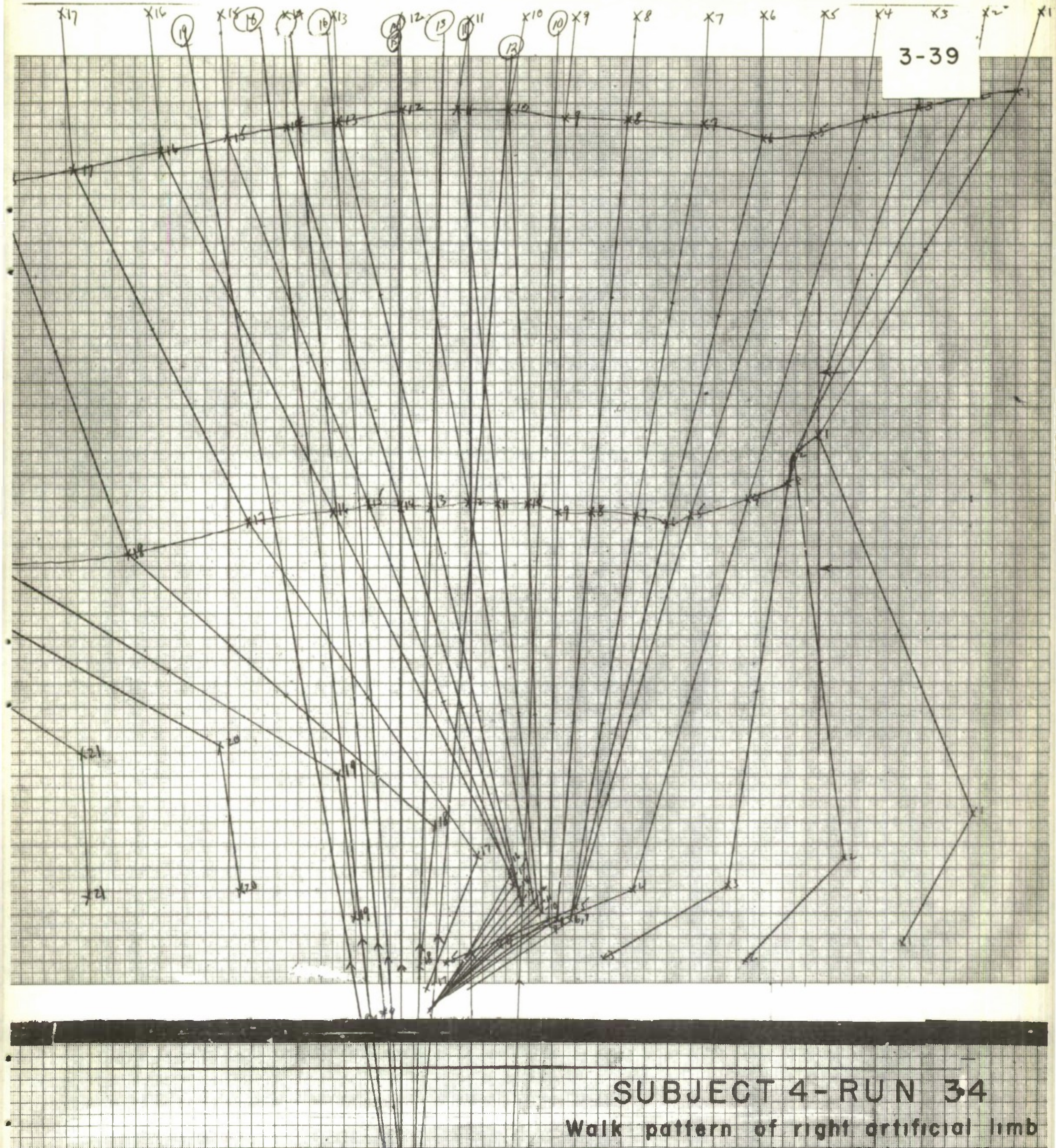

SUBJECT 4 - RUN 33
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
120
50
40
30
20
10
0
-10
-20
Angle of leg with vertical
Inc. angle of knee
180
160
140
120
30
20
10
0
-10
-20
-30
Angle of thigh & vertical
130
140
150
160
170
180
190
Included angle of hip
Knee vs hip
Knee vs thigh

Fig.3-13b



SUBJECT 4 - RUN 34

Walk pattern of right artificial limb wearing conventional V.A. prosthesis.

Fig. 3-14a

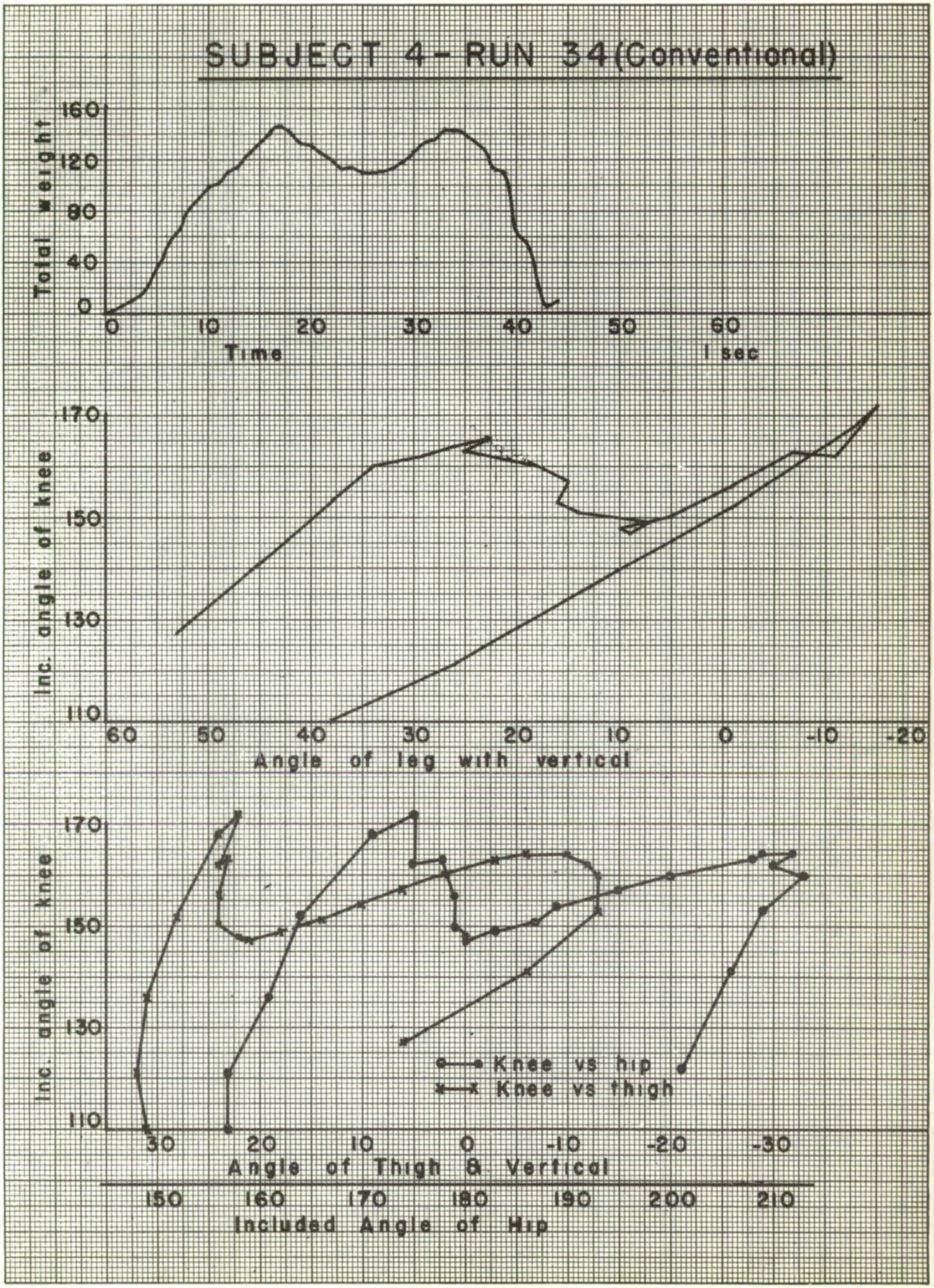
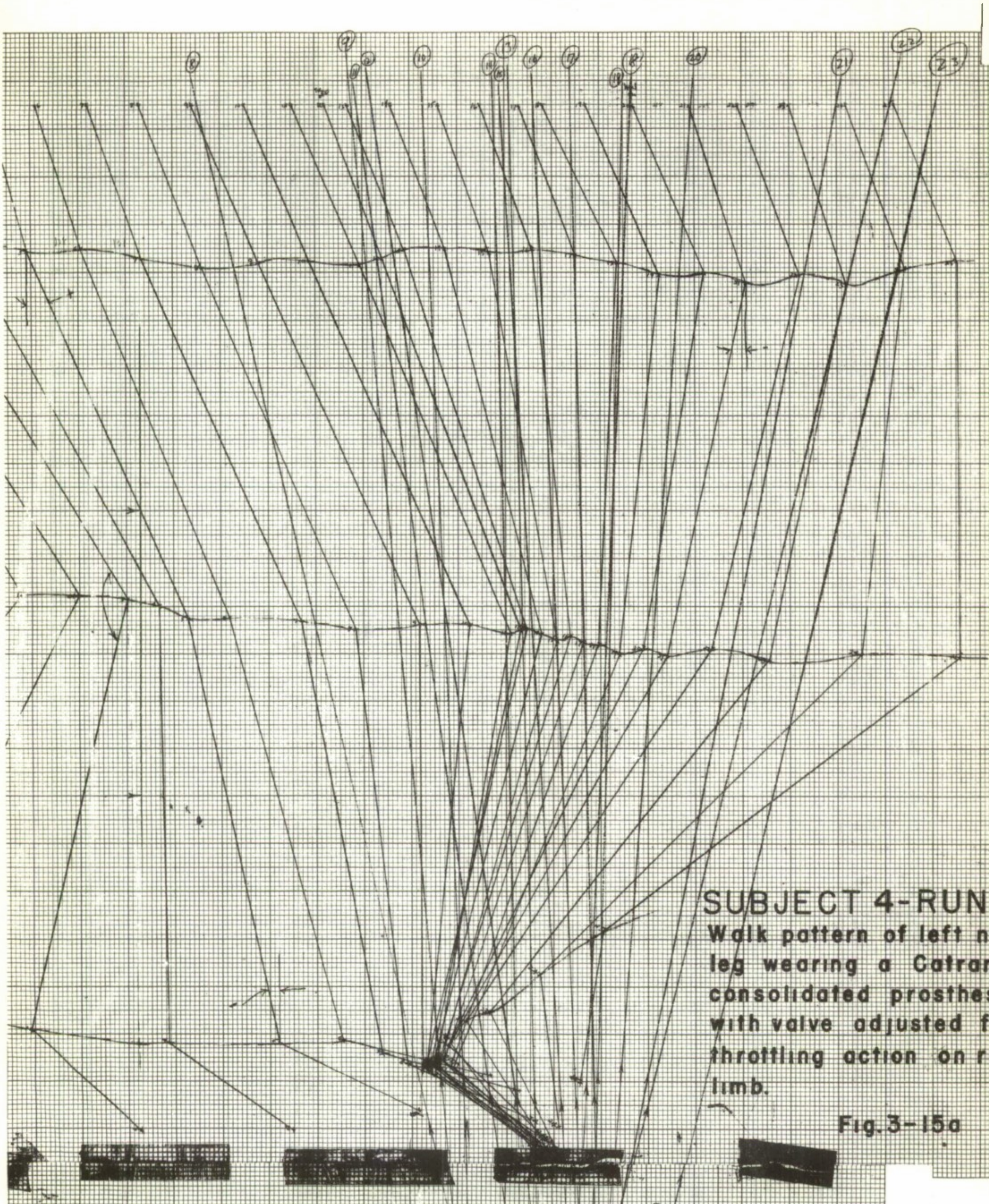

SUBJECT 4 - RUN 34(Conventional)
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
170
150
130
110
60
50
40
30
20
10
0
-10
-20
Angle of leg with vertical
Inc. angle of knee
170
150
130
110
Knee vs hip
Knee vs thigh
30
20
10
0
-10
-20
-30
Angle of Thigh & Vertical
150
160
170
180
190
200
210
Included Angle of Hip

Fig.3-14b



SUBJECT 4-RUN 34

Walk pattern of left normal leg wearing a Catranis consolidated prosthesis with valve adjusted for throttling action on right limb.

Fig. 3-15a

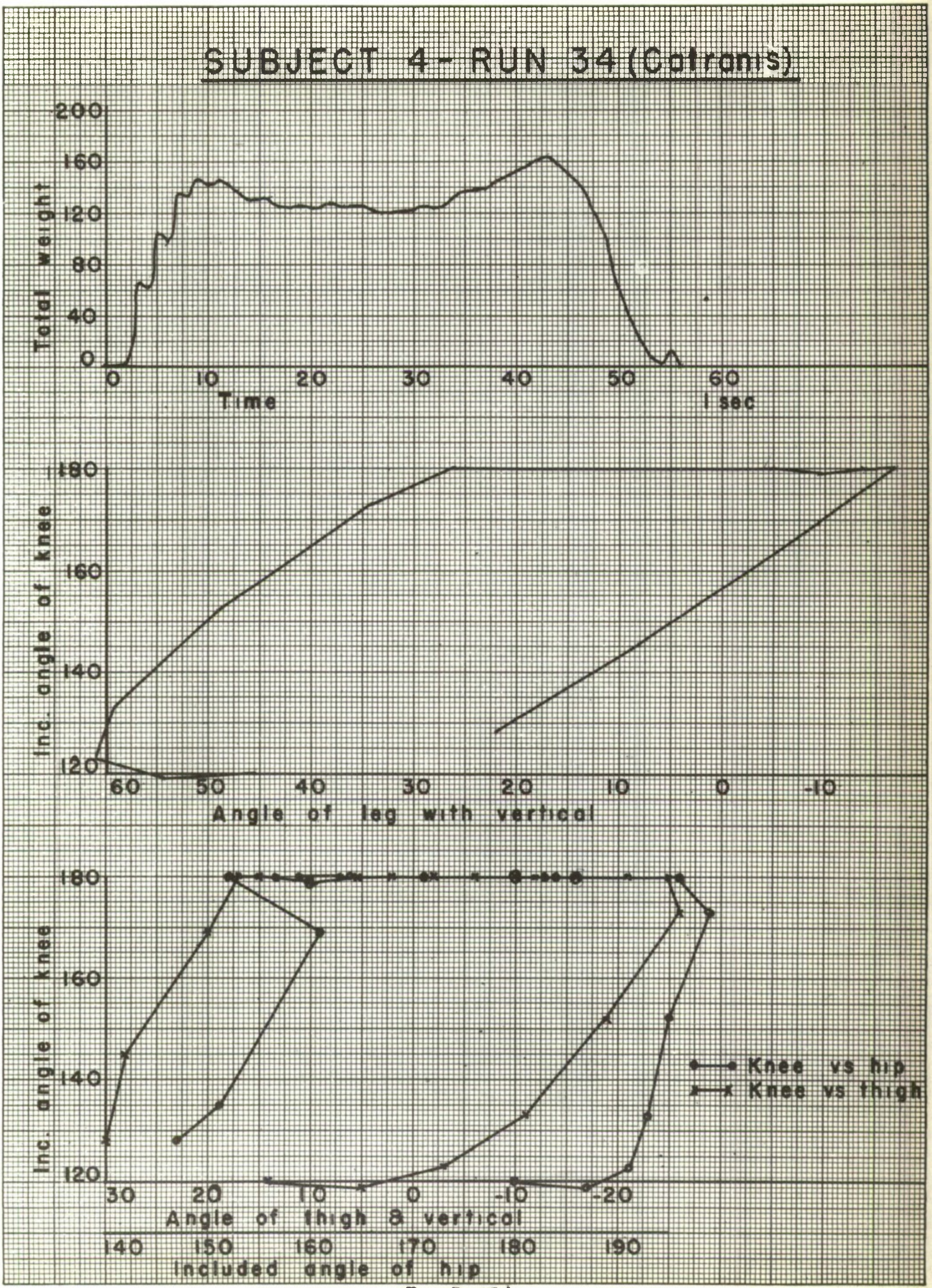
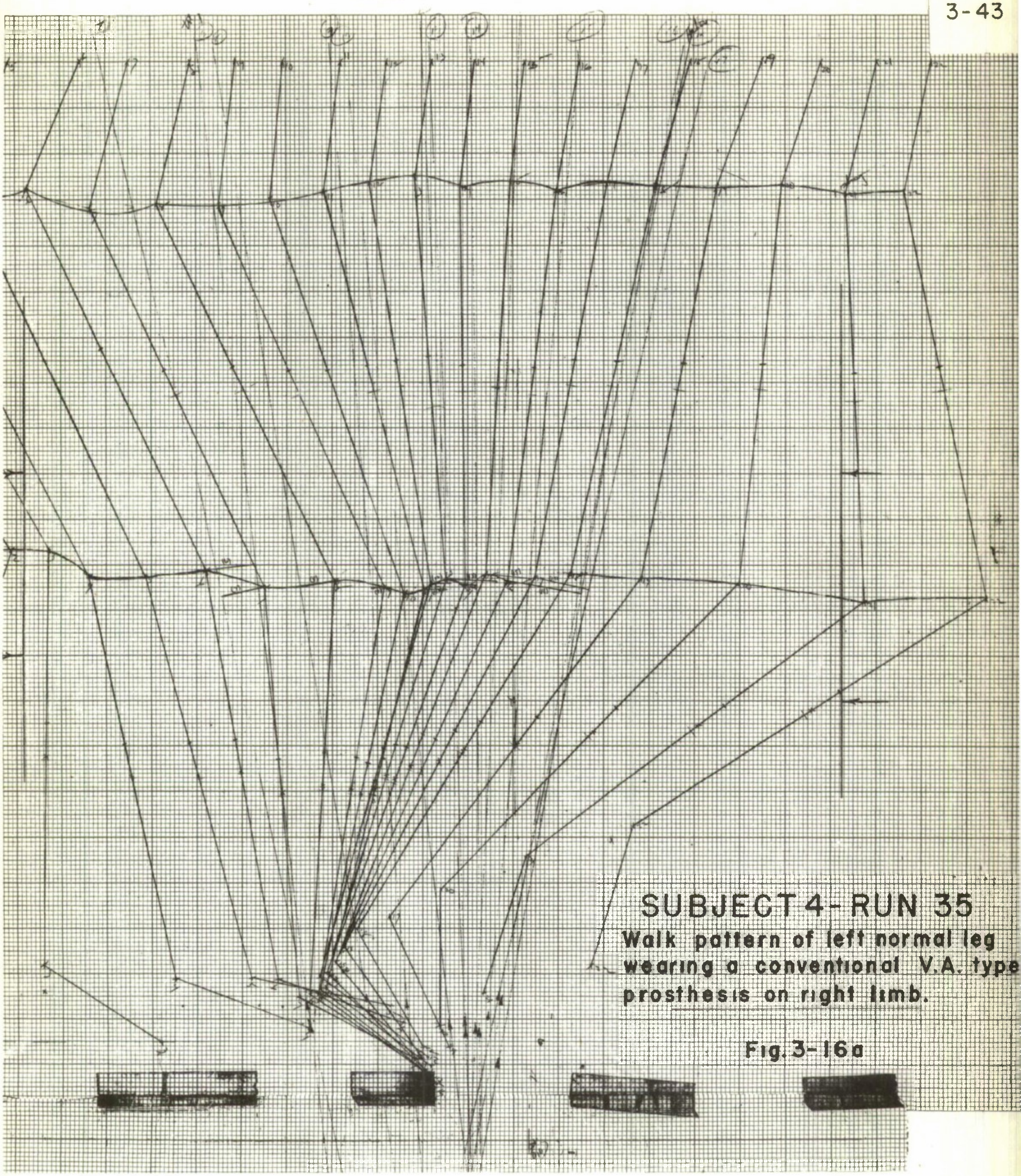

SUBJECT 4 - RUN 34 (Cotronis)
Total weight
200
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
120
60
50
40
30
20
10
0
-10
Angle of leg with vertical
Inc. angle of knee
180
160
140
120
30
20
10
0
-10
-20
Angle of thigh & vertical
140
150
160
170
180
190
Included angle of hip
Knee vs hip
Knee vs thigh

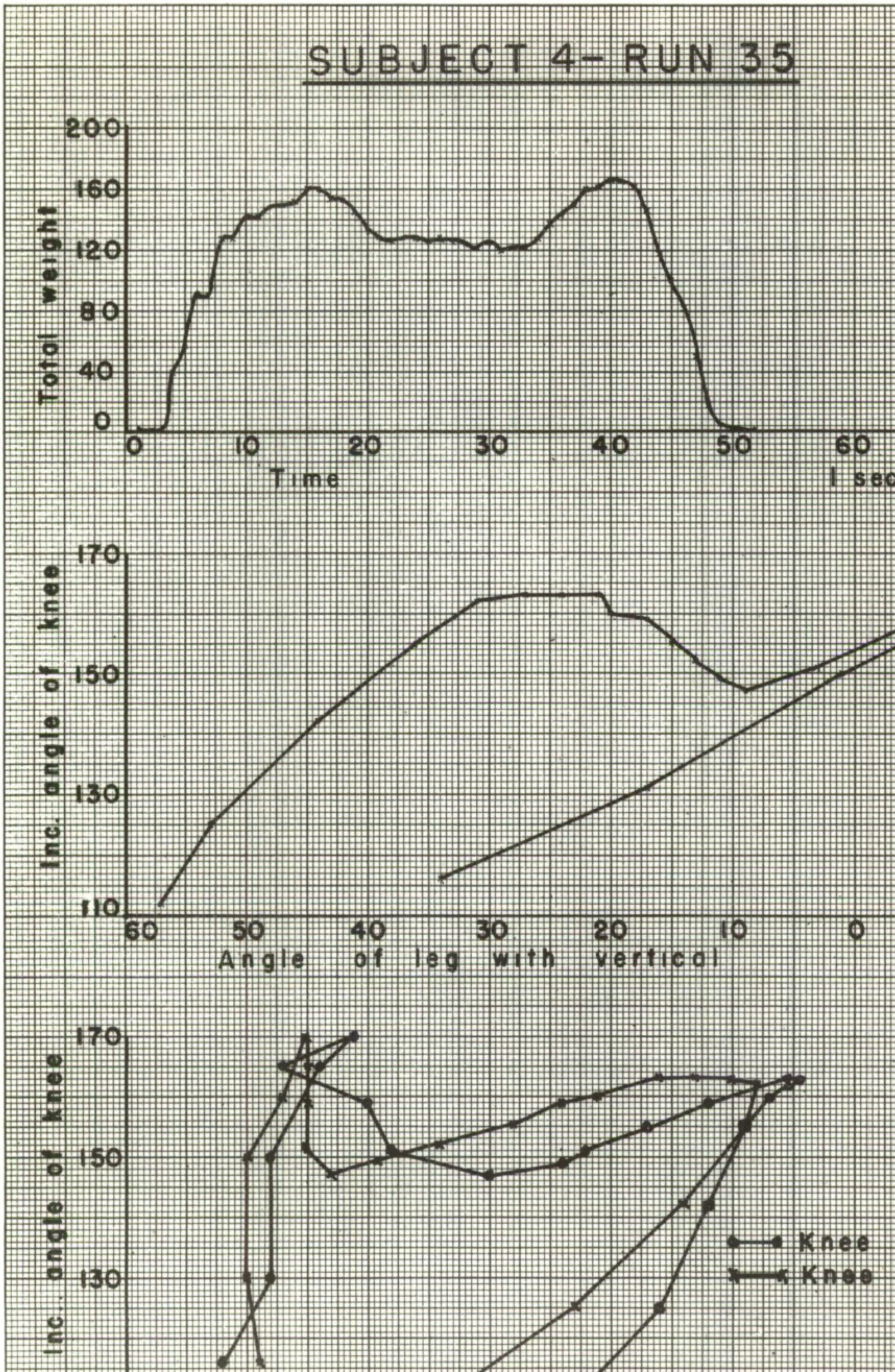
Fig.3-15 b



SUBJECT 4 - RUN 35

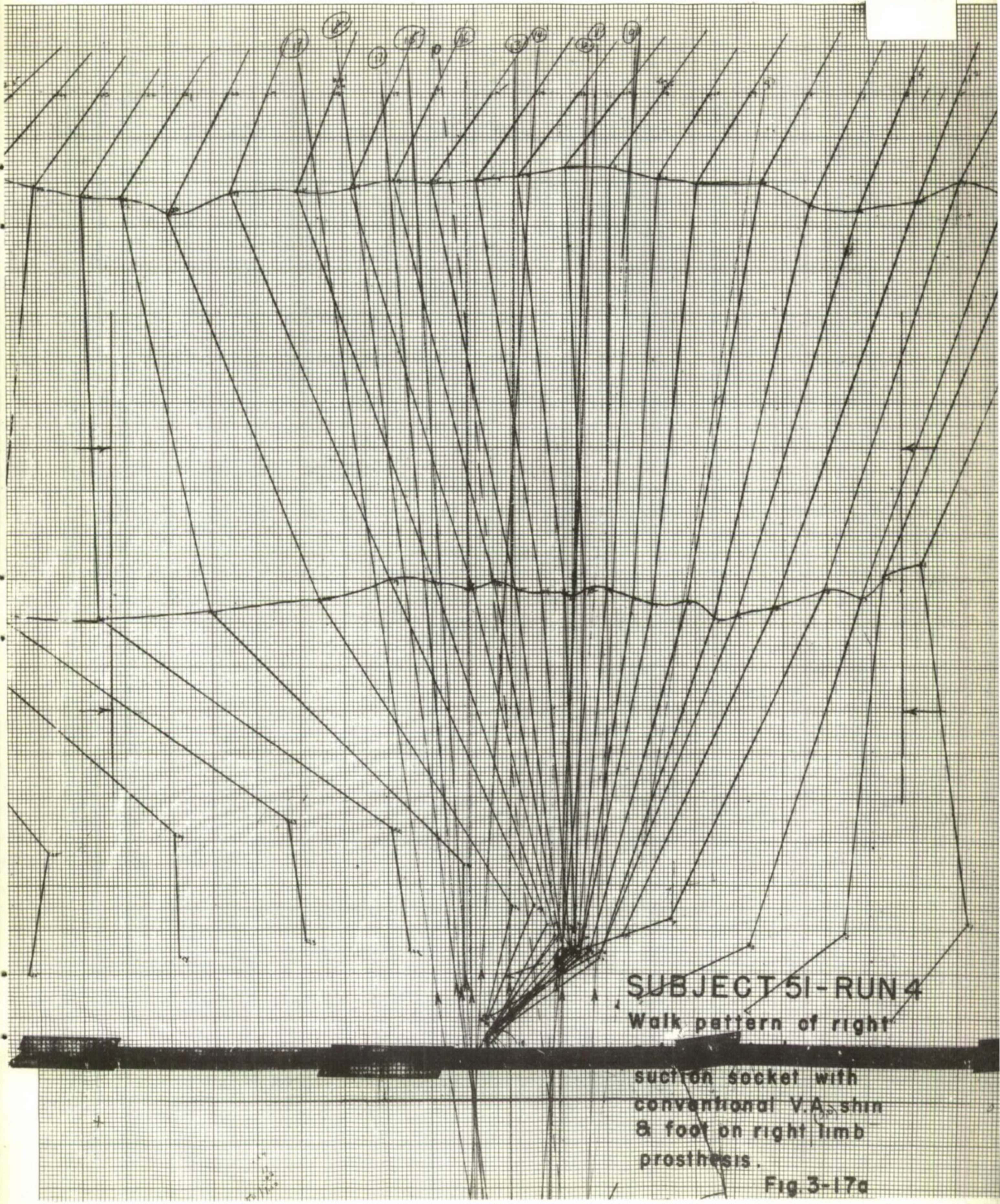
Walk pattern of left normal leg wearing a conventional V.A. type prosthesis on right limb.

Fig. 3-16a



SUBJECT 4- RUN 35

Fig. 3-16b



SUBJECT 51 - RUN 4

Walk pattern of right suction socket with conventional V.A. shin & foot on right limb prosthesis.

Fig. 3-17a

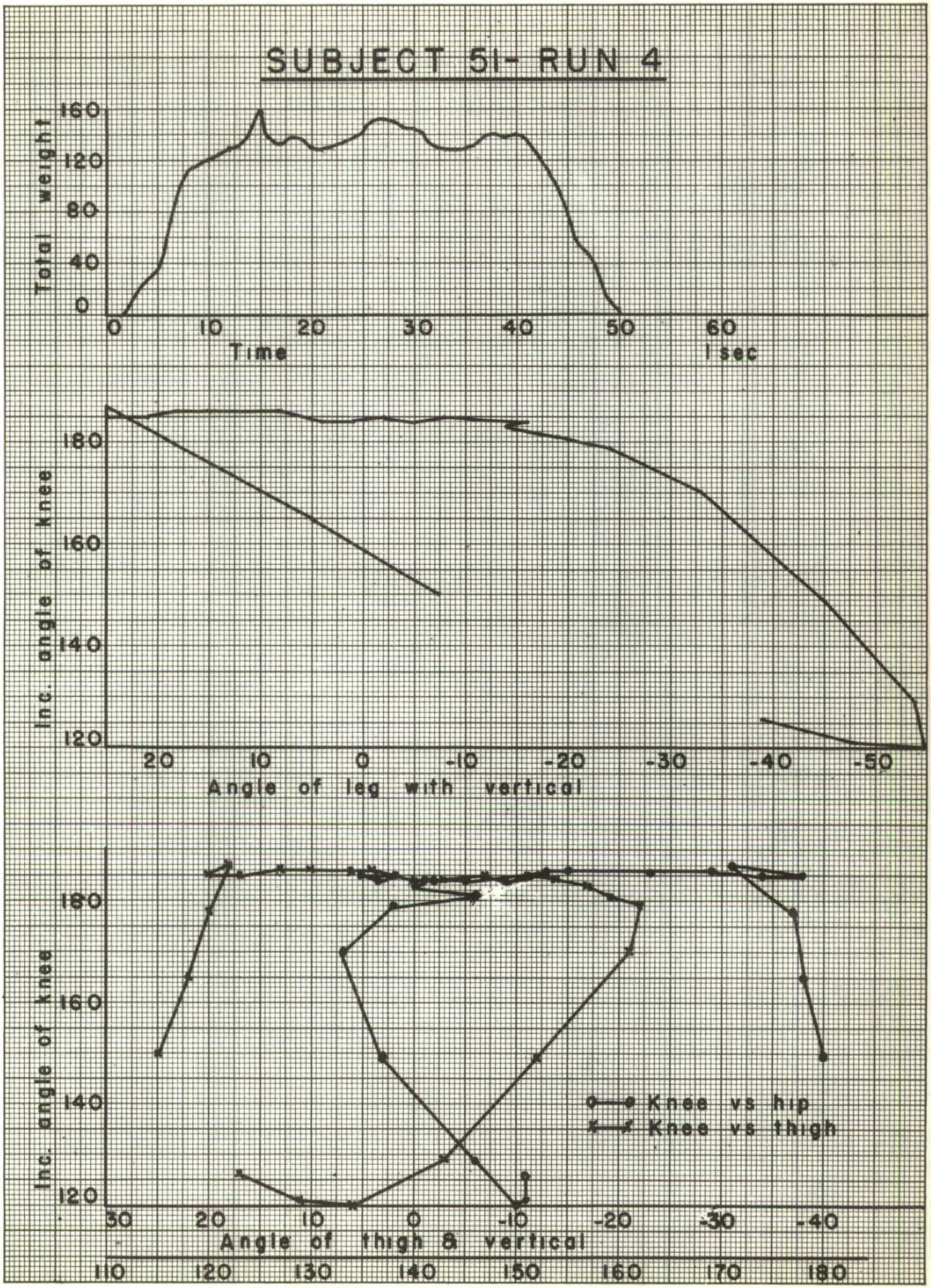
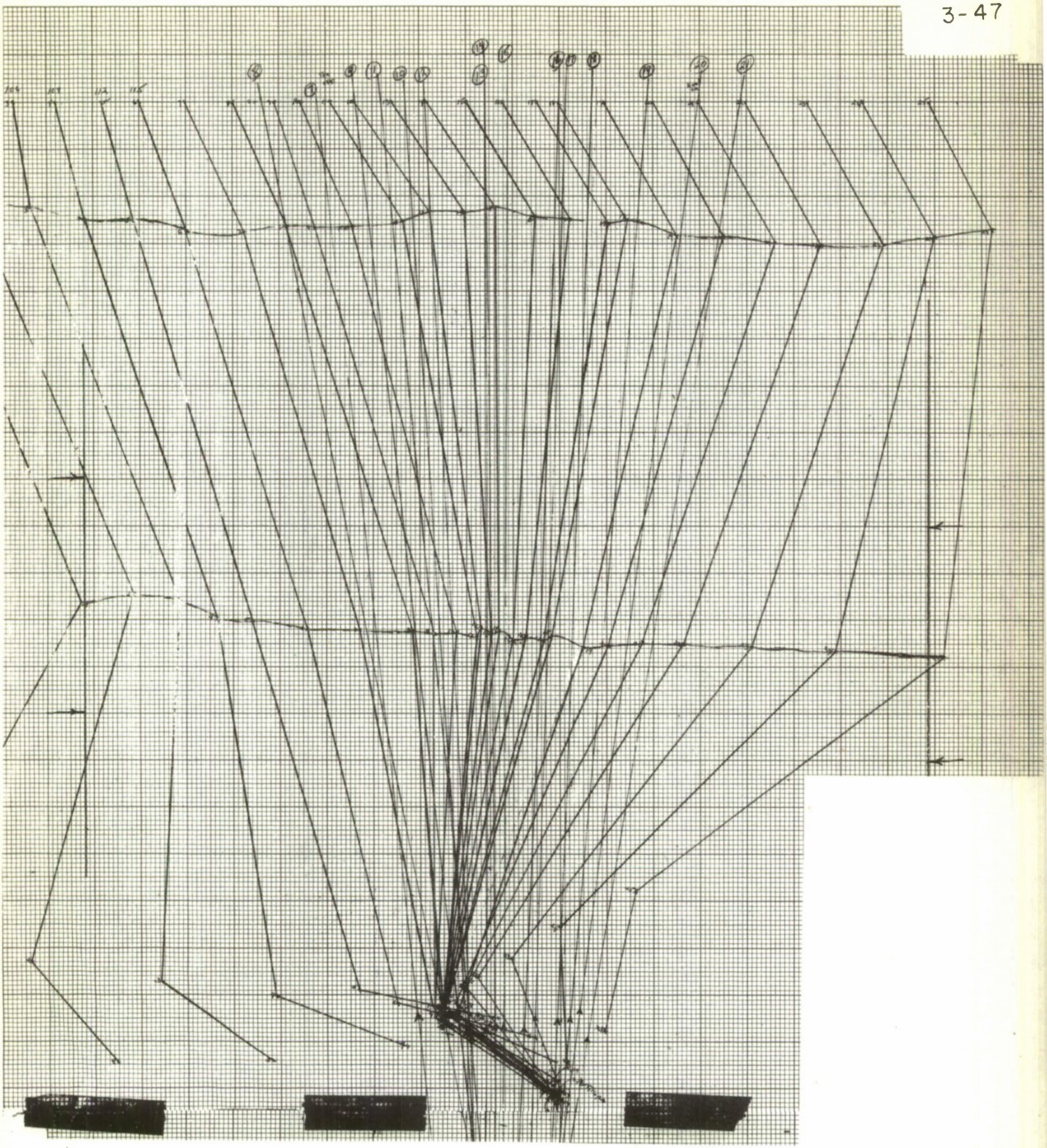

SUBJECT 51- RUN 4
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
120
20
10
0
-10
-20
-30
-40
-50
Angle of leg with vertical
Inc. angle of knee
180
160
140
120
30
20
10
0
-10
-20
-30
-40
Angle of thigh & vertical
110
120
130
140
150
160
170
180
Included angle of hip
Knee vs hip
Knee vs thigh

Fig. 3-17b



SUBJECT 51-RUN 5

Walk pattern of left normal limb wearing suction socket with conventional V.A. shin & foot on right limb prosthesis.

Fig.3-18a

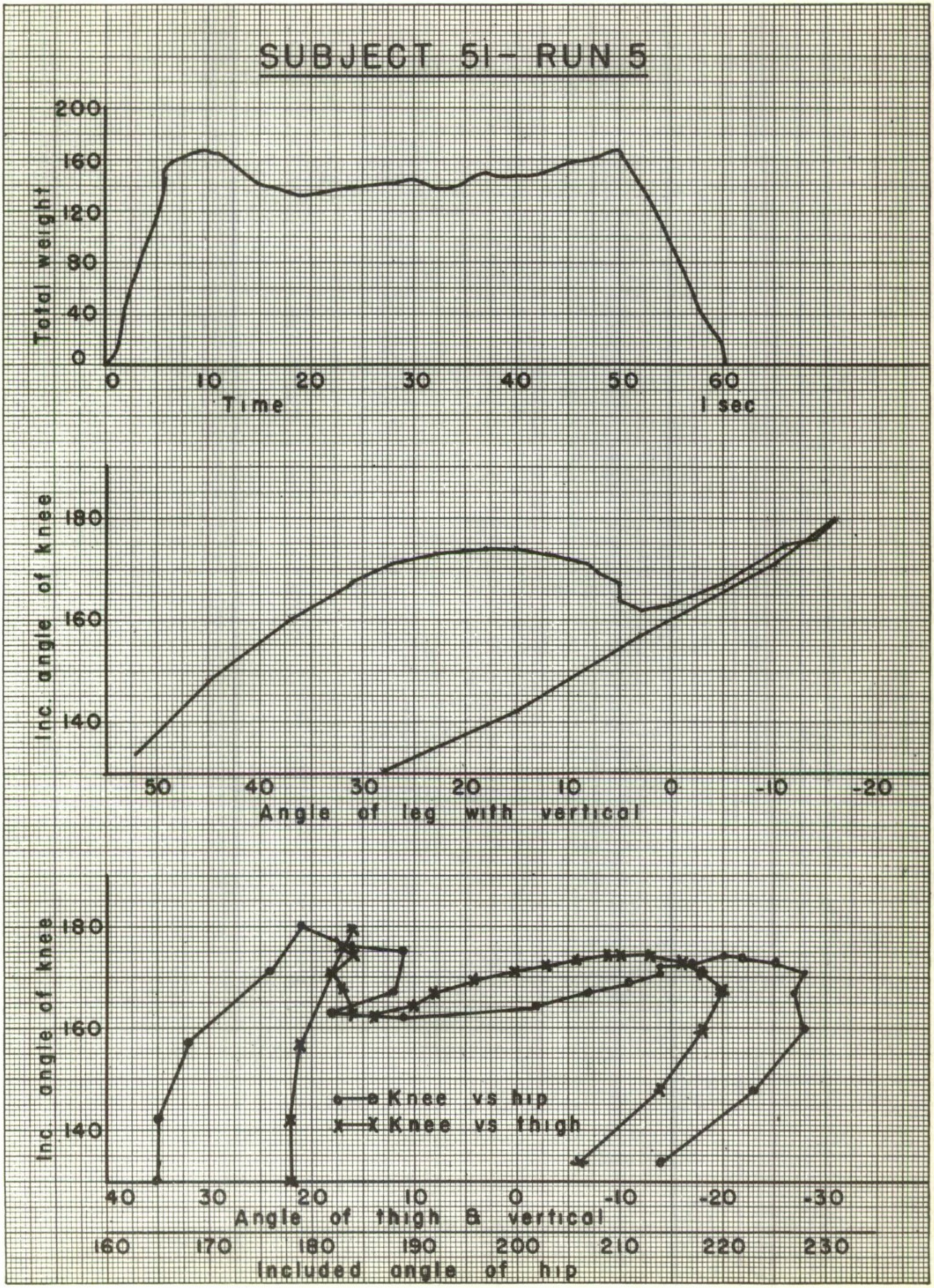
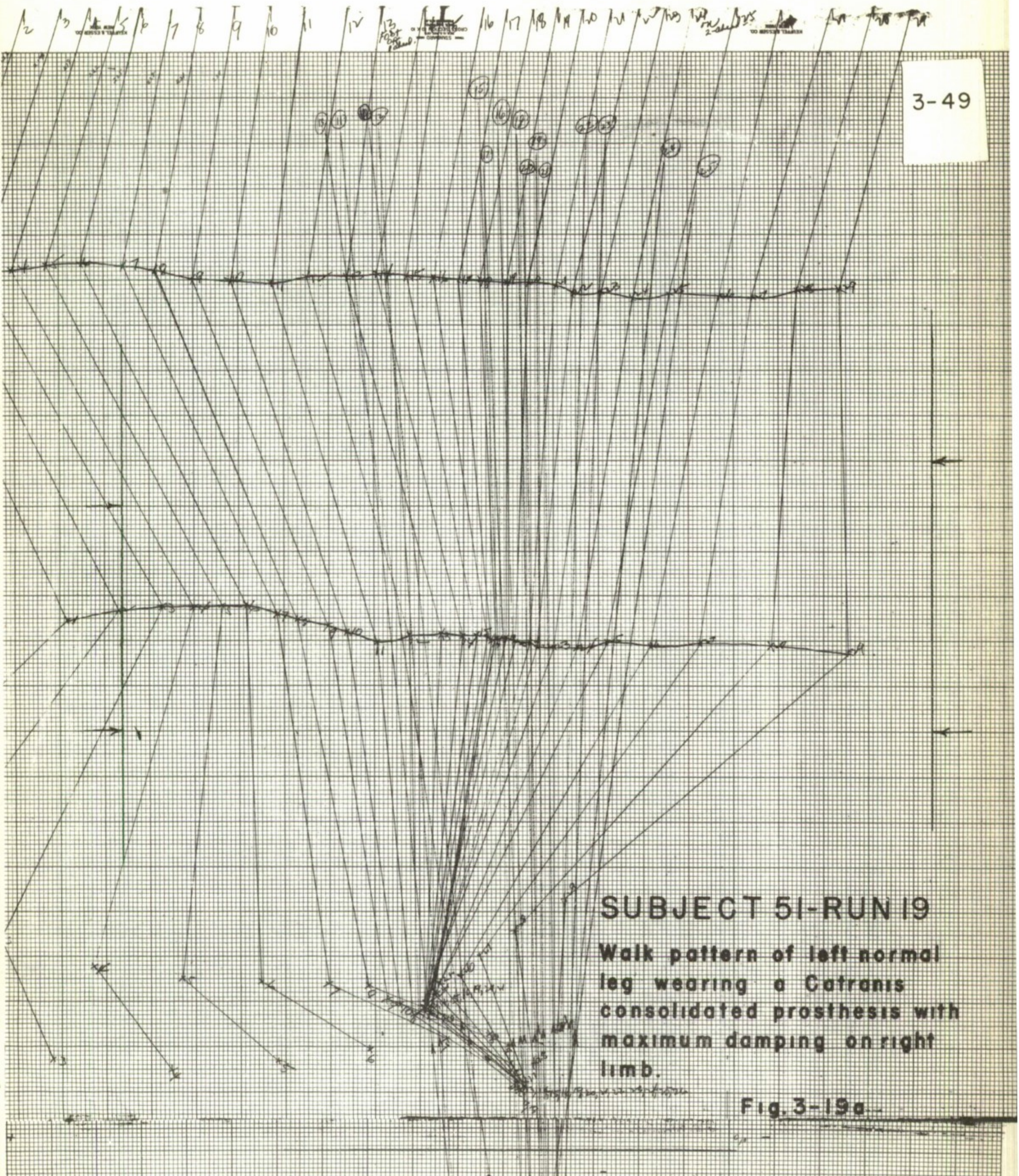

SUBJECT 51- RUN 5
Total weight
200
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
50
40
30
20
10
0
-10
-20
Angle of leg with vertical
Inc. angle of knee
180
160
140
Knee vs hip
Knee vs thigh
40
30
20
10
0
-10
-20
-30
Angle of thigh & vertical
160
170
180
190
200
210
220
230
Included angle of hip

Fig.3-18b



SUBJECT 51-RUN 19

Walk pattern of left normal leg wearing a Catranis consolidated prosthesis with maximum damping on right limb.

Fig. 3-19a.

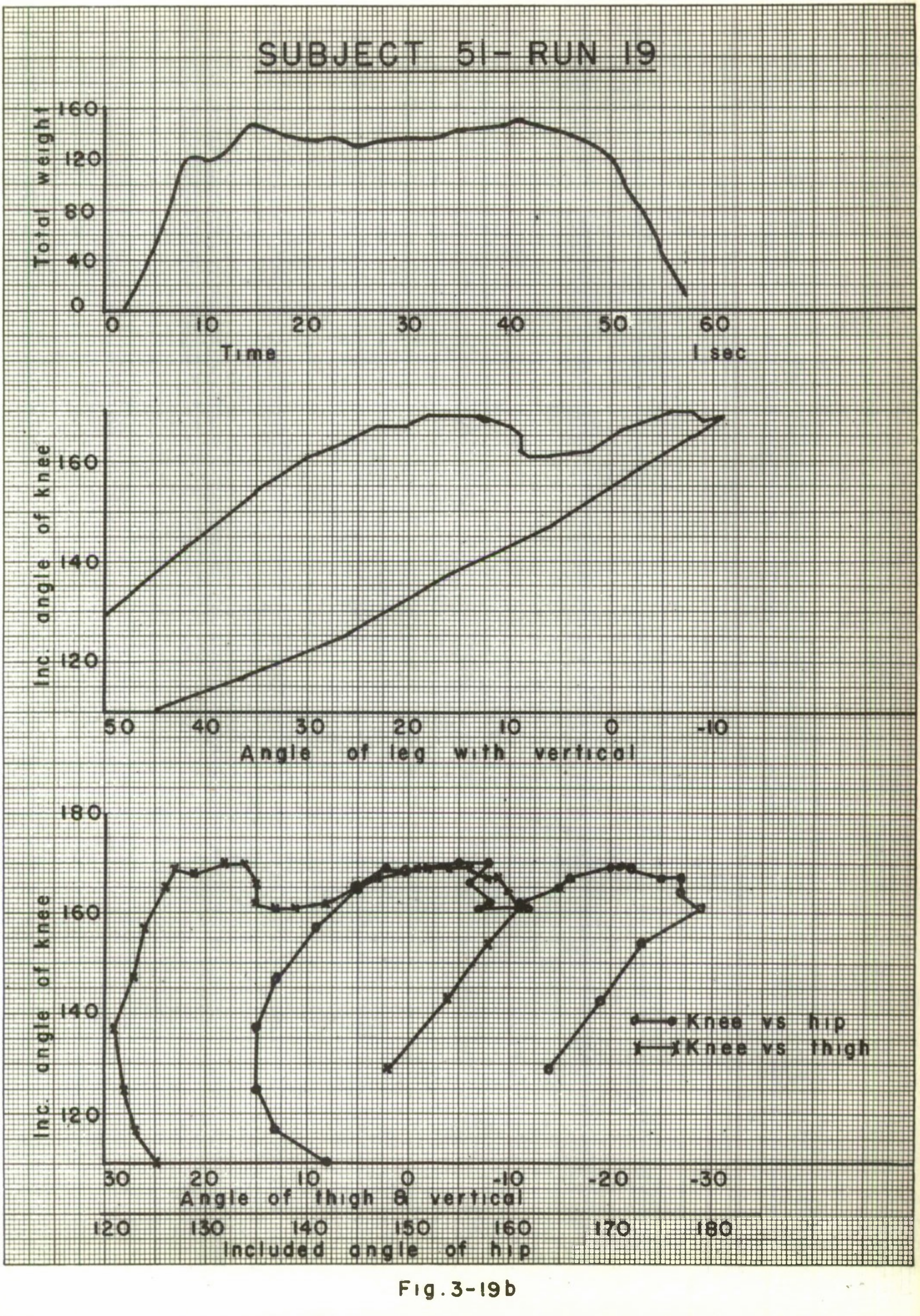
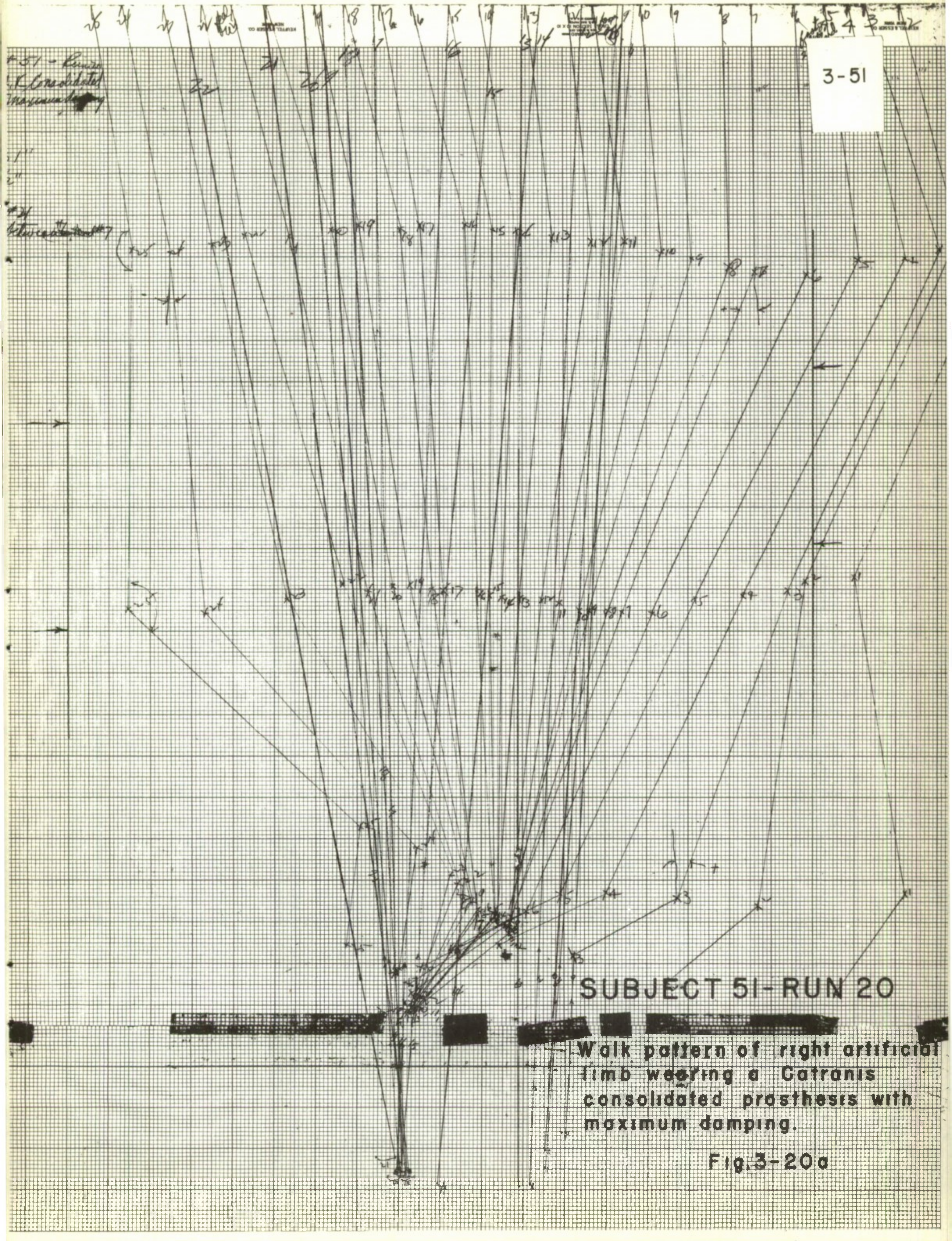

SUBJECT 51– RUN 19
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
I sec
Inc. angle of knee
160
140
120
50
40
30
20
10
0
-10
Angle of leg with vertical
Inc. angle of knee
180
160
140
120
30
20
10
0
-10
-20
-30
Angle of thigh & vertical
120
130
140
150
160
170
180
Included angle of hip
Knee vs hip
Knee vs thigh

Fig. 3-19b



SUBJECT 51-RUN 20

Walk pattern of right artificial limb wearing a Catranis consolidated prosthesis with maximum damping.

Fig. 3-20a

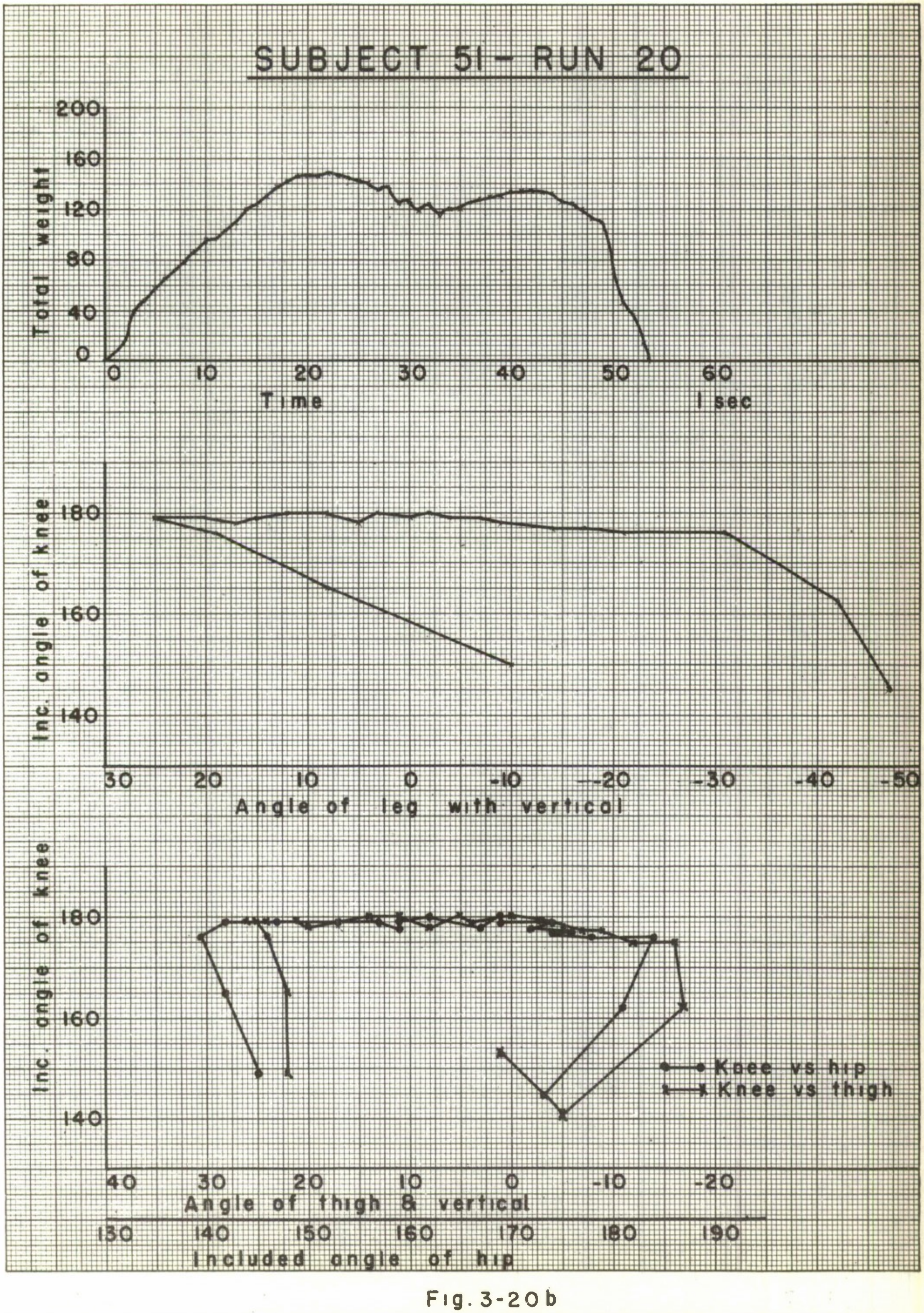
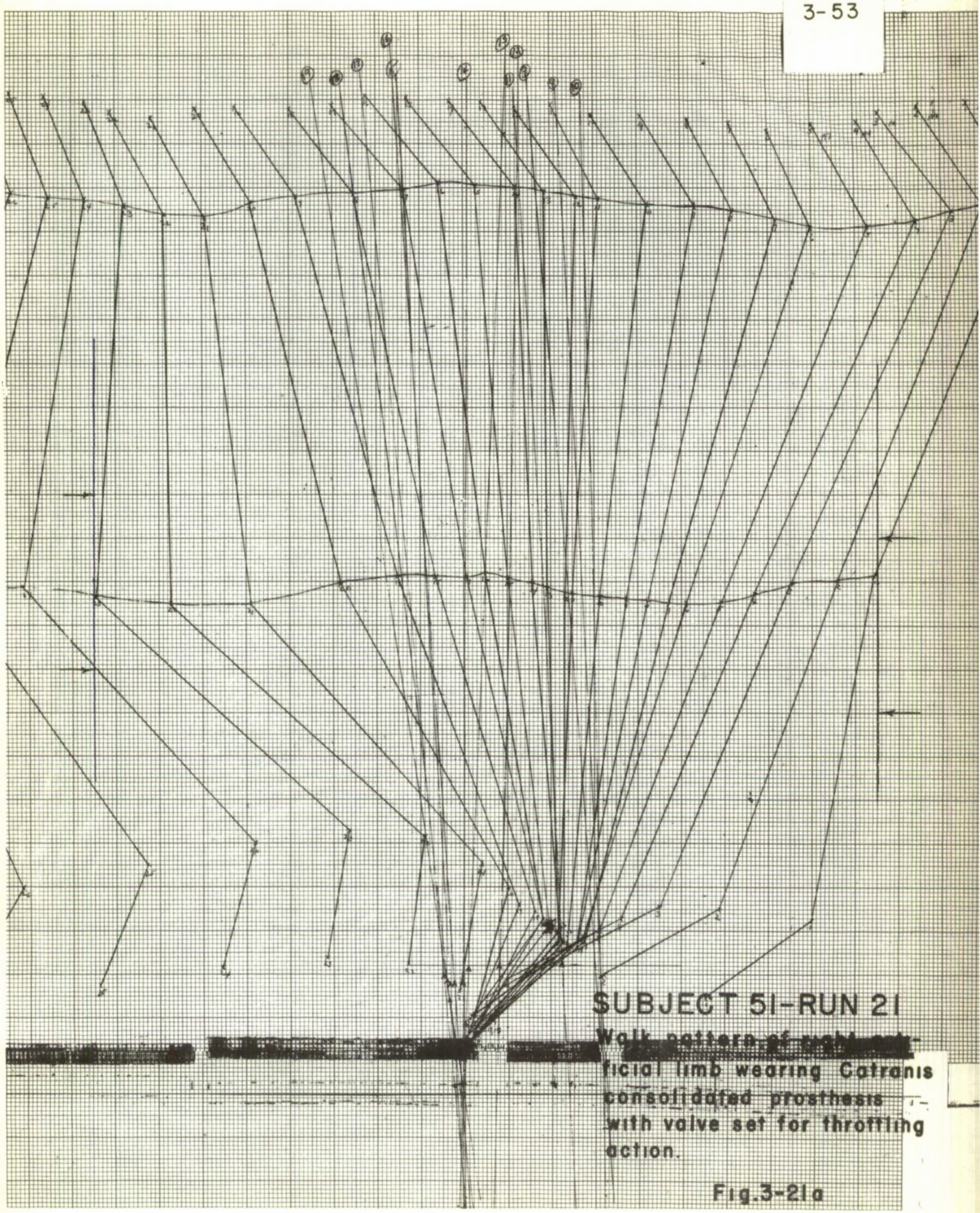

SUBJECT 51 – RUN 20
Total weight
200
160
120
80
40
0
0
10
20
30
40
50
60
Time
1 sec
Inc. angle of knee
180
160
140
30
20
10
0
-10
-20
-30
-40
-50
Angle of leg with vertical
Inc. angle of knee
180
160
140
Knee vs hip
Knee vs thigh
40
30
20
10
0
-10
-20
Angle of thigh & vertical
130
140
150
160
170
180
190
Included angle of hip

Fig. 3-20b



SUBJECT 51-RUN 21

Walk pattern of right artificial limb wearing Catranis consolidated prosthesis with valve set for throttling action.

Fig. 3-21a

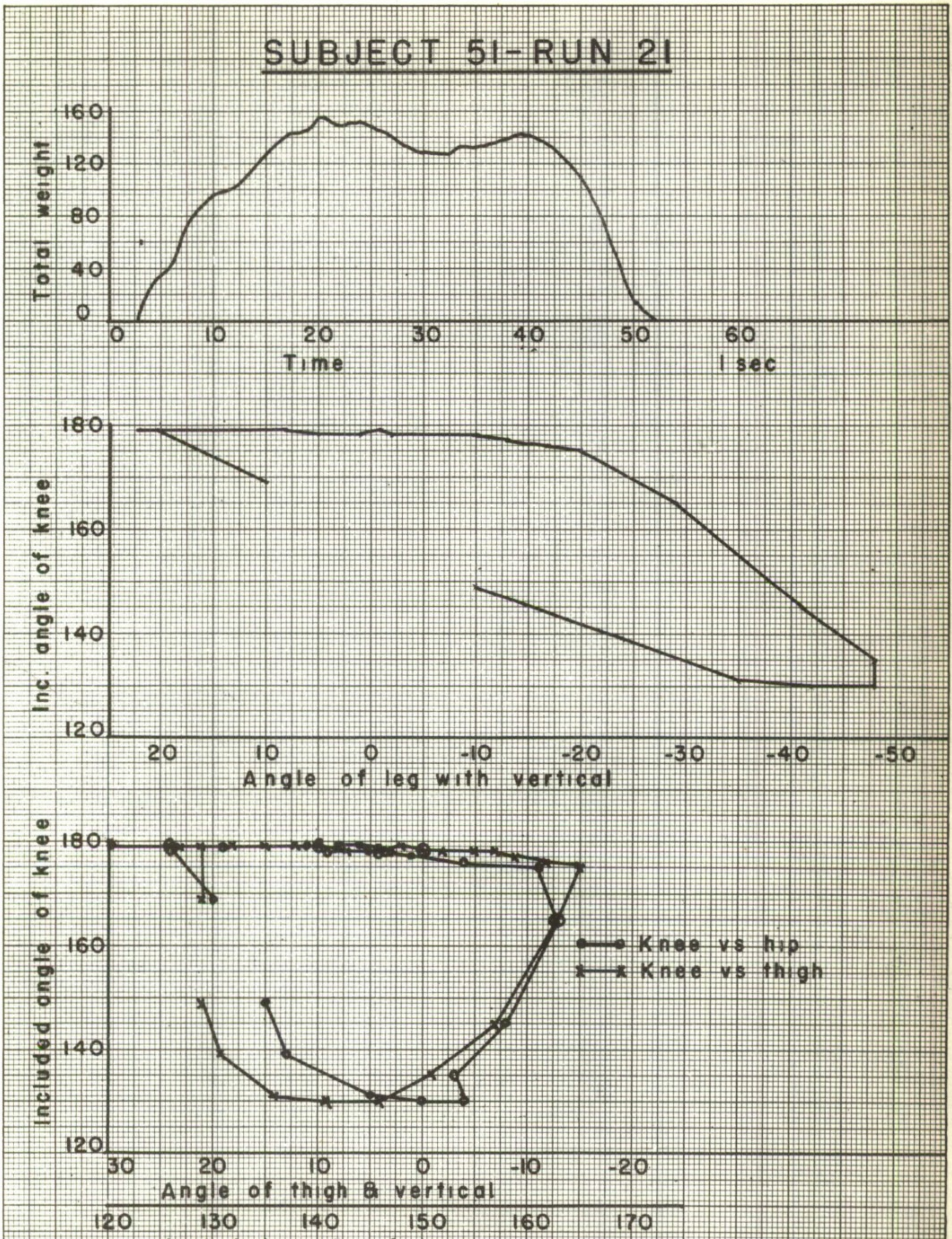
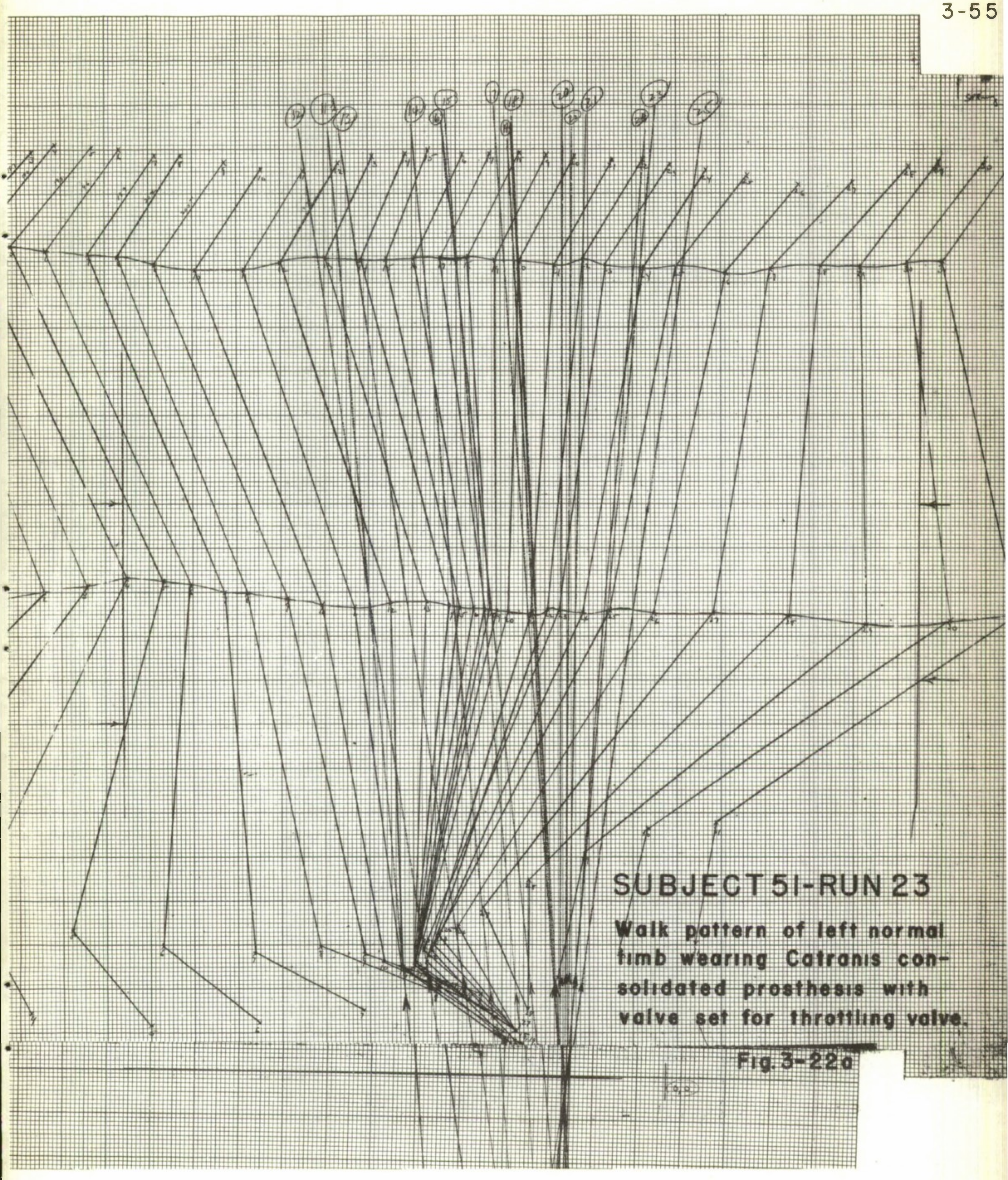

SUBJECT 51-RUN 21
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
I sec
Inc. angle of knee
180
160
140
120
20
10
0
-10
-20
-30
-40
-50
Angle of leg with vertical
Included angle of knee
180
160
140
120
30
20
10
0
-10
-20
Angle of thigh & vertical
120
130
140
150
160
170
Included angle of hip
Knee vs hip
Knee vs thigh

Fig. 3-21b



SUBJECT 51-RUN 23

Walk pattern of left normal limb wearing Catranis consolidated prosthesis with valve set for throttling valve.

Fig. 3-22a

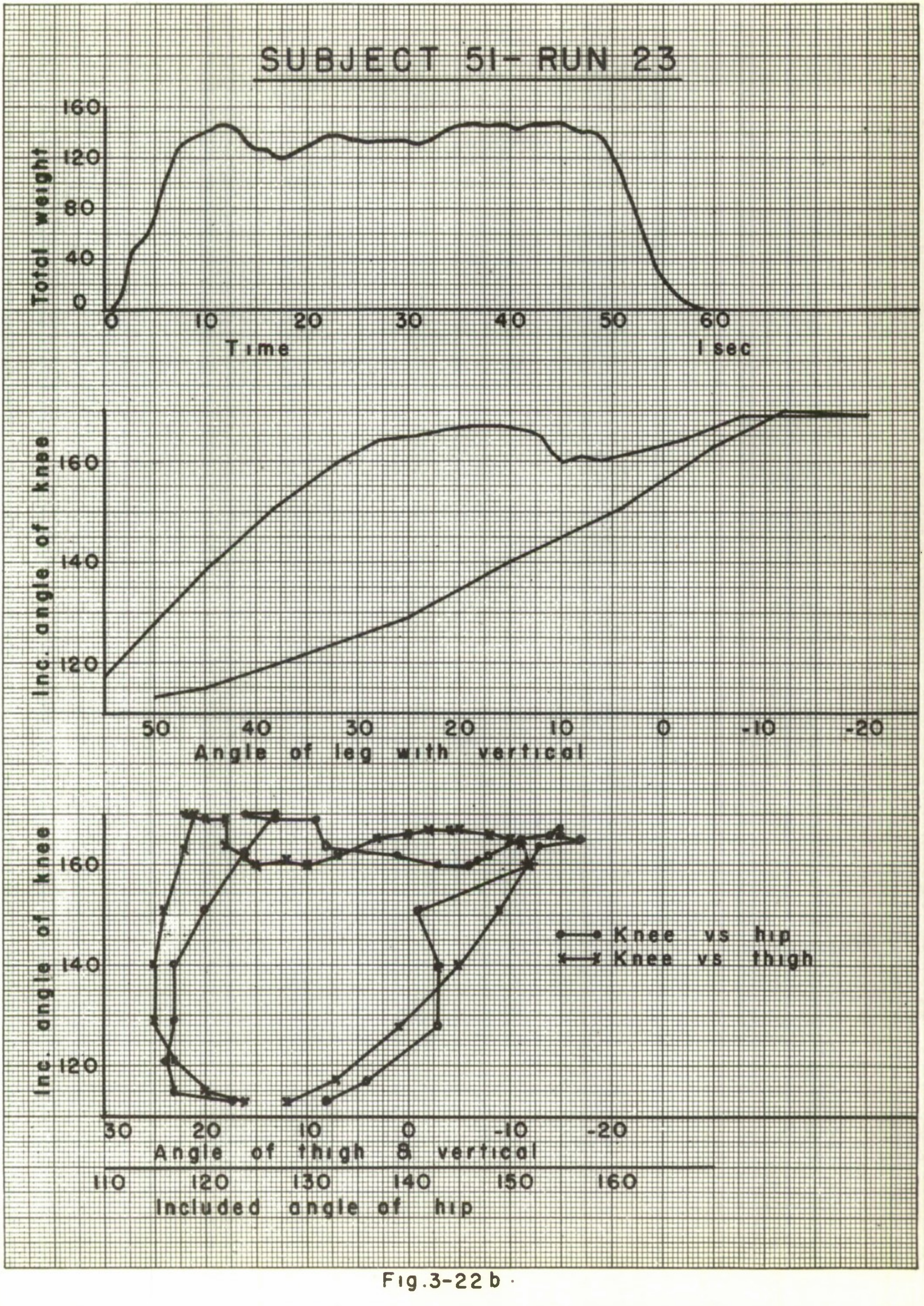

SUBJECT 51- RUN 23
Total weight
160
120
80
40
0
0
10
20
30
40
50
60
Time
I sec
Inc. angle of knee
160
140
120
50
40
30
20
10
0
-10
-20
Angle of leg with vertical
Inc. angle of knee
160
140
120
Knee vs hip
Knee vs thigh
30
20
10
0
-10
-20
Angle of thigh & vertical
110
120
130
140
150
160
Included angle of hip

Fig.3-22b.

VIII. FORCE PLATE RESULTS

1. From the pool of veterans available, approximately sixty subjects have been evaluated while wearing the conventional limb. About fifteen subjects have also been evaluated wearing suction sockets. Of those that have been fitted and tested on the Catranis Consolidated Leg model, data on three men who appeared best adopted to the new limb have been evaluated. The vector diagrams of two of these individuals have been analyzed by Dr. H. E. Elftman and his comments follow the actual data in a separate section. No further evaluation is being undertaken on this leg in view of the model's redesign.

2. Figures 11-A to 22-A are the vector diagrams for the two subjects whose data is available for the three types of prosthesis. (Conventional, Suction, Socket and Catranis Consolidated). The stick diagrams consist of lines from an upper body point centered in the fore and aft direction to the hip center; then to the knee center from which it is joined to the ankle center and finally to the ball of the foot.

3. Superimposed upon these "stick men" are the load vector resultants, plotted in the plane of the foot which strikes the force plate, and consequently in the plane of the stick man. The resultants are extended considerably to allow simple estimation of the moments that arise from the vector's passing at a certain moment arm relative to the stick joints. The absolute value of the vector is indicated in that portion of the vector extending from the floor line to the arrow tip. This section is scaled at fifty pounds to the inch. Both stick diagrams and vectors are correspondingly numbered to make identification simple; these numbers are without absolute significance.

4. The computation of moments about the knee, in the stance phase, is

simplified by using ground reactions only. A check series of computations has shown the effect of the leg inertia to be insignificant on this phase - the only one considered. The same is true for ankle moments. Knee and ankle moments in the fore and aft direction have been or are being computed for all subjects.

5. In addition to the vector diagrams, Figures 11-B to 22-B indicate other data available for the above two subjects. These include total weight versus time graphs and hip and knee deflections. Such curves are available for all subjects and are used as additional patterns with which to compare subjects. The group of four curves is used to evaluate a given step.

IX. FORCE-PLATE AND STICK-DIAGRAM ANALYSIS OF WALKING WITH PROSTHESES.

1. A preliminary analysis of some of the features of the performance of the Catranis Consolidated Leg has been conducted on the basis of the records made by two individuals on the New York University force plate. When plotted in conjunction with stick diagrams constructed from moving pictures taken concurrently with the force plate records, the ground reaction and its point of application provide illuminating information concerning performance. The present analysis is confined to movements and forces in the vertical plane of progression. Lateral movements are also important, but their consideration may properly be postponed until later.

2. For comparison with the Catranis Consolidated Leg there were available similar records by the same individuals using V. A. Conventional Limbs. Although a performance similar to that of the normal limb may be the proper ideal goal in the design of prostheses, a limb which falls far short of this ideal may still represent a significant advance over conventional devices.

3. The Consolidated Leg demonstrates an improvement over the conventional limb in the forward swing of the leg as it prepares for contact with the ground. Although the part played by the distribution of mass in the prosthesis should be investigated, it would seem much more likely that the improvement in the forward swing is attributable to decreased resistance to movement in the knee joint. A more accurate evaluation of this feature may be obtained by investigating its variations with faster and slower rates of swing.

4. The maximum vertical reaction with the Consolidated Leg is comparable with that achieved with a normal leg, in general. It is possible that this is an expression of the confidence of the wearer but it may also be related to his comfort. The increase in vertical reaction immediately after foot contact is slower with the Consolidated Leg than it is in either the normal leg paired with it or in normal walking in general. This slowness in accepting vertical load is associated with an exaggerated advance of the prosthetic foot with an associated increase in the angulation of its extremity with the vertical. This would suggest that a more rapid increase in the vertical reaction may be achieved rationally only by remedying the cause of the long prosthetic step.

5. The fundamental cause of the long prosthetic step appears to be the lack of the ankle moment which provides the push-off in normal walking, with its accompanying upward acceleration. Since the prosthesis lacks this ability to terminate the forward vaulting with an upward push, it is advisable to shorten the advance of the opposite leg so as to bring it into action sooner. From this point of view it would appear that the walker actually exhibits a shortening of the advance of the "normal" leg, the use of the term "longer prosthetic step" being a projection into the picture of the attitude of the observer. Correlated with the features just described is the shorter period of contact of the prosthetic leg than of the opposite limb. The Consolidated Leg has no more deficiency of ankle push off than do other legs, nor does it

offer advantages. Until ankle-push-off can be introduced into prostheses a duplication of normal progression is beyond rational expectation.

6. The ingenious but complicated linkages between the knee and ankle in the Consolidated Leg provide a complex mechanism affecting movement in these two joints. In the absence of experiments which would permit the separate analysis of the effects of the components of this sytem, it will be best to describe the performance of the system as a whole in general terms.

7. Initial knee flexion was not a noticeable feature of the small number of records available for this preliminary study. Since the action of the device ultimately depends on the balance between the moments of force introduced by the mechanism and the amounts of gravity and effective forces, it is possible for the walker to contrive results other than those intended by the designer. It seems probable that the feeling of security engendered by the lack of initial knee flexion entices the wearer of a novel prosthesis to control his movements so as to diminish knee flexion. Further observation will be necessary to determine whether later desire for proficiency changes this situation.

8. A desirable feature in the performance of the Consolidated Leg is the ability which is shows of retaining the ground reaction behind the ankle joint during the first portion of the period of contact. At this time the mechanism acting at the ankle produce a marked dorsiflexor moment, simulating the normal action of the tibialis antèrior. After the center of gravity of the body has approached a position approximately over the ankle joint, the moment about the ankle joint becomes plantar flexor in nature, and the point of application travels forward in the foot, with somewhat more celerity than in the normal. It may consequently be concluded that the mechanism as used by the two subjects in the records used in this study has shown virtue in the production of good initial dorsiflexor moment at the

ankle, fair forward migration of the ground reaction and adequate control by a plantar flexor moment of the ground reaction in its more forward positions. Additional provision of terminal push-off would allow a creditable facsimile of normal gait if the walker were willing to hazard initial knee flexion.

X. LOAD SURVEY

1. To better establish existent walking loads a survey has been made of force plate data, with a view towards aiding leg designers in establishing a sound picture of the stresses involved. While normal walking loads should not be considered ultimate load factors, i.e., ramp loads are substantially greater, the fact that the amputee spends most of his walking time in level walking means that fatigue failures will occur in general as a result of level walking. Consequently, load reverals pictured in this study are of extreme importance.

2. Existing knowledge of fatigue failure in wood is small, but H. D. Treeman: Wood Techology, Page 226, suggests a safety factor of three based on the maximum reversing stress for a life of 2,000,000 cycles. Knowledge of metallic fatigue is far more extensive and methods for dealing with it are well known.

3. Reaction loads are plotted against both time and distance axes. The time axis is divided into per cent of the effective footstep length as measured from the first reaction point to the last recorded. Accordingly, load values plotted against the effective foot length will have a definite value for the 0% condition (heel strike). On the other hand, load values plotted against a time axis will start and finish with a load of zero.

4. The graphs which comprise figure group No. 23 are those of total vertical reaction against both time and distance axes. The form is one of

percentage, obtained by dividing the total vertical reaction by the subject's weight and multiplying by 100. Data is presented for both conventional and suction socket type legs. It is seen that the average men on either type leg never realizes his full weight. This corresponds to a downward acceleration in the stance phase. There is no appreciable difference between suction socket and conventional patterns. In each case the maximum load obtained approaches 130% of the subject's weight or 1.3g.

5. The group curves composing Fig. 24 are those for fore and aft loading. The method of plotting is the same as that above. The results indicate that the patterns are symmetrical about the 50% footstep point, reaching a maximum sustained load of 30 pounds in either direction and peaking at 40 pounds. Again there is no appreciable difference between patterns of suction socket and conventional leg wearers. Minimum loads approach zero. Side or lateral load records (see Fig. 25) for conventional socket wearers indicate a maximum load of 16 pounds and the average sustained load to be 5 pounds. Minimum loads approach zero at all times.

6. The above study is based on the records of 48 conventional leg wearers and 10 suction socket wearers. Right and left leg wearers are very nearly equal in number, the conventional group having four more right than left amputees and the suction socket group two more left than right.

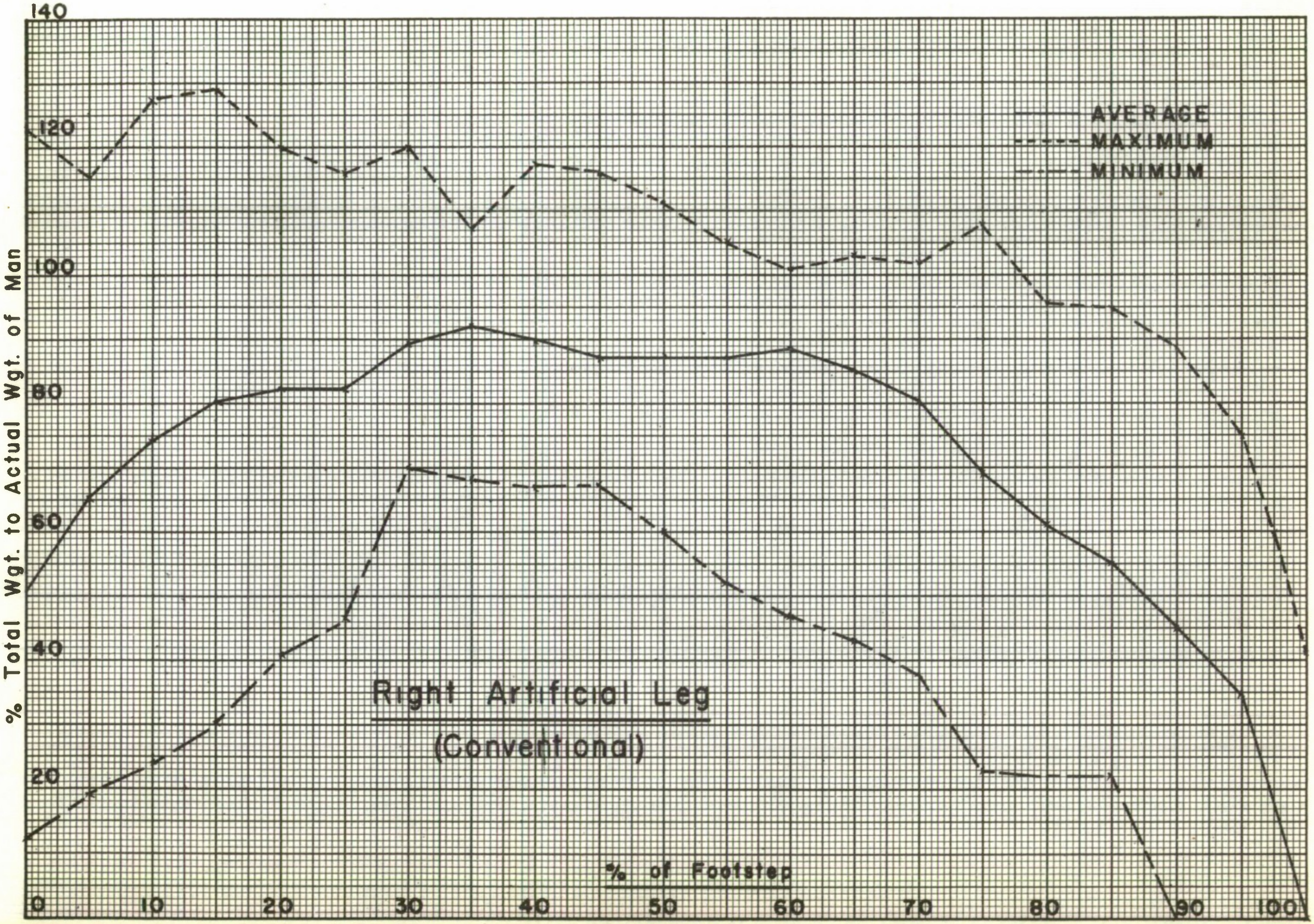

Right Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM
% Total Wgt. to Actual Wgt. of Man
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
% of Footstep

Fig. 3-23a

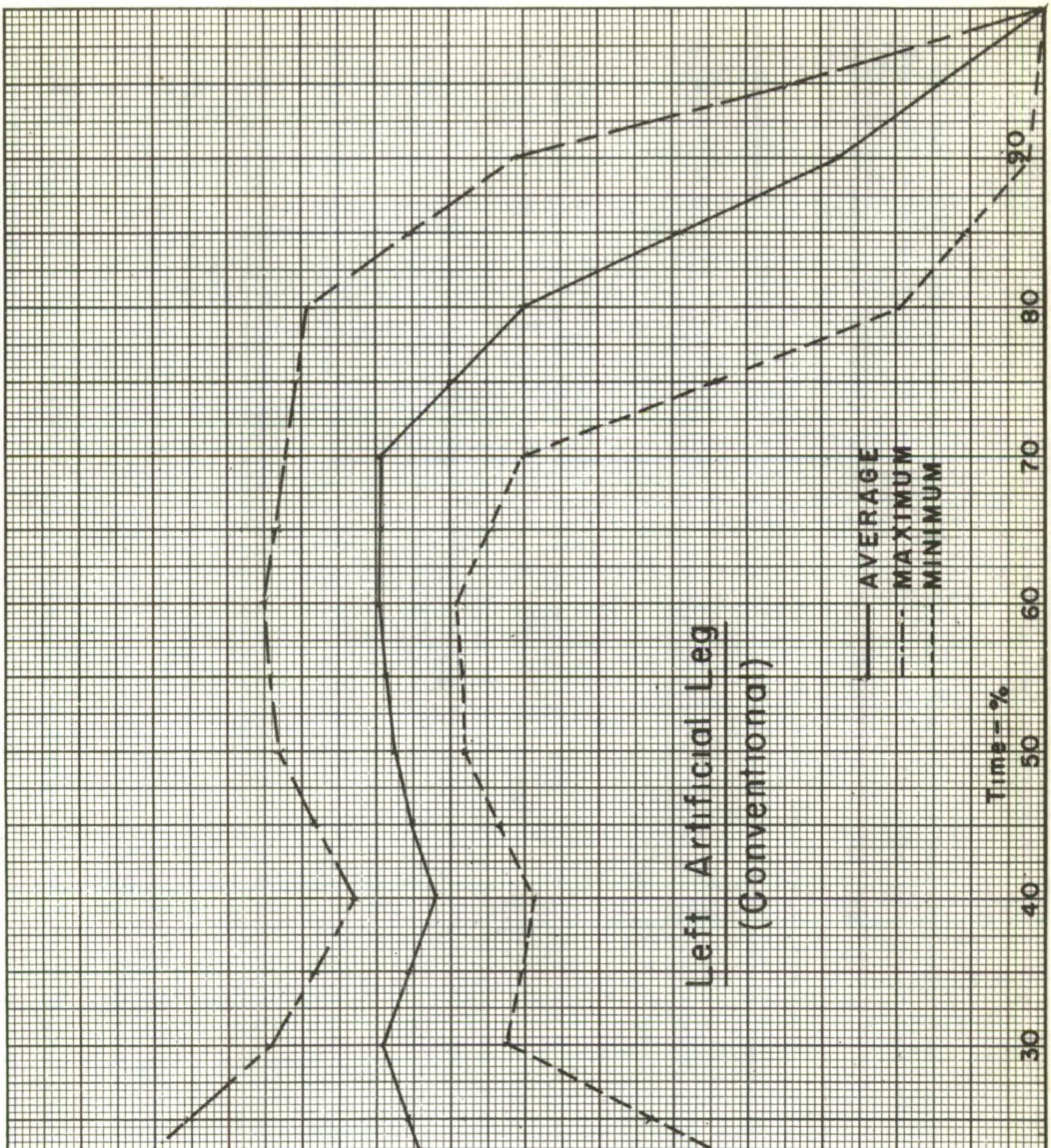

Left Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM
% Total Wgt. to Actual Wgt. of Man
20
40
60
80
100
120
Time – %
10
20
30
40
50
60
70
80
90

Fig.3-23b

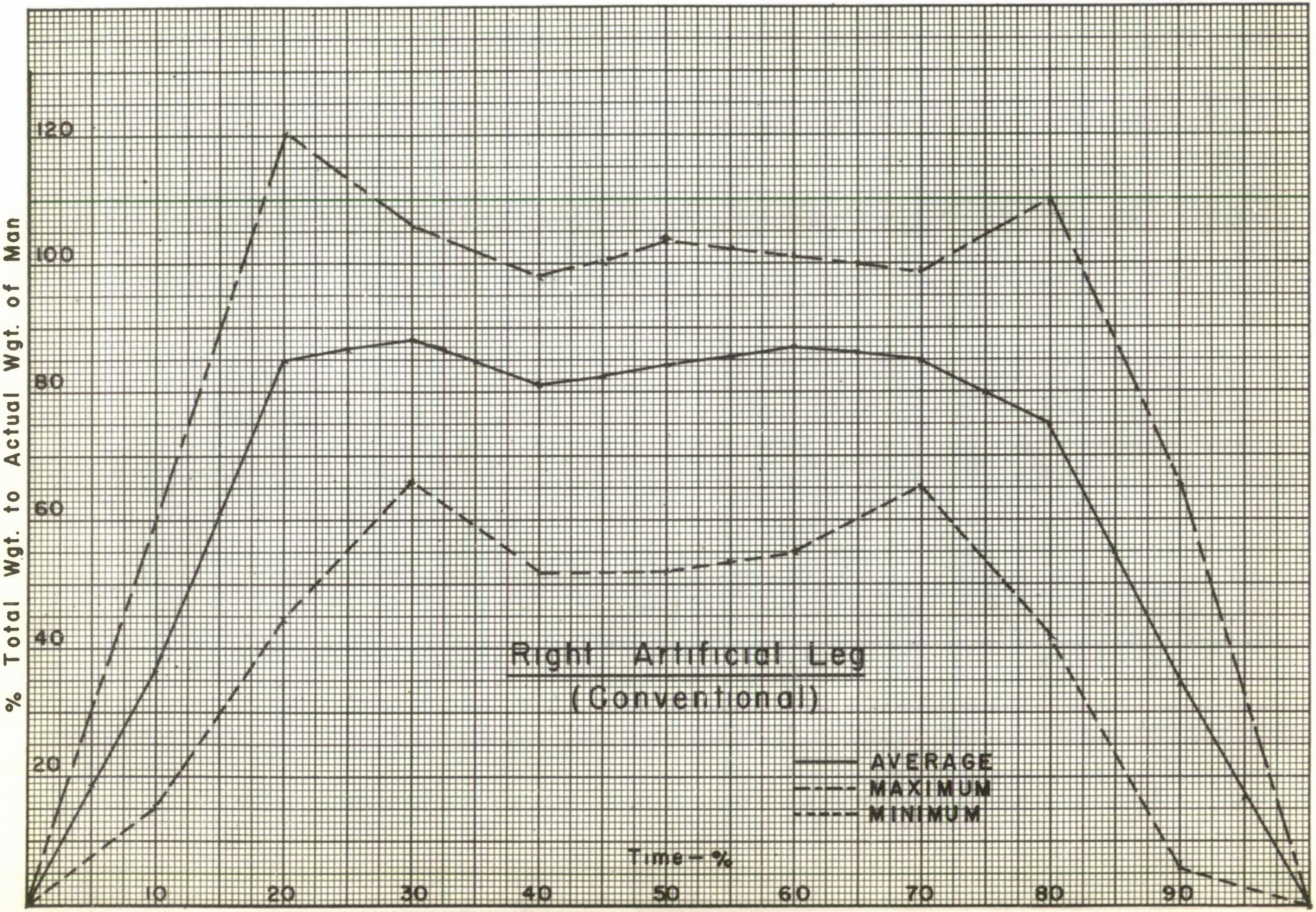
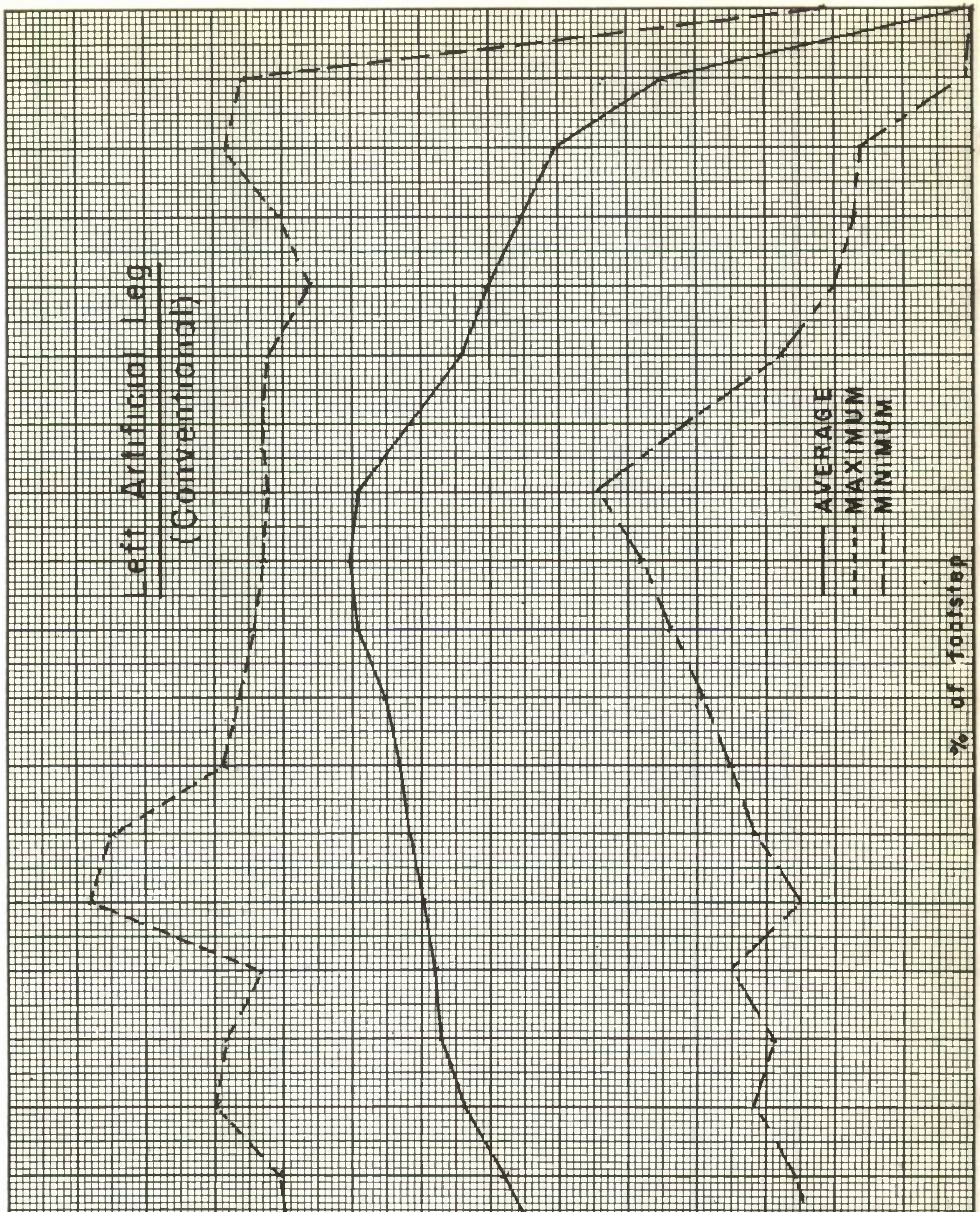

% Total Wgt. to Actual Wgt. of Man
120
100
80
60
40
20
Right Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM
Time — %
10
20
30
40
50
60
70
80
90

Fig.3-23c


Left Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM
% Total Wgt. To Actual Wgt. of Man
0
20
40
60
80
100
120
% of Footstep
10
20
30
40
50
60
70
80
90


Right Artifical Leg
(Suction)
% Total Weight to Actual Wght. of Man
% Of footstep
0
10
20
30
40
50
60
70
80
90
100
20
40
60
80
100
120
AVERAGE
MAXIMUM
MINIMUM

Fig. 3-23e

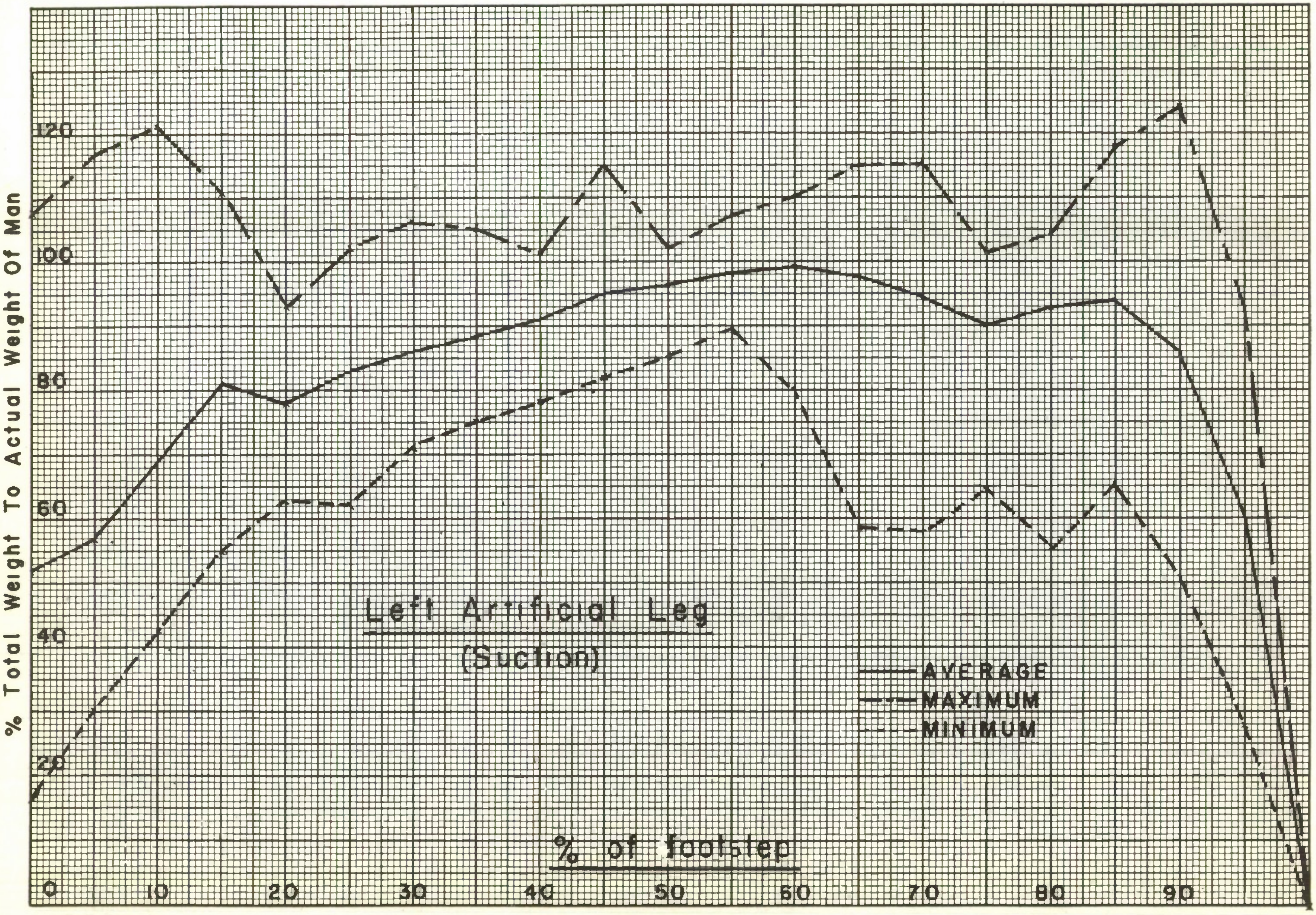

Left Artificial Leg
(Suction)
AVERAGE
MAXIMUM
MINIMUM
% Total Weight To Actual Weight Of Man
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
% of footstep

Fig.3-23f

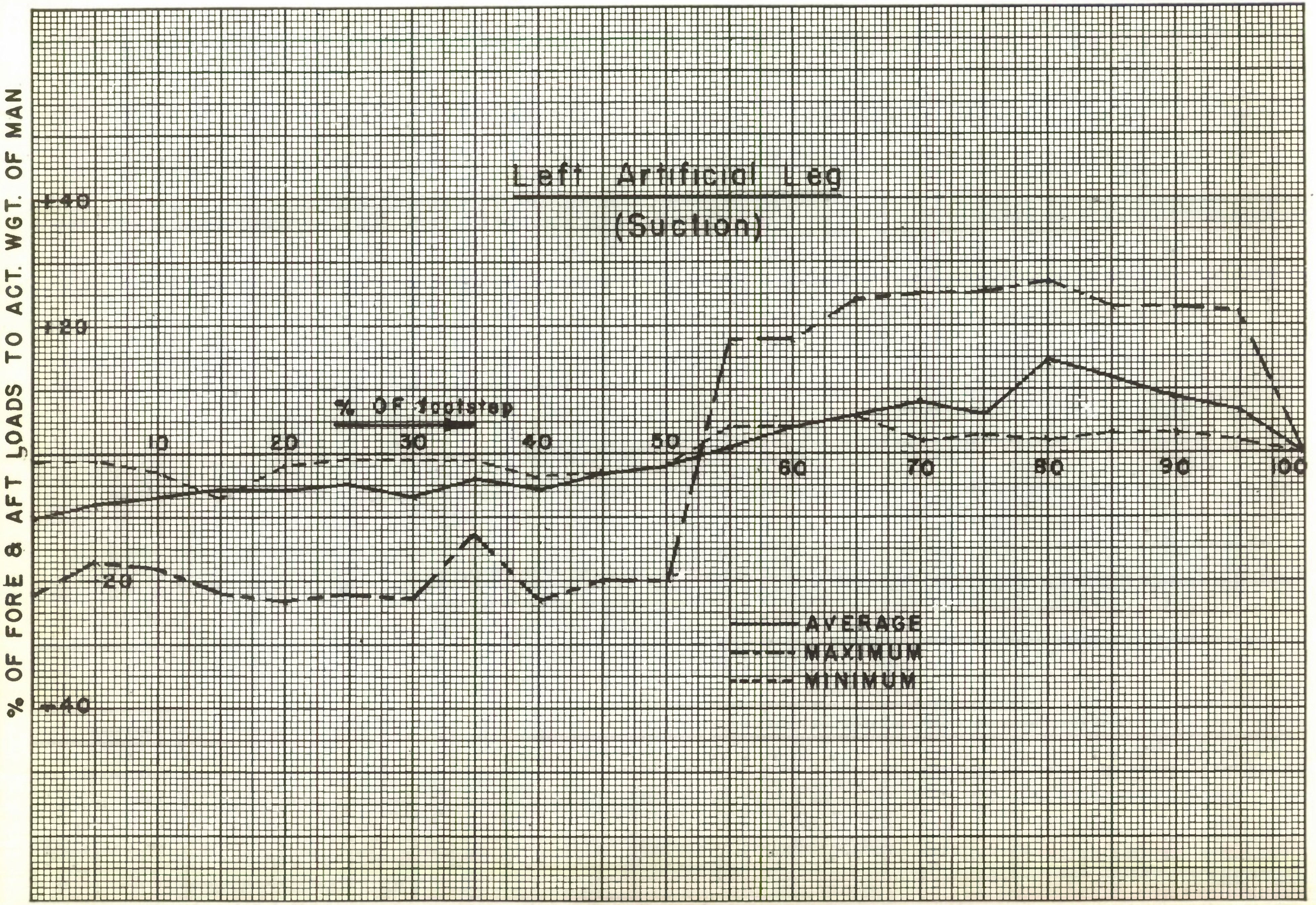

Left Artificial Leg
(Suction)
% OF FORE & AFT LOADS TO ACT. WGT. OF MAN
+40
+20
-20
-40
% OF footstep
10
20
30
40
50
60
70
80
90
100
AVERAGE
MAXIMUM
MINIMUM

Fig.3-24f

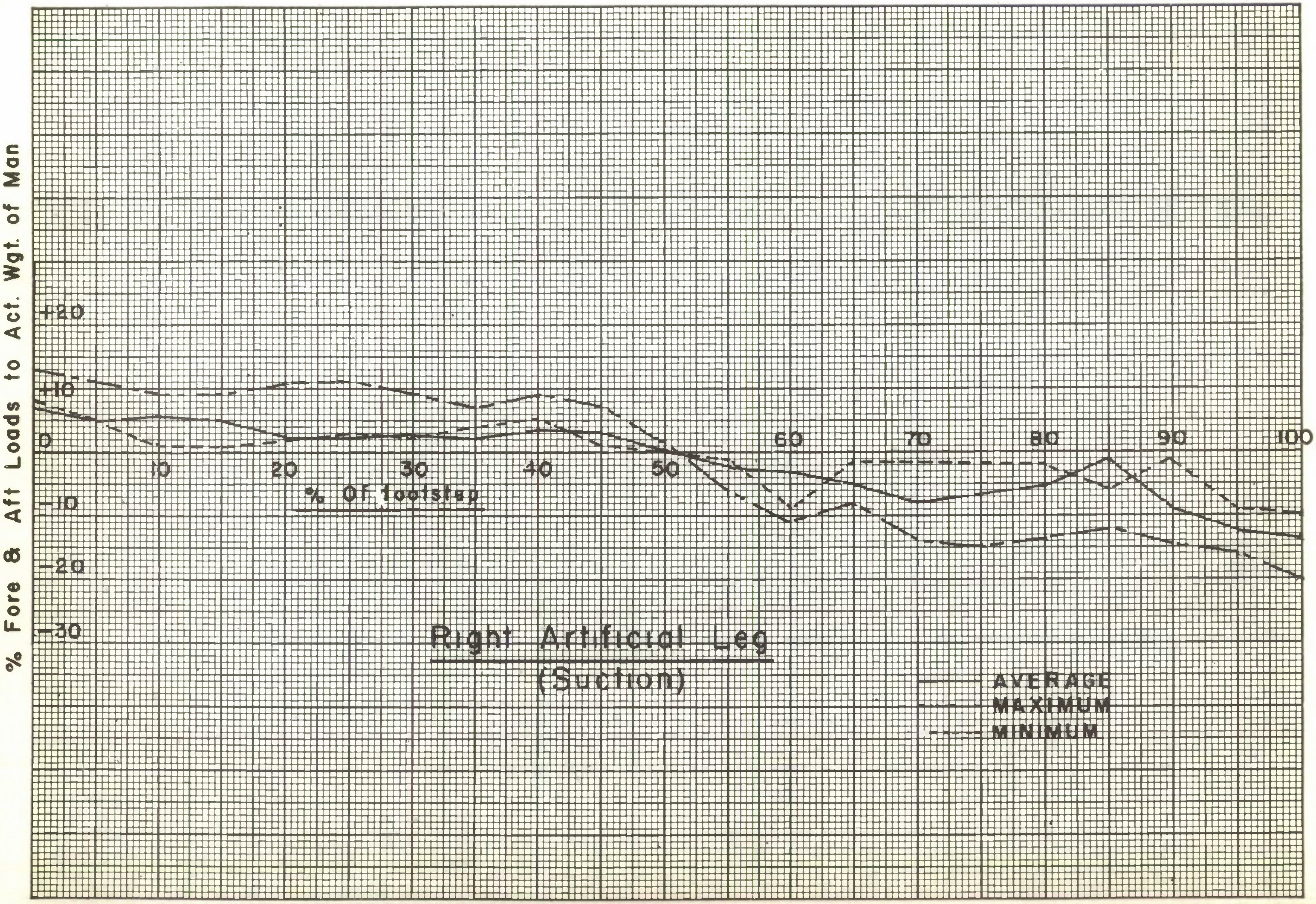

% Fore & Aft Loads to Act. Wgt. of Man
+20
+10
0
-10
-20
-30
10
20
30
40
50
60
70
80
90
100
% Of footstep
Right Artificial Leg
(Suction)
AVERAGE
MAXIMUM
MINIMUM

Fig. 3-24e

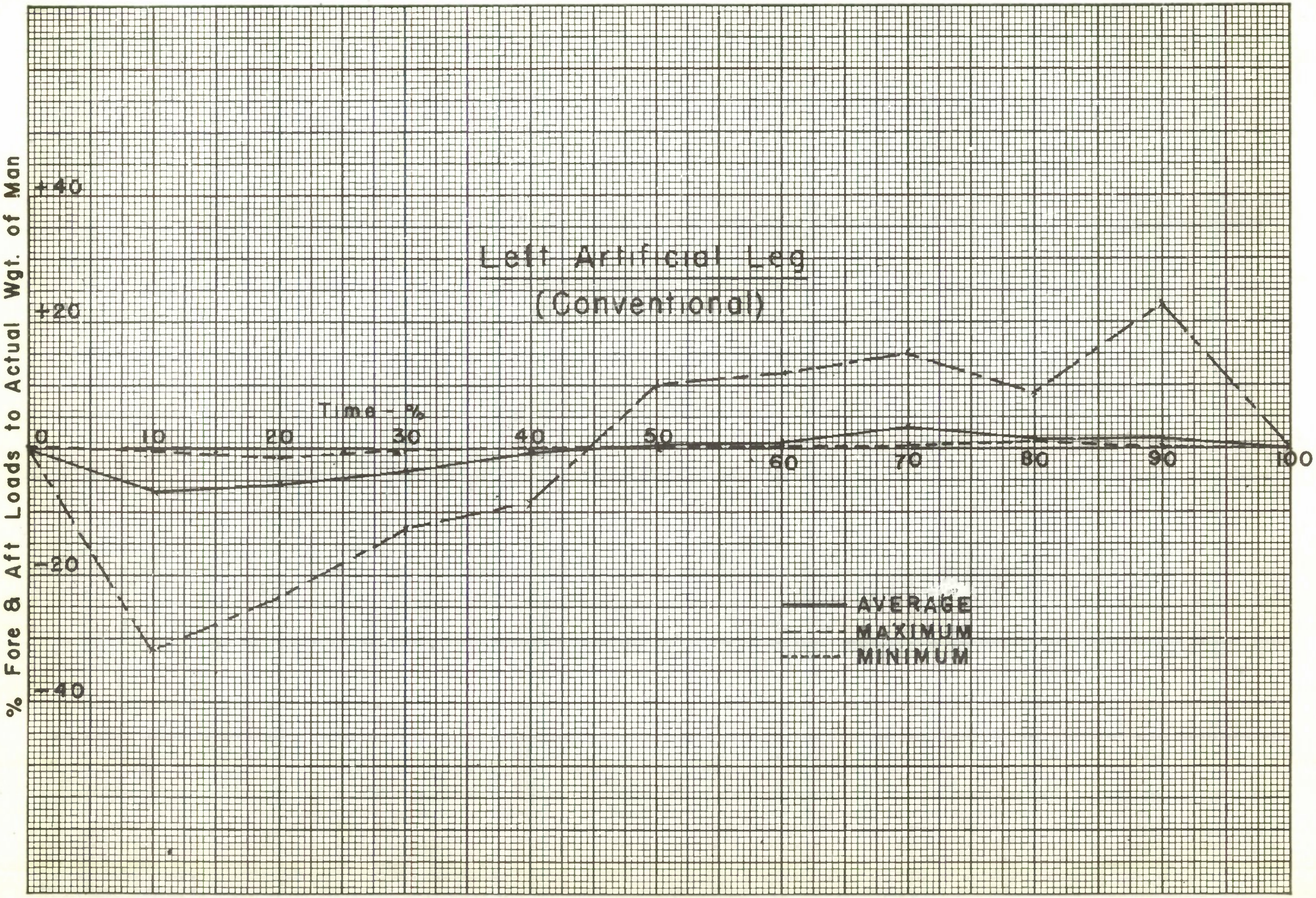

Left Artificial Leg
(Conventional)
% Fore & Aft Loads to Actual Wgt. of Man
+40
+20
-20
-40
Time - %
0
10
20
30
40
50
60
70
80
90
100
AVERAGE
MAXIMUM
MINIMUM

Fig. 3-24d

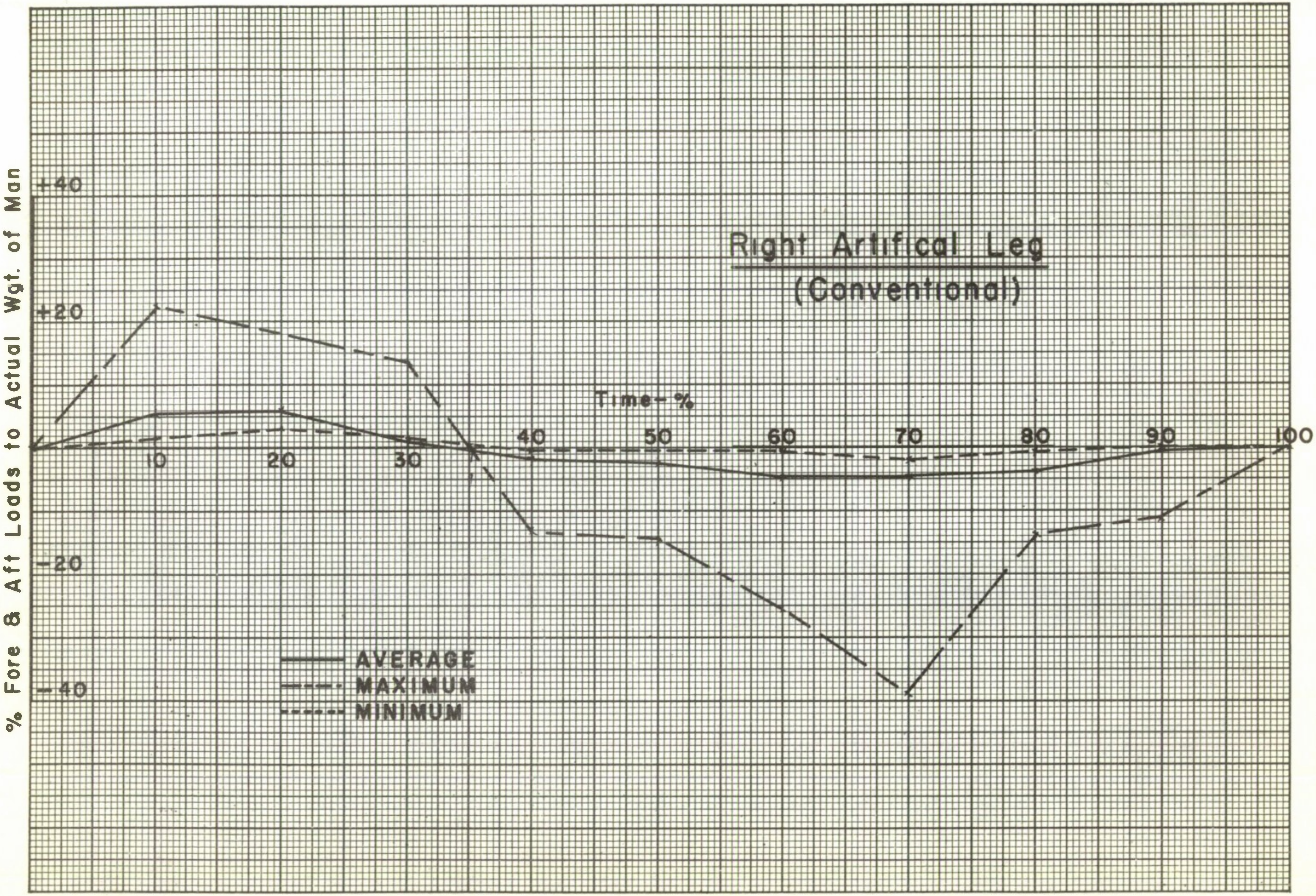

Right Artifical Leg
(Conventional)
Time-%
% Fore & Aft Loads to Actual Wgt. of Man
+40
+20
-20
-40
10
20
30
40
50
60
70
80
90
100
AVERAGE
MAXIMUM
MINIMUM

Fig.3-24c

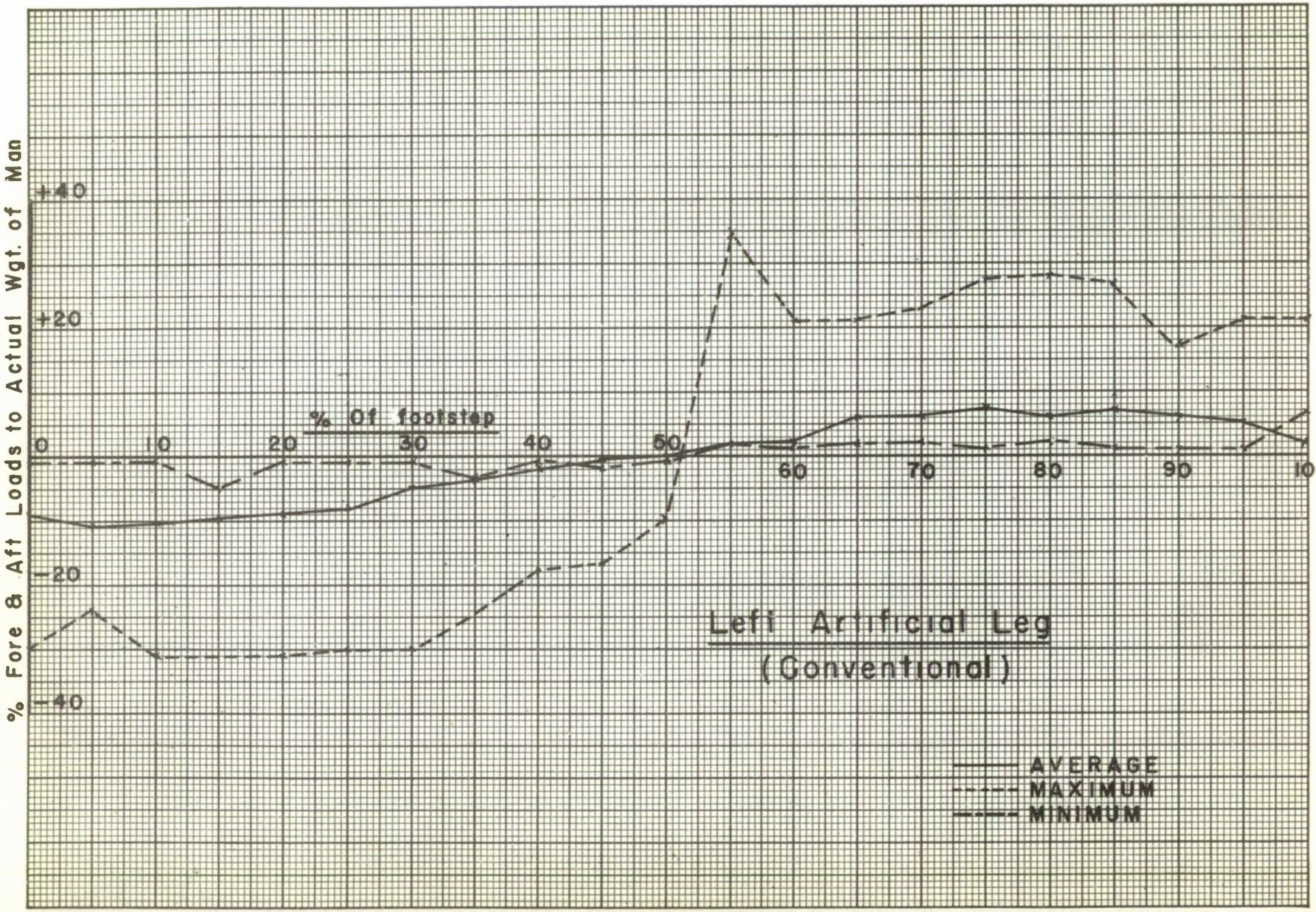

% Fore & Aft Loads to Actual Wgt. of Man
+40
+20
0
-20
-40
% Of footstep
0
10
20
30
40
50
60
70
80
90
100
Left Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM

Fig.3-24b


% Fore & Aft Loads to Actual Wgt. of Man
+40
+20
-20
-40
% of footstep
0
10
20
30
40
50
60
70
80
90
100
Right Artificial Leg
(Conventional)

Fig.3-24a

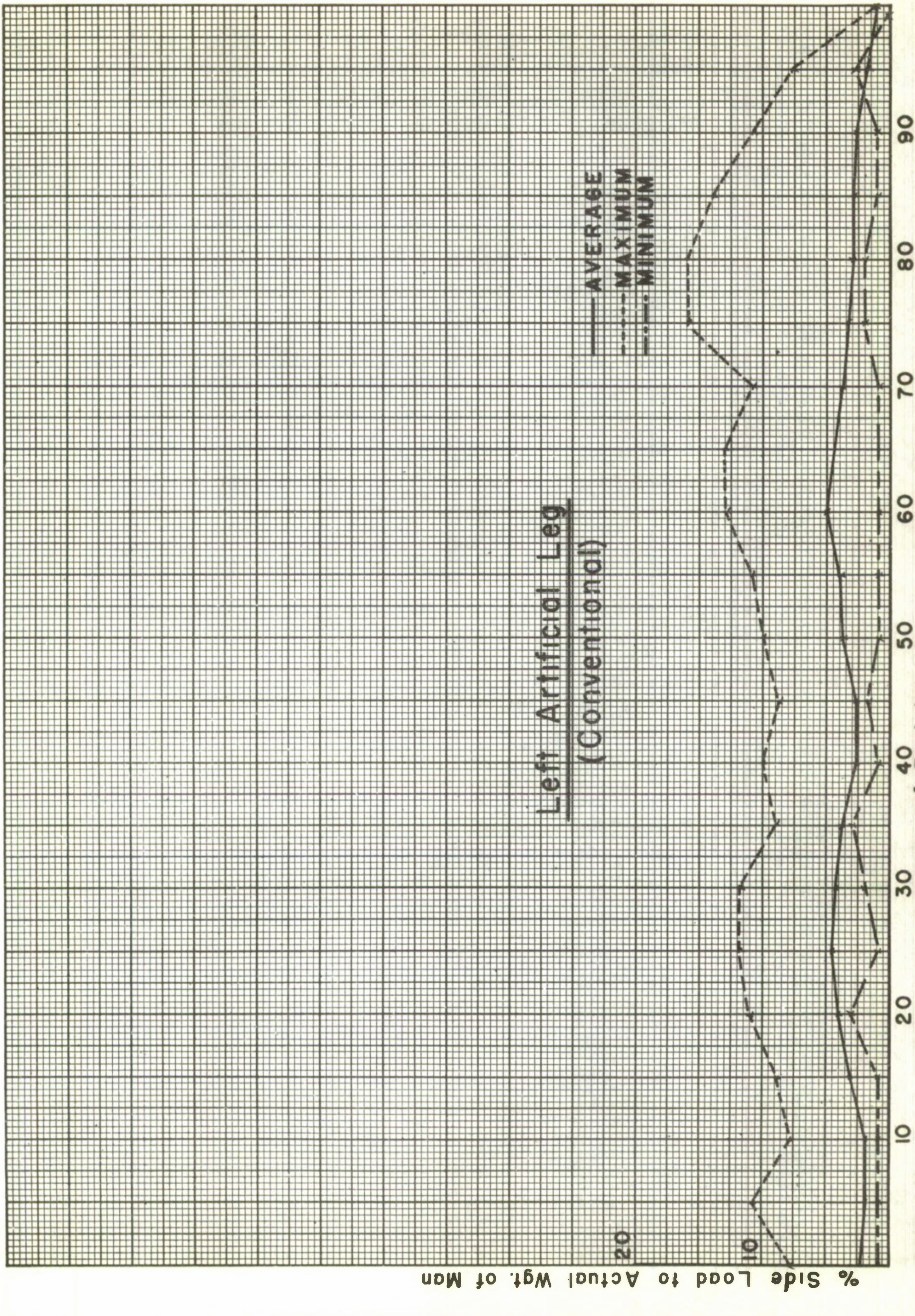

Left Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM
% Side Load to Actual Wgt. of Man
10
20
% of Footstep
10
20
30
40
50
60
70
80
90

Fig. 3-25b

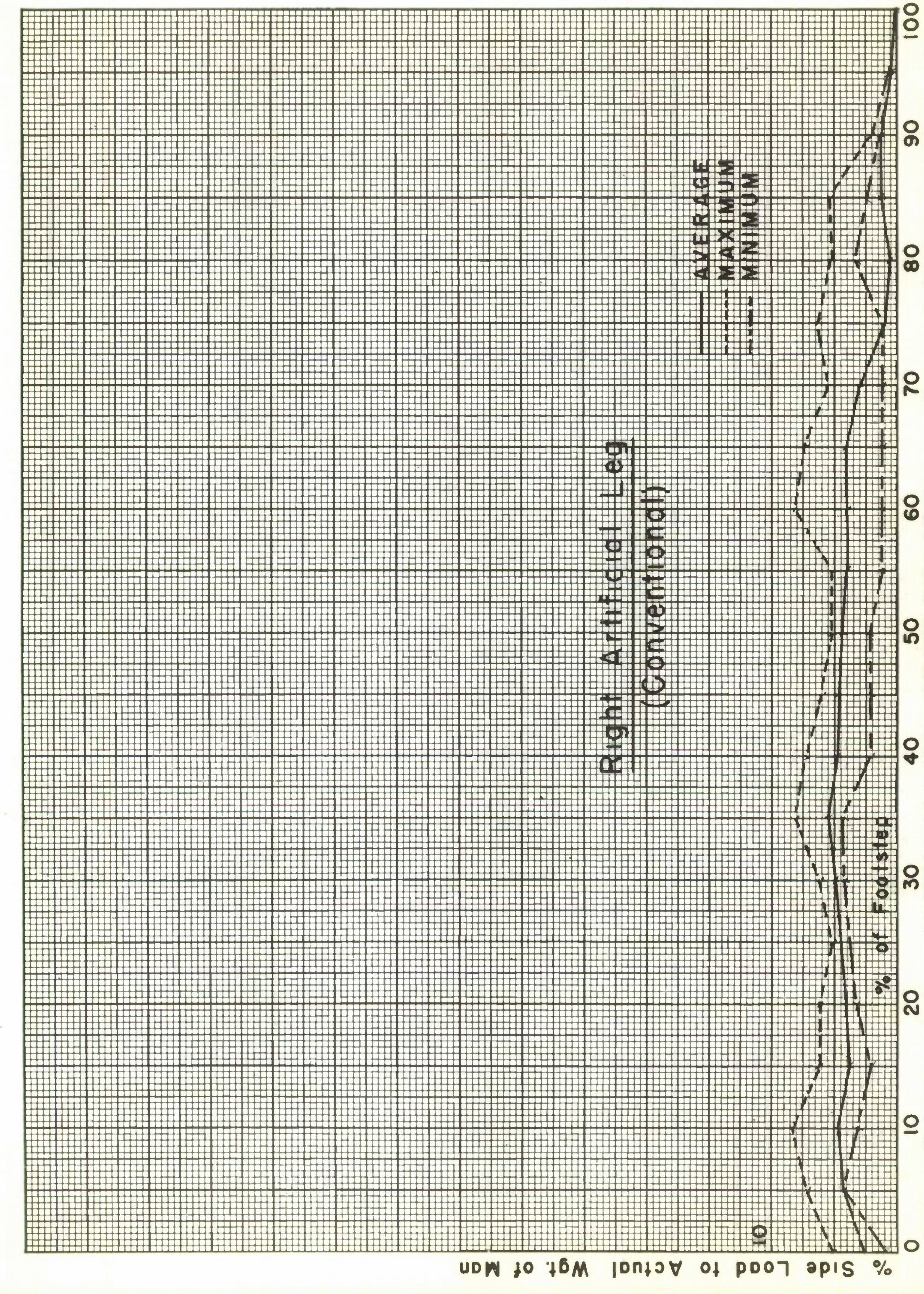

Right Artificial Leg
(Conventional)
AVERAGE
MAXIMUM
MINIMUM
% of Footstep
0
10
20
30
40
50
60
70
80
90
100
% Side Load to Actual Wgt. of Man
10

Fig. 3-25a

SECTION 4

VARIABLE KNEE POSITION STUDIES

Prepared by: Leon Bennett

Albert Yatkauskas

Section 4. VARIABLE KNEE

I. Introduction:

1. The variable knee was designed to investigate the effect of the knee bolt position on the amputee's gait.

2. The variable knee and adjustable pylon shin were attached to a conventional foot and socket. Adjustments allowed the placement of the knee center anywhere within a three-inch circle as well as permitting variable friction, constant leg length, hyperextension control, toe-in and toe-out regulation.

II. Model Description:

1. The leg was attached to the socket with a circular cap. A rotating movement about the cap allowed toe-in and toe-out. Bolted to the horizontally rotating member, the vertical travel unit contained lift screws bearing on the knee bolt. Actuation of these screws together with a proper rotational positioning of the unit would place the knee center in any position within a three-inch circle. The knee bolt bearings were supported in a groove by the cover plate. Set screws locked the rotating members in place at marked angular settings. Hyperextension was regulated through a padded stop screw, adjustable for the leg position, which arrested the shin member.

2. The shin member consisted of aluminum tubing of variable length; adjustment was through a turnbuckle sleeve with left and right threaded ends. Adjustment assured a constant length leg. Attachment to the knee bolt was made through a force fit at the shin's upper end. The lower end was bolted to a conventional foot.

3. Friction was introduced at the knee bolt by having its extreme ends threaded for a circular pad of brakelining which bore on the cover plate. A complete range of friction was available.

III. Test Program:

1. Extensive tests were made on one subject, Mr. Herbert Kramer. Runs were made at fifteen degree intervals on circles with diameters of one, two and three inches. (See Fig. 4-1). Runs were taken of the prostheses and good limb on the level walkway at every position. In addition, runs were taken on the ramps at positions 0, 25, 28, 31, 34, 37, 40, 43, and 46.

2. In this group of tests, friction employed was held as nearly constant as possible. Some toe-out and knockknee adjustment was used to make the artificial limb more symmetrical with respect to normal leg. These adjustments being constant, the only test variable was knee bolt position. Careful adjustment of the shin turnbuckle assured a leg of constant length. The variation in inertia of the shin as a result of lengthening the shin when the knee center is moved upwards, has been found to be small.

3. The following is an analysis of the film records taken of pilot wearer on level walkway with knee bolt in positions 25, 28, 31, 34, 37, 40, 43 and 46. These runs represent extreme positions of the knee center.

4. A complete investigation of the moments about the knee, at the various positions, is being undertaken and will be included in a later report.

IV. Test Results:

1. The following material contains Dr. H. E. Elftman's comments on the extreme position motion picture records. As noted, a study of moments about the knee is under way. Preliminary results of this study

seem to indicate a lack of pointed results - no simple trend being discernable. In part, this may result from the choice of an unusually skilled test subject; one whose adaptability to any prosthesis is so good as to negate knee center adjustments. It is felt that more decisive results might have been obtained with a less adaptable amputee.

2. Influence on Gait of Variations in Position of Knee-Axis.

(A.) The variations in gait which accompanied changes in position of the knee-axis were studied from cinematic records made at New York University. A single subject with good adaptability to prosthetic devices used the adjustable knee with the axis of the knee joint in eight different positions. These positions had been selected so as to lie at equal radial distances from the neutral position of the axis, the direction of displacement varying by 45° between successive positions. The designation of the positions used in this report follows that incorporated in the titles of the moving picture record.

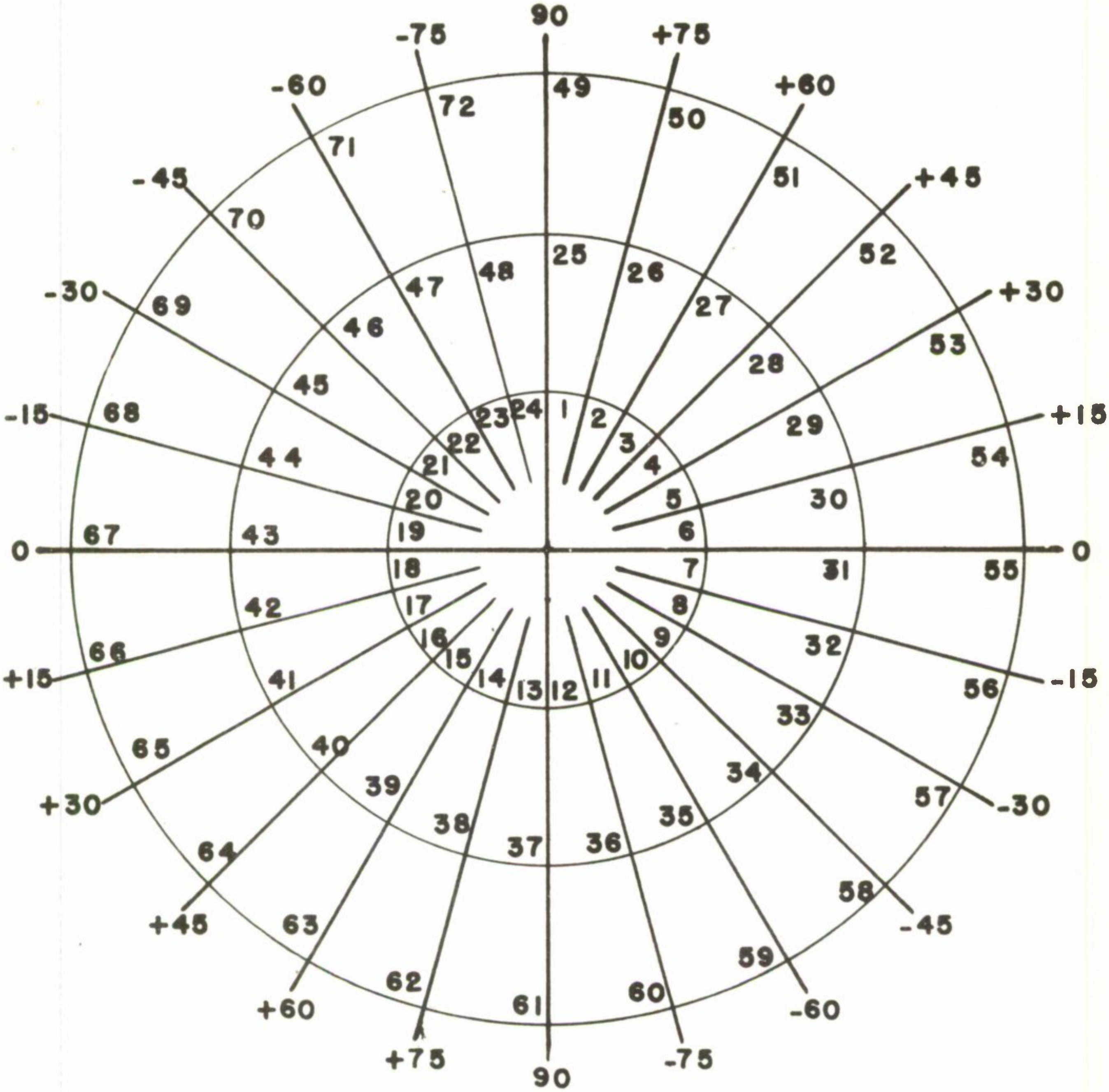
(B.) Noticeable changes take place in the process of walking as the position of the knee axis is moved through the locations described. Although it would take a more extensive series of records to fully evaluate the numerous factors which enter in to gait, it is possible to make preliminary observations which are at least of suggestive value from the records now at hand.

(C.) The records studies indicate that the influence of different positions of the knee axis may be analyzed in terms of two major variables, vertical displacement and antero-posterior position. These two types of displacement seem to affect different aspects of locomotion and a combination of the two, or oblique displacement, has effects attributable to both.

(D.) The most noticeable change in gait which accompanies a downward positioning of the knee axis occurs during the free swing of the leg. Instead of reaching the position in which it can be applied to the ground with a gradual deceleration, the forward movement terminates with an abruptness incompatible with smoothness of performance. The upward displacements recorded result in more even execution of the forward swing but with some evidence of retractile effort on the part of the thigh. It is possible that records of a greater number of vertical positions of the knee axis, some more exaggerated than those at present included, might establish an optimum.

(E.) The second major variable is the antero-posterior or fore-and-aft position of the knee axis. In contract to the vertical displacement, the antero-posterior position affects the conduct of the leg while it is in contact with the ground rather than during the swing. When the knee axis is located posterior to the neutral position in the device employed for the current study, flexion of the knee near the termination of the supporting phase is delayed. The longer duration of the forward vaulting on the prosthetic leg is not only a noticeable visual feature in itself, but it also necessitates some change in the performance of the opposite lower extremity. When the knee axis is located in front of its neutral position, its effect is in the opposite direction. The flexion of the knee occurs earlier. This may be an undesirable feature, especially if accentuated.

(F.) The features which have been discussed pertain to the effect of varying knee-axis position on a dynamic process, walking. It is hardly necessary, but still salutary, to mention the fact that some features of an artificial limb which have untoward effects on movement may be extremely desirable for stability in standing. This consideration is certainly a factor in ariving at a final judgment concerning antero-posterior position of the knee axis.

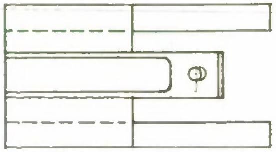


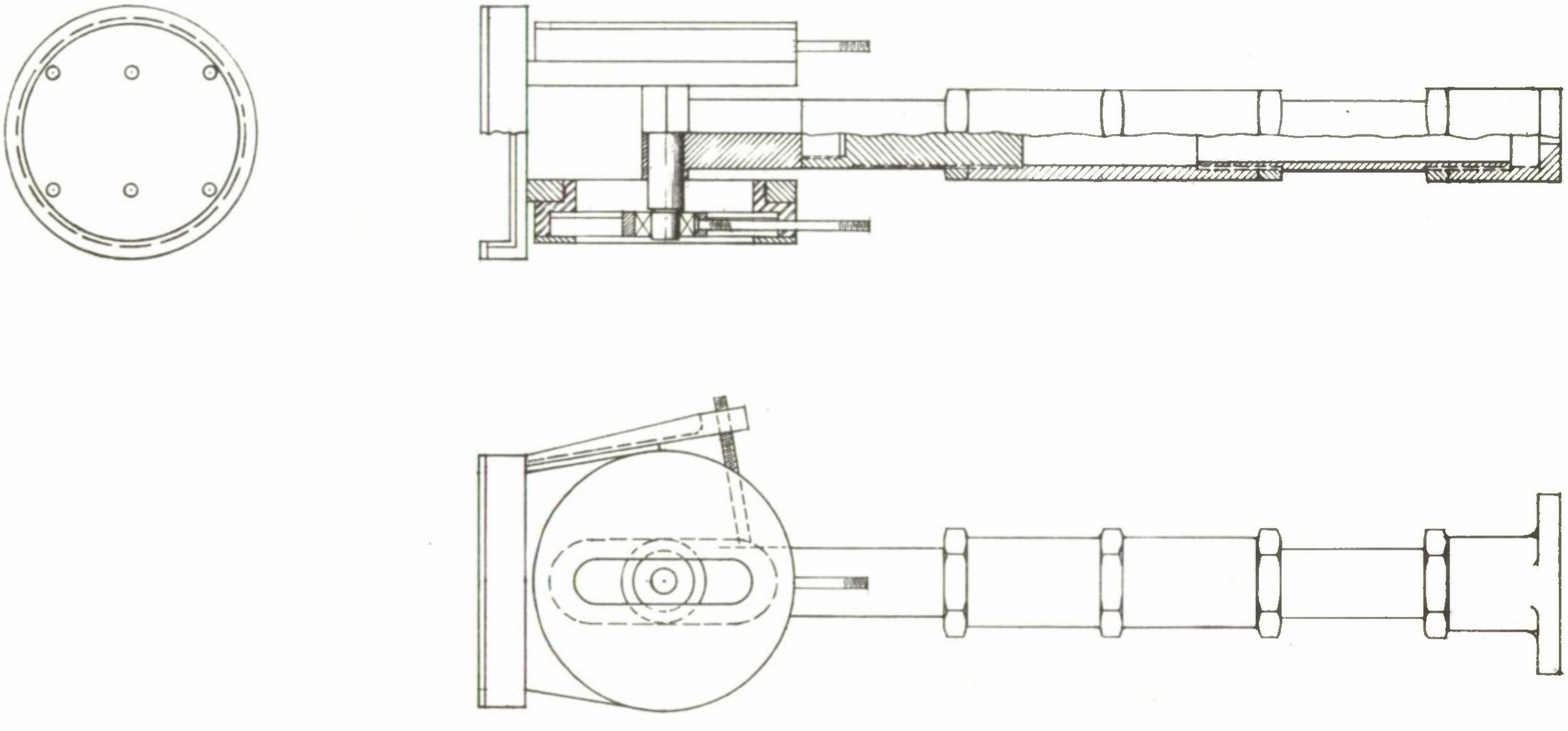
72 TESTED POSITIONS OF KNEE BOLT

Fig. 4-1

A.K. PROSTHESIS WITH ALIGNMENT FEATURES

1. KNEE BOLT LOCATION - VERTICAL AND HORIZONTAL RANGE OF MOTION 3 INCHES
2. KNEE BOLT ANGULAR RANGE - 7° CONE ABOUT A HORIZONTAL AXIS.
3. LENGTH KNEE BOLT TO ANKLE BOLT 14 INS. TO 21 INS.
4. SHIN CAN BE ROTATED ABOUT VERTICAL LEX AXIS.
5. FOOT CAN BE ROTATED ABOUT LONGITUDINAL SHIN AXIS.
6. HYPEREXTENSION AVAILABLE.



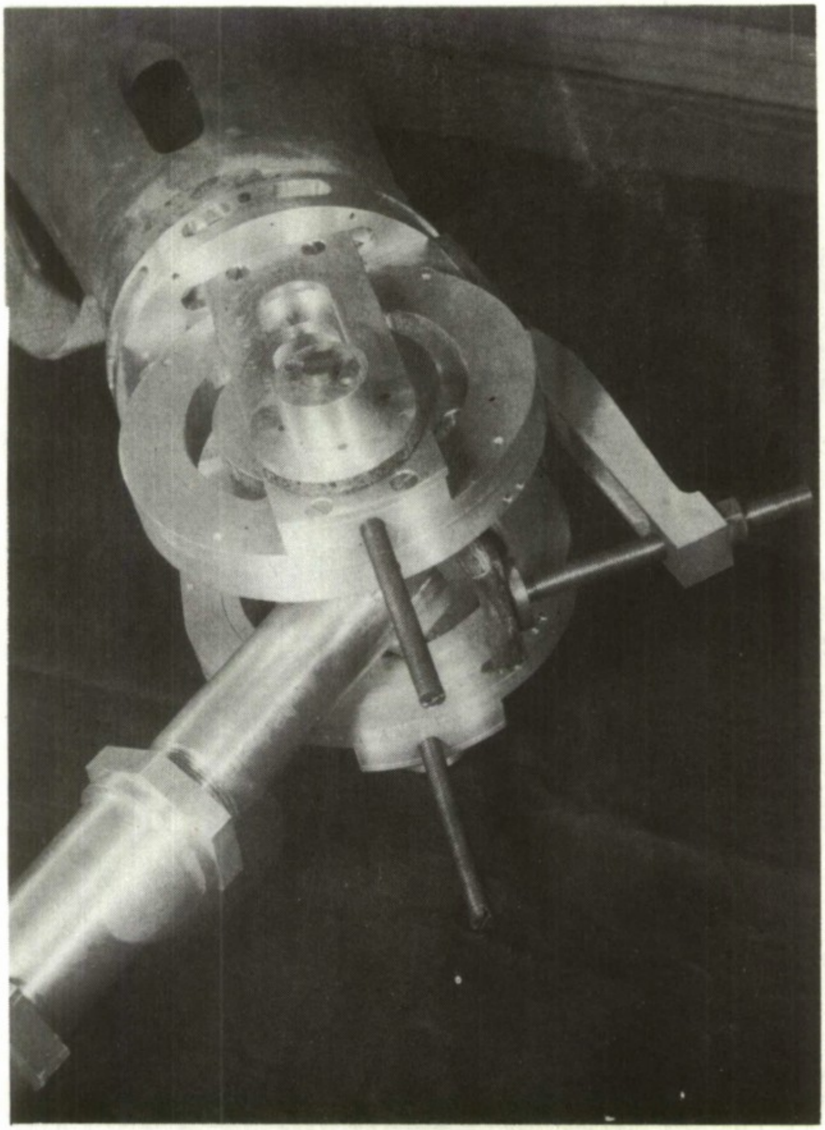


KNEE POSITIONING (VARIABLE KNEE)

PROSTHESIS ASSEMBLY

CONTINI 12-29-47

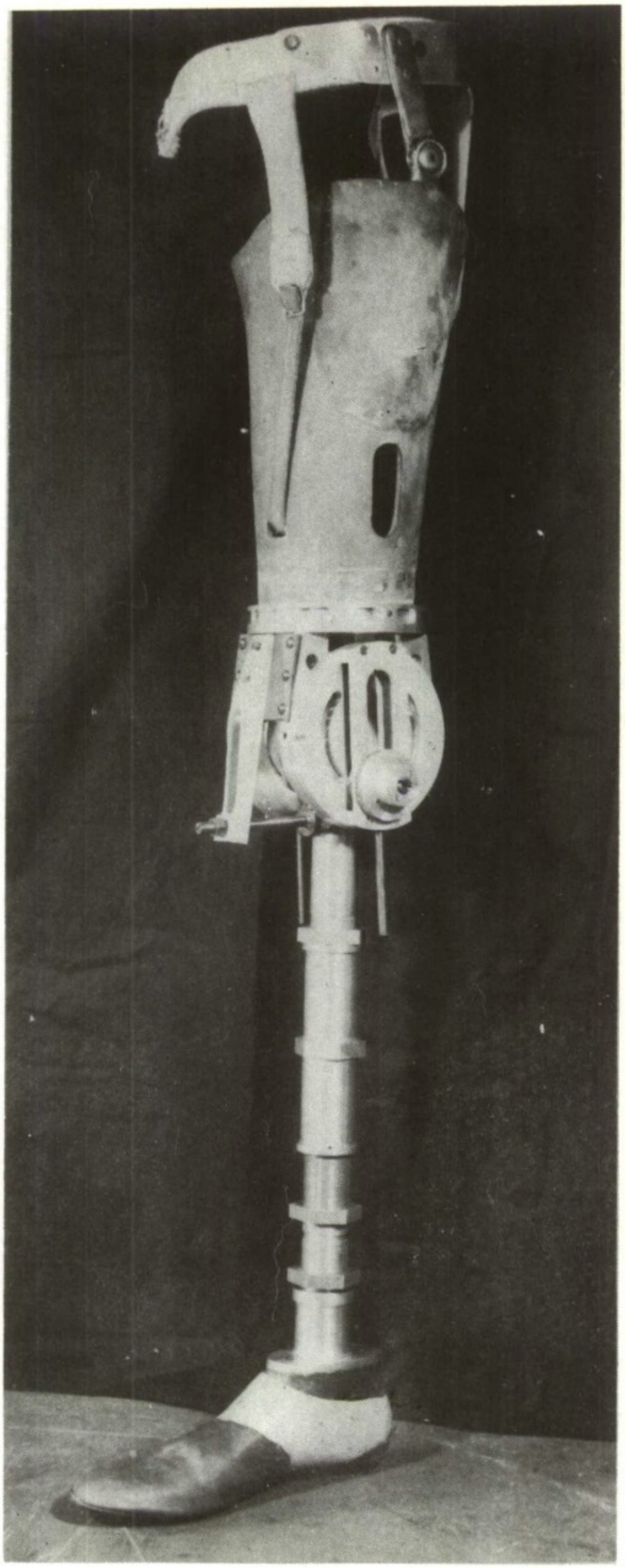
Fig. 4-2



KNEE MECHANISM

Pylon leg, lower left, rotates on movable knee bolt- positioned by a combination of rotation of the bearing frame and translation of the bearing.

Fig. 4-3



PROSTHESIS WITH KNEE BOLT POSITIONING DEVICE

Fig. 4-4

SECTION 5

ROTARY HYDRAULIC DAMPER

Prepared by: Leon Bennett

Harry Slater

SECTION 5 ROTARY HYDRAULIC DAMPER

I. Summary and Conclusions

1. Investigations were conducted of a rotary type damper for possible use as a stabilizing device in the knee box of above-knee amputees. Four variations of one basic type were investigated. In each of these, high resistance was anticipated in the direction of rotation equivalent to the flexion phase of the walking cycle, but comparatively low resistance was expected in the direction equivalent to extension.

2. Resistance to rotation in one direction was provided by forcing the hydraulic fluid through a small orifice area formed by the clearance between the vanes fixed to the housing and the body of the shaft of the rotating vanes. Variations in the orifice area were obtained by changing the clearance. Two spring type relief valves attached one each to the fixed vanes permitted the fluid to by-pass during the rotation in the opposite direction (the extension phase) and reduced the resistance. A number of hydraulic fluids of different viscosities, and different temperature viscosity gradients were used in these tests.

3. Extensive tests on the four variations of this basic design indicate that damping may be obtained under laboratory conditions of a magnitude satisfactory for stabilization of the knee. These damping moments could be achieved, however, only with extremely low clearances, with high viscosity fluids, and under controlled conditions.

4. It does not appear that such a device will be suitable for general application. The fabrication tolerances appear to be such as may not be maintained readily in a production situation. The maintenance problem under operating conditions due to wearing action and hydraulic erosion appears to

be one that would disaffect the amputee. The variations in damping effect due to temperature variations would have a further deterring effect on the amputee acceptance.

5. It is not believed therefore that further work on a rotary hydraulic damping device based on these designs is indicated. Other variations can be tried, but generally it is felt that certain of these difficulties will appear in any variation.

II. <u>Development of the Study</u>

1. Investigation of the needs of above-knee amputees, by conferences with surgeons, limb fitters, and amputees had indicated that stability at the knee joint was a primary consideration. A device developed for above-knee prostheses should assure the amputee stability in standing and walking, and allow time for recovery in stumbling or in other unexpected flexion of the artificial limb. Along with this, the device should permit free extension of the shin relative to the thigh, and further should modulate the extension at the end of the extension phase.

2. It was agreed that this combination of events could be obtained with an hydraulic unit in better fashion than with a mechanical unit. It was realized from the start, however, that such a unit would require precise machining and assembly and consequently would be an expensive device. It could be justified only by simplicity in design and success in function.

3. Previous experience was available. Rotary dampers had been used in the automotive and aircraft industries. It was decided that dampers such as those used in aircraft landing gears could be modified and adapted to this purpose. Accordingly an idealized damper (shown in Figure 5-17) was conceived. In this figure the unit is shown as it might be installed in the distal space of the socket of an A/K prosthesis.

4. This design indicates a unit in which the essential features are a pair of vanes fixed to the body of the damper, and a pair of rotating vanes attached to an axial shaft. These vanes divide the chamber which is filled with hydraulic fluid into four compartments. As the shaft is rotated pressure builds up in the two compartments on the advancing face of the moving vanes. Clearance between the moving vanes and the shaft permits flow from these two compartments into the two compartments on the receding face of the moving vanes. The restriction offered to rotation by the damper is a function of this clearance.

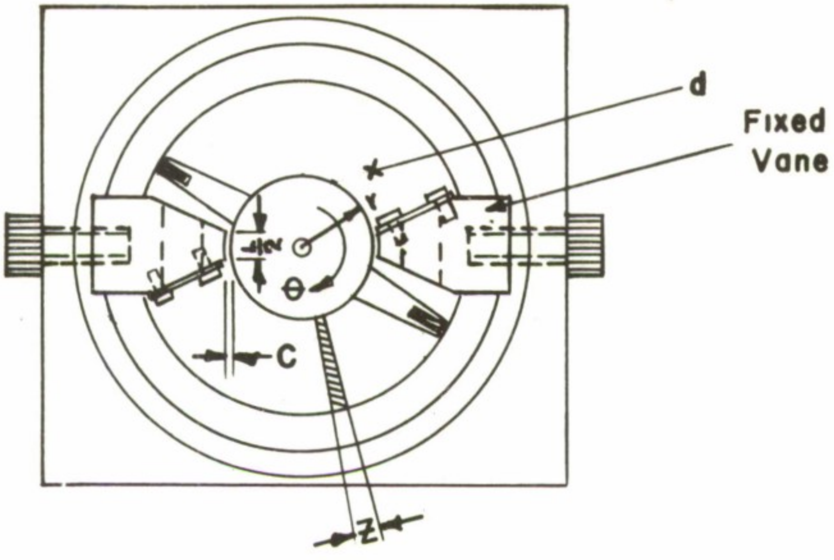
5. It was believed that the variation in the amount of damping required during different phases of the walking cycle could be obtained by making the shaft of the rotating vanes eccentric in section. As shown in this figure in the position of maximum leg extension the clearance between vanes and shaft would be a minimum and would gradually increase as the leg is flexed. This would result in maximum resistance to flexion at the first part of the flexion phase in walking, or in standing. The resistance would decrease as flexion continued. This is in accordance with the predetermined requirements.

6. In order to reduce the resistance to rotation further during the extension cycle, a bypass valve is indicated on each of the rotating vanes. Minimum resistance to extension would occur at the beginning of the extension cycle, gradually increasing as extension increased and reaching a maximum again in the fully extended position. The influence of the variation in clearance during the extension cycle would not be as great as during the flexion cycle because of the bypass valves.

7. In order to assure continuing function and to compensate for fluid losses, a replenishing unit is shown on the upper side of the chamber.

This reservoir is filled with fluid under a spring loaded piston. A check valve between this reservoir and the main chamber permits flow only from the reservoir to the chamber. If fluid should in any way leak out or evaporate from the main chamber it would be replenished from the reservoir.

8. Such an idealized version could not be designed and fabricated without adequate knowledge of the damping moments desired in the knee, nor without knowledge of the restriction and damping moments available with different clearances (orifice areas) and with hydraulic fluids of different viscosities. Studies described in Section 3 were under way to determine the desired damping moments. Similar information was being received from the work being conducted at the University of California. A theoretical analysis of the interrelationship of the rotational velocity, fluid pressure, fluid viscosity and the clearance was being developed. Concurrently it was decided to fabricate a simplified version of this ideal damper and perform tests to verify the theory.



L —— The piston is considered to be that portion of moving vane directly across the edge of the fixed vane, of length L.

C —— The orifice area is formed by the clearance between fixed and moving vanes, of width C.

v' —— The velocity of fluid, relative to piston, at some distance x into the clearance.

v —— The average velocity of fluid through the orifice area.

P —— The difference in fluid pressure on both sides of the moving vane.

Q —— The volume of flow per unit length of vane.

d —— The distance between end caps, or vane length.

u —— Coefficient of absolute viscosity.

θ' —— Angular velocity of the moving vane.

Z —— Volume of fluid displacement per unit degree of rotation.

w —— Angular velocity.

r —— Shaft Radius

ROTARY DAMPER

NOMENCLATURE

3-29-49 LHM

Fig. 5-1

III. THEORETICAL DERIVATION

1. The approach to the study was based on accepted practices in the consideration of problems in fluid mechanics. The nomenclature and symbols used in this discussion are shown in Figure 5-1.

2. The differential equation for uniform motion in a fluid is:

$$\frac{d^2v'}{dx^2} = -\frac{P}{uL} \qquad \text{Eq. 5.1}$$

From which by integrating twice there is obtained:

$$v' = -\frac{P}{uL}\left(\frac{X}{2} + B\,x + D\right) \qquad \text{Eq. 5.2}$$

When: $v' = 0$

Then: $x = 0$ and $D = 0$

When: $v' = -k\theta'$

Then: $x = C$

And: $-k\theta' = -\frac{P}{uL} \; \frac{C^2}{2} + \frac{B}{C}$

From which: $B = \frac{uLk\theta'}{PC} - \frac{C}{2}$

And: $$v' = -\frac{Px^2}{2uL} - \frac{k\theta' x}{C} + \frac{CPx}{2uL} \qquad \text{Eq. 5.2.1}$$

3. The volume of flow per unit depth of vane is expressed:

$$Q = \int_0^C v'dx$$

$$= \int_0^C \left(-\frac{Px^2}{2uL} - \frac{k\theta' x}{C} + \frac{CPx}{2uL}\right) dx$$

$$= -\frac{Px^3}{6uL} - \frac{k\theta'x^2}{2C} + \frac{CPx^2}{4uL}\Bigg|_0^C$$

$$= \frac{PC^3}{12uL} - \frac{k\theta'C}{2}$$

Then by dividing both sides of the equation through by the clearance (C), the average velocity across the clearance relative to the moving vane per unit of depth of the vane may be obtained.

$$\frac{Q}{C} = \frac{PC^2}{12uL} - \frac{k\theta'}{2}$$

If the velocity of the moving vane, kθ', is added to the above equation the absolute fluid velocity per unit depth of vane is obtained.

$$\frac{Q}{C} = \frac{PC^2}{12uL} + \frac{k\theta'}{2} \qquad \text{Eq. 5.3}$$

4. The absolute fluid velocity, however, can be considered as:

$$v = \frac{Q}{A}$$

$$= \frac{(\text{ins}^3/\text{deg})\ (\text{deg./sec.})}{\text{clearance x depth}}$$

Expressing this in the terms indicated in Figure 5-1 we get the expression:

$$v = \frac{Z\theta'}{Cd} \qquad \text{Eq. 5.4}$$

5. By equating (5.3) and (5.4) we obtain the expression:

$$\frac{Z\theta'}{Cd} = \frac{PC^2}{12uL} + \frac{k\theta'}{2}$$

Solving then for P, the difference in fluid pressure:

$$P = \frac{12uL}{C^2}\left[\frac{Z\theta'}{Cd} - \frac{k\theta'}{2}\right] \qquad \text{Eq. 5.5}$$

6. In order to simplify this general equation, the actual values used in this design for some of the constants are introduced:

$$L = 0.250 \text{ inches}$$

(This is twice the distance on the moving vane covered by each of the two fixed vanes.)

$$Z = 0.0222 \text{ ins.}^3 \text{ per degree}$$

(The total fluid volume of the damper was measured to be 38 milliliters, and the total rotation was measured to be 104.4 degrees. The value of Z was obtained from these measured quantities.)

$$r = 0.375 \text{ inches}$$

$$d = 1.381 \text{ inches}$$

7. In order to evaluate $k\theta'$ we know that:

$$v' = k\theta' \text{ (when } x = C\text{)}$$

$$= wr \text{ (expressed as a function of angular velocity)}$$

Therefore:

$$k\theta' = wr$$

$$= 0.00655\ \theta' \text{ inches per second}$$

8. Substituting the quantities in paragraphs 5 and 6 into the equation for the pressure differential (Eq. 5.5) we obtain:

$$P = \frac{u}{C^2}\left[\frac{.0482\theta'}{C} = .00969\theta'\right].$$

When it is realized that in these tests the values of C range between C = .011 and C = .0006 inches, the second term of this equation may be considered negligible in magnitude relative to the first term. The pressure differential is then expressed in terms of the angular velocity, the coefficient of absolute viscosity and the clearance.

$$P = \frac{.0482u\theta'}{C^3} \qquad \text{Eq. 5.5.1}$$

The final general equation for angular velocity becomes:

$$\theta' = \frac{kP^{1.00}C^3}{u^{1.00}} \qquad \text{Eq. 5.6}$$

9. Some error may result due to losses through the sidewall clearance. Comparator studies made indicated a total clearance of 0.0005 inches. Assuming the pressure distribution to be constant, a value for C of 0.002 inches and the damping to vary with the third power of the clearance, the effective loss area due to end clearance is of this order of magnitude:

$$\frac{1.000}{1.381} \times \left(\frac{.0005}{.002}\right)^3 \times 100\% \doteq 1.13\%$$

This effect is therefore comparatively negligible.

IV. Description of Test Models

1. It was realized that the ideal design previously discussed could not be made without adequate information as to the necessary clearances in combination with properly chosen fluids. A simplified version was designed for these tests. This first model referred to in the tests as Model A is shown in Figure 5-18. Simplification was made by eliminating the fluid reservoir and socket attachments. Difficulties were experienced with this model. The design of the shaft was inadequate in torsional stiffness. Leakage occurred at the end caps.

2. A modification of this first model, designated as Model B is shown exploded in Figure 5-19 and assembled in Figure 5-20. This model differed from the first in the design of the end caps and in the greatly increased shaft diameter. This last was achieved by machining the cam surfaces integrally with the shaft extensions which project through the end caps. Numerous tests were performed with this model. There was evidence however, that leakage occurred around the poppet valves and that the clearances obtainable were too large for adequate damping and resistance moments. Sufficient promise from these tests warranted further trials.

3. A second modification designated as Model C (Figure 5-21) was made. The changes consisted in a redesign of the bypass valves from the poppet type to the leaf spring type mounted on the stationary vanes, and the introduction of means for further reducing the clearance between the vanes and the shaft. This model had adequate torsional characteristics, but test results were inconsistent. This inconsistency was attributed to the thin wall aluminum case which apparently distorted under the high static fluid pressure. Examination of the edges of the moving vanes showed scoring, which indicated an eccentricity in the bearings. It was suspected also,

that much fluid was passing between these edges of the vanes and the inner surface of the case.

4. A final model D incorporating changes indicated by these experiences was designed and fabricated. This model is shown in section in Figure 5-23, and in its component parts in Figure 5-22. The body was machined from a 2-1/8 x 2-3/4 block of cold rolled steel. All external edges were ground. The fixed vanes were recessed into the block to a depth of 5/16" to provide greater stability for shim insertion. Steel endcaps were bolted to the body. A blind hole in the rear endcap providing end bearing as well as absorbing end thrust. The other endcap served as a through bearing, containing an O-Ring, washer, snap-ring assembly. Machining tolerances were held to the minimum possible.

5. The shaft, cam, and moving vanes were made as a unit, preventing possible misalignment. Oilite wipers were mounted in a recess at the outer edge of the moving vane, to be pressed against the bored cylinder wall by leaf springs. This piece of X-4130 steel was heat treated to 150,000 PSI. The same valve arrangement as that of Model C was employed. The keyed shaft was joined, by means of a stepped collar, to the wheel hub, which last was drilled to take bicycle spokes.

V. Description of Test Equipment and Procedures

1. In order to obtain a relationship between angular velocity and fluid pressure at known clearances and with fluids whose characteristics were known, the test apparatus shown in Figure 5-24 was developed. With this apparatus it was possible to impress a known moment on the damper and record the resultant angular velocity.

2. A rigid steel tube framework was erected. Two ball bearing pillow blocks were mounted on the crossbars at the top of this framework. A large diameter wheel (11.25 inches) was supported on a shaft rotating in the ball bearings. A dial face divided into two hundred major divisions (representing 1.8 degrees) was soldered to one end of the wheel shaft. A pointer rigidly fixed to the frame indicated the extent of rotation at any given time, from a given original position. Stops for the wheel in positions of extreme flexion and extension were provided by rubber bumpers.

3. A bed was welded to one of the two upper cross bars of the frame oppositely to the side on which the dial was mounted. On this bed was welded a tubular support into which the damper could be inserted. The damper was aligned and retained in place by three sets of adjustment screws set 120 degrees apart. These screws supported the damper in all directions and absorbed the torsional loads as well. The damper shaft was connected to the wheel shaft through a universal joint which expedited the tests by eliminating the necessity for exact shaft alignment. One of the models is shown in position on the test stand in Figure 5-25.

4. A microchronometer was suspended below the dial. A motion picture camera was mounted rigidly along the imaginary extension of the wheel axis. The camera was operated by a synchronous motor so that pictures could be taken at sixty frames per second. The shutter opening was set at one-fourth full opening so that the exposure time for each frame was approximately .002 seconds. This permitted clarity in reading the angular displacement.

5. While the above device was used in tests of models A, B, and C, the need for perfect alignment as clearance tolerances became smaller, led to a change in the setup in the test of model D. In this arrangement the wheel shaft and damper shaft were combined. Spokes strung from this shaft allowed

the mounting of a conventional bicycle rim. From this rim, or wheel in the case of models A, B, and C, a cable was suspended allowing the mounting of various weights, so as to put the damper shaft in torsion.

6. One end cap was removed from the damper. Shims were inserted between the stationary vanes and the housing so as to adjust the clearance to the desired value. The chamber was filled to overflowing with hydraulic fluid. The end cap was replaced with the excess fluid bleeding through a loosened screw in the cap or the body. When the system was bled the screw was tightened. The damper was then mounted in the test stand.

7. A known weight was suspended by a cable which went around the rim of the wheel and which was anchored to the wheel rim at one point. The wheel was rotated to the position of extreme flexion or extreme extension. The camera was started. The weight was released. When the wheel came to a stop against one bumper the operation was reversed in direction. Clockwise rotation as seen by the camera simulated an extension of the leg while counter-clockwise rotation simulated flexion. Two runs in each direction were made for each combination of variables. When necessary or when desirable additional check runs were made.

VI. TABULATED AND PLOTTED DATA

Table 5-I

Results Model B

RUN NO.	TYPE	TORSIONAL MOMENT IN. LBS.	TEST CONDITIONS	DAMPING VELOCITY DEG./SEC.
2	Free	11.25	Test Run	Accelerating
10	Flexion	22.50	Full Clearance-SAE 10	Accelerating
13	Extension	22.50	.011 Clear.-SAE 10	Accelerating
14	Flexion	22.50	.011 Clear.-SAE 10	213.0
16	Extension	22.50	.0072 Clear.-SAE 10	Accelerating
19	Flexion	22.50	.0072 Clear.-SAE 10	53.3
25	Extension	22.50	.0059 Clear.-SAE 10	53.3
26	Flexion	11.25	.0059 Clear.-SAE 10	21.3
27	Flexion	33.75	.0059 Clear.-SAE 10	96
28	Flexion	45.00	.0059 Clear.-SAE 10	133.5
29	Flexion	56.25	.0059 Clear.-SAE 10	186.8
36	Flexion	22.50	.011 Clear.-SAE 60	Decelerating
37	Flexion	22.50	.007 Clear.-SAE 60	37.8
38	Flexion	56.25	.007 Clear.-SAE 60	106.8
40	Flexion	22.50	.006 Clear.-SAE 60	8.0
42	Flexion	56.25	.006 Clear.-SAE 60	47.8

Table 5-II

Results Model C

RUN	TYPE	TORSIONAL MOMENT	TEST CONDITIONS	DAMPING VELOCITY
NO.		IN. LBS.		DEG./SEC.
0-1	Free	11.25	Test Run-Damper Not Mounted	Accelerating
0-2	Free	11.25	Test Run-Damper Not Mounted	Accelerating
0-3	Free	22.50	Test Run-Damper Not Mounted	Accelerating
0-4	Free	22.50	Test Run-Damper Not Mounted	Accelerating
0-5	Free	56.25	Test Run-Damper Not Mounted	Accelerating
0-6	Free	56.25	Test Run-Damper Not Mounted	Accelerating
1-1	Free	11.25	Test Run-Damper Run Dry	Accelerating
1-2	Free	11.25	Test Run-Damper Run Dry	Accelerating
1-3	Free	22.50	Test Run-Damper Run Dry	Accelerating
1-4	Free	22.50	Test Run-Damper Run Dry	Accelerating
1-5	Free	56.25	Test Run-Damper Run Dry	Accelerating
1-6	Free	56.25	Test Run-Damper Run Dry	Accelerating
2-1	Flexion	11.25	Clearance .0075, RL 34C, 63°F	133.5
2-2	Extension	11.25	Clearance .0075, RL 34C, 63°F	Accelerating
2-3	Flexion	22.50	Clearance .0075, RL 34C, 63°F	228
2-4	Extension	22.50	Clearance .0075, RL 34C, 63°F	254.0
2-5	Flexion	56.25	Clearance .0075, RL 34C, 63°F	Accelerating
2-6	Extension	56.25	Clearance .0075, RL 34C, 63°F	Accelerating

Table 5-II (Continued)

RUN NO.	TYPE	TORSIONAL MOMENT IN. LBS.	TEST CONDITIONS	DAMPING VELOCITY DEG./SEC.
3-1	Flexion	11.25	Clearance .0075, Terresso 80, 64° F	53.3
3-2	Extension	11.25	Clearance .0075, Terresso 80, 64° F	106.7
3-3	Flexion	22.50	Clearance .0075, Terresso 80, 64° F	101.2
3-4	Extension	22.50	Clearance .0075, Terresso 80, 64° F	Accelerating
3-5	Flexion	56.25	Clearance .0075, Terresso 80, 64° F	267.0
3-6	Extension	56.25	Clearance .0075, Terresso 80, 64° F	Accelerating
4-1	Flexion	11.25	Clearance .0075, Univis 90, 63° F	66.7
4-2	Extension	11.25	Clearance .0075, Univis 90, 63° F	Accelerating
4-3	Flexion	22.50	Clearance .0075, Univis 90, 63° F	226.5
4-4	Extension	22.50	Clearance .0075, Univis 90, 63° F	Accelerating
4-5	Flexion	56.25	Clearance .0075, Univis 90, 63° F	Accelerating
4-6	Extension	56.25	Clearance .0075, Univis 90, 63° F	Accelerating
5-1	Flexion	11.25	Clearance .0055, G.G. D, 72° F	160.0
5-2	Extension	11.25	Clearance .0055, G.G. D, 72° F	Accelerating
5-3	Flexion	22.50	Clearance .0055, G.G. D, 72° F	Accelerating
5-4	Extension	22.50	Clearance .0055, G.G. D, 72° F	Accelerating
5-5	Flexion	56.25	Clearance .0055, G.G. D, 72° F	Accelerating
5-6	Extension	56.25	Clearance .0055, G.G. D, 72° F	Accelerating
6-1	Flexion	11.25	Clearance .0055, RL34A, 72° F	106.8
6-2	Extension	11.25	Clearance .0055, RL34A, 72° F	Accelerating
6-3	Flexion	22.50	Clearance .0055, RL34A, 72° F	186.8

Table 5-II (Continued)

RUN	TYPE	TORSIONAL MOMENT	TEST CONDITIONS	DAMPING VELOCITY
NO.		IN. LBS.		DEG./SEC.
6-4	Extension	22.50	Clearance .0055, RL34A, 72 °F	Accelerating
6-5	Flexion	56.25	Clearance .0055, RL34A, 72 °F	Accelerating
6-6	Extension	56.25	Clearance .0055, RL34A, 72 °F	Accelerating
7-1	Flexion	11.25	Clearance .0055, RL34C, 76 °F	47.8
7-2	Extension	11.25	Clearance .0055, RL34C, 76 °F	Accelerating
7-3	Flexion	22.50	Clearance .0055, RL34C, 76 °F	106.8
7-4	Extension	22.50	Clearance .0055, RL34C, 76 °F	Accelerating
7-5	Flexion	56.25	Clearance .0055, RL34C, 76 °F	267.0
7-6	Extension	56.25	Clearance .0055, RL34C, 76 °F	Accelerating
8-3	Flexion	22.50	Clearance .0055, Univis 90, 76 °F	106.8
8-4	Extension	22.50	Clearance .0055, Univis 90, 76 °F	Accelerating
8-5	Flexion	56.25	Clearance .0055, Univis 90, 76 °F	267.0
8-6	Extension	56.25	Clearance .0055, Univis 90, 76 °F	Accelerating
8-7	Flexion	33.75	Clearance .0055, Univis 90, 76 °F	146.9
8-8	Extension	33.75	Clearance .0055, Univis 90, 76 °F	Accelerating
9-3	Flexion	22.50	Clearance .0055, Terresso 80, 76°	53.3
9-4	Extension	22.50	Clearance .0055, Terresso 80, 76°	Accelerating
9-7	Flexion	33.75	Clearance .0055, Terresso 80, 76°	101.2
9-8	Extension	33.75	Clearance .0055, Terresso 80, 76°	Accelerating
9-5	Flexion	56.25	Clearance .0055, Terresso 80, 76°	160.0
9-6	Extension	56.25	Clearance .0055, Terresso 80, 76°	Accelerating

Table 5-II (Continued)

RUN	TYPE	TORSIONAL MOMENT	TEST CONDITIONS	DAMPING VELOCITY
NO.		IN. LBS.		DEG./SEC.
10-3	Flexion	22.50	Clearance .0045, RL34C, 74°	111.1
10-4	Extension	22.50	Clearance .0045, RL34C, 74°	Accelerating
10-7	Flexion	33.75	Clearance .0045, RL34C, 74°	173.5
10-8	Extension	33.75	Clearance .0045, RL34C, 74°	Accelerating
10-5	Flexion	56.25	Clearance .0045, RL34C, 74°	289.0
10-6	Extension	56.25	Clearance .0045, RL34C, 74°	Accelerating
11-3	Flexion	22.50	Clearance .0045, Univis 90, 65°F	66.7
11-4	Extension	22.50	Clearance .0045, Univis 90, 65°F	Accelerating
11-7	Flexion	33.75	Clearance .0045, Univis 90, 65°F	106.8
11-8	Extension	33.75	Clearance .0045, Univis 90, 65°F	Accelerating
11-5	Flexion	56.25	Clearance .0045, Univis 90, 65°F	240.0
11-6	Extension	56.25	Clearance .0045, Univis 90, 65°F	Accelerating
12-3	Flexion	22.50	Clearance .0045, Terresso 80 71°F	26.7
12-4	Extension	22.50	Clearance .0045, Terresso 80 71°F	Accelerating
12-7	Flexion	33.75	Clearance .0045, Terresso 80 71°F	40.0
12-8	Extension	33.75	Clearance .0045, Terresso 80 71°F	Accelerating
12-5	Flexion	56.25	Clearance .0045, Terresso 80 71°F	79.0
12-6	Extension	56.25	Clearance .0045, Terresso 80 71°F	Accelerating
13-3	Flexion	22.50	Clearance .0045, SAE 60, 74°F	15.6
13-4	Extension	22.50	Clearance .0045, SAE 60, 74°F	155.8
13-7	Flexion	33.75	Clearance .0045, SAE 60, 74°F	21.1

Table 5-II (Continued)

RUN	TYPE	TORSIONAL MOMENT	TEST CONDITIONS	DAMPING VELOCITY
NO.		IN. LBS.		DEG./SEC.
13-8	Extension	33.75	Clearance .0045, SAE 60, 74°F	
13-5	Flexion	56.25	Clearance .0045, SAE 60, 74°F	26.7
13-6	Extension	56.25	Clearance .0045, SAE 60, 74°F	
13-9	Flexion	112.50	Clearance .0045, SAE 60, 74°F	64.5
13-10	Extension	112.50	Clearance .0045, SAE 60, 74°F	
13-13	Flexion	281.25	Clearance .0045, SAE 60, 74°F	Accelerating
14-3	Flexion	22.50	Clearance .0035, RL34C, 75°F	75.7
14-4	Extension	22.50	Clearance .0035, RL34C, 75°F	
14-7	Flexion	33.75	Clearance .0035, RL34C, 75°F	170.0
14-8	Extension	33.75	Clearance .0035, RL34C, 75°F	
14-5	Flexion	56.25	Clearance .0035, RL34C, 75°F	209.0
14-6	Extension	56.25	Clearance .0035, RL34C, 75°F	
15-3	Flexion	22.50	Clearance .0035, Univis 90°, 75°F	93.5
15-4	Extension	22.50	Clearance .0035, Univis 90°, 75°F	
15-7	Flexion	33.75	Clearance .0035, Univis 90°, 75°F	144.7
15-8	Extension	33.75	Clearance .0035, Univis 90°, 75°F	
15-5	Flexion	56.25	Clearance .0035, Univis 90°, 75°F	267.0
15-6	Extension	56.25	Clearance .0035, Univis 90°, 75°F	
15-9	Flexion	225.0	Clearance .0035, Univis 90°, 75°F	Accelerating
16-3	Flexion	22.50	Clearance .0035, Terresso 80, 75°F	13.6
16-4	Extension	22.50	Clearance .0035, Terresso 80, 75°F	

Table 5-II (Continued)

RUN	TYPE	TORSIONAL MOMENT	TEST CONDITIONS	DAMPING VELOCITY
NO.		IN. LBS.		DEG./SEC.
16-7	Flexion	33.75	Clearance .0035, Terresso 80 75°F	23.4
16-8	Extension	33.75	Clearance .0035, Terresso 80 75°F	
16-5	Flexion	56.25	Clearance .0035, Terresso 80 75°F	42.3
16-6	Extension	56.25	Clearance .0035, Terresso 80 75°F	
16-9	Flexion	112.5	Clearance .0035, Terresso 80 75°F	95.7
16-13	Extension	112.5	Clearance .0035, Terresso 80 75°F	
17-3	Flexion	22.50	Clearance .0035, SAE 60, 74°F	11.1
17-4	Extension	22.50	Clearance .0035, SAE 60, 74°F	
17-7	Flexion	33.75	Clearance .0035, SAE 60, 74°F	12.5
17-8	Extension	33.75	Clearance .0035, SAE 60, 74°F	
17-5	Flexion	56.25	Clearance .0035, SAE 60, 74°F	26.7
17-6	Extension	56.25	Clearance .0035, SAE 60, 74°F	
17-9	Flexion	112.5	Clearance .0035, SAE 60, 74°F	66.7
17-13	Extension	280.75	Clearance .0035, SAE 60, 74°F	320.0
18-3	Flexion	22.50	Clearance .0025, RL34C, 74°F	93.5
18-4	Extension	22.50	Clearance .0025, RL34C, 74°F	
18-7	Flexion	33.75	Clearance .0025, RL34C, 74°F	155.8
18-8	Extension	33.75	Clearance .0025, RL34C, 74°F	
18-5	Flexion	56.25	Clearance .0025, RL34C, 74°F	Accelerating
18-6	Extension	56.25	Clearance .0025, RL34C, 74°F	

Table 5-III

Results Model D

RUN NO.	TYPE	TORSIONAL MOMENT IN. LBS.	TEST CONDITIONS	DAMPING VELOCITY DEG./SEC.
100-5	Free	56.25	Test Run	Accelerating
101-5	Free	56.25	Test Run	Accelerating
102-5	Free	56.25	Test Run	Accelerating
103-5	Free	56.25	Clearance .0032, Terresso 80	40.0
105-5	Flexion	56.25	Clearance .0012, Terresso 80	28.9
106-5	Extension	56.25	Clearance .0012, Terresso 80	Accelerating
107-25	Flexion	281.25	Clearance .0012, Terresso 80	227.0
109-5	Flexion	56.25	Clearance .0012, Terresso 80	Accelerating
110-5	Free	56.25	Damper Not in Place	Accelerating
111-25	Flexion	281.25	Clearance .0012, Terresso 80	445.0
112-25	Free	281.25	Damper Not in Place	Accelerating
113-5	Flexion	56.25	Clearance .0012, Terresso 80	26.7
115-5	Flexion	56.25	Clearance .0016, Terresso 80	42.3
117-25	Flexion	281.25	Clearance .0016, Terresso 80	128.0
119-10	Flexion	112.50	Clearance .0016, Terresso 80	61.2
121-20	Flexion	225.00	Clearance .0016, Terresso 80	133.5
123-5	Flexion	56.25	Clearance .0011, Terresso 80	21.2
125-25	Flexion	281.25	Clearance .0011, Terresso 80	168.0

Table 5-III (Continued)

RUN NO.	TYPE	TORSIONAL MOMENT IN. LBS.	TEST CONDITIONS	DAMPING VELOCITY DEG./SEC.
127-5	Flexion	56.25	Clearance .0006, Terresso 80	66.7
129-25	Flexion	281.25	Clearance .0006, Terresso 80	Accelerating
131-5	Flexion	56.25	Clearance .0006, Terresso 120	26.7
133-25	Flexion	281.25	Clearance .0006, Terresso 120	186.8
135-5	Flexion	56.25	Clearance .0006, Univis 115	59.0
137-25	Flexion	281.25	Clearance .0006, Univis 115	Accelerating

VII. Sample Calculation and Discussion of Results

1. The motion pictures taken were projected greatly magnified frame by frame. The time interval between successive frames was constant, .0166 seconds, but could be verified by reading the microchronometer dial. The change in angular position was read off the dial. Although the divisions indicated 1.8 degrees, interpolation was possible by virtue of the large magnification to one-tenth of this or 0.18 degrees.

2. Calculations were generally concerned with the damping velocity obtained under a given torsional moment. As the weight would accelerate under non-constant damping velocity conditions, the applied moment was a dependent function of the damper acceleration. Results for a given moment were read at some constant damping velocity, making inertia corrections unnecessary. The constant damping velocity was chosen toward the end of each run when flow conditions had stabilized. These velocities and moments are listed in Part 5-VI (Tabulated and Plotted Data) of this report.

3. The abcissa of the velocity-time curves represents units of time, which for the pictures exposed per frame is .0166 seconds. The ordinate represents damping velocity in degrees per second. Absolutely correct values should incorporate a tare of frictional damping. These values, while measured in numerous test runs, were not utilized because of the small practical difference. A sample calculation is made considering Run 25, Model B.

Raw data appears as:

Motion Picture Frame	Dial Reading	Dial Reading	Dial Reading
65	6240	40	
66	6200	20	
67	6180	20	20
68	6160	20	0
69	6140	20	0
70	6120	20	0
71	6100	20	0
72	6080	20	0

4. Where the circular dial is divided into 10,000 units, the angular increment, between successive time readings (listed as Angle), are proportional to the velocity. These represent the first derivative of the angle. Since the time interval is constant, the second angular increment, Angle, indicates acceleration or the second derivative. As this is zero over most of the data range, we have a zero inertia condition and the applied moment is equal to the weight (2 lbs.) x the radius of the wheel (11.25"). At this time the average damping velocity = $\frac{20 \times 360 \text{ degrees}}{10{,}000 \text{ intervals}} \times \frac{60}{\text{secs}} = 43.2$ deg/per sec.

5. A sample computation of theoretical damping is performed assuming the angular velocity θ' to be 50 degrees per second, the clearance C to be 0.002 inches, and using Univis 90 oil at an operating temperature of 70° F for which u is equal to 31×10^{-6} pounds seconds per square inch. Each vane area is 0.625 square inches and the effective moment arm is 0.625 inches.

6. Equation 5.5.1 yields the following expression for the pressure difference P

$$P = \frac{.0482\,u\theta'}{C^3}$$

Substituting the values above for the equation's variables,

$$P = \frac{.0482 \times 31 \times 10^{-6} \times 50}{(.002)^3}$$

$$= 935 \text{ pounds per square inch.}$$

7. With constant pressure distribution of the vane wall surface, and a zero pressure effect on the opposite wall of the moving vane, the damping force may be evaluated:

$$\text{Damping Force} = \text{Pressure} \times \text{Area}$$

$$= 935 \times 2 \times 0.625$$

$$= 1170 \text{ pounds}$$

$$\text{Damping Moment} = \text{Damping Force} \times \text{Moment Arm}$$

$$= 1170 \times 0.625$$

$$= 731 \text{ inch pounds}$$

8. The theoretical treatment of the damper flow, Section V-III leads to this final expression for damping velocity:

$$\theta' = \frac{k_1 P^{1.00}\,C^3}{u^{1.00}} \qquad \text{Eq. 5.6}$$

The following empirical relation for the damping velocity expressed as a function of the applied moment (expressed as a pressure), the clearance and the oil viscosity, is obtained from graphs and figures.

$$\theta' = \frac{k_2 P^{1.03} C^{3.04}}{u^{.935}} \text{ and } \frac{k_2 P^{1.33}\,C^{5.65}}{u^{.935}}$$

9. It is seen that the qualitative agreement is extremely good. The empirical relation has been derived from the extensive tests conducted with B and C configurations. Figure 5-8 indicates that the damping velocity varies between the 3.04 and 5.65 power of the clearance. Figure 5-2 indicates that the velocity varies as the pressure to the 1.33 power for the B model, while Figure 5-14 indicates that the velocity varies as the pressure to the 1.032 power for the C model. The latter figure, crossplotted for a moment of 30 inch pounds, is presented on Figure 5-15. It is seen that the velocity varies inversely as the viscosity to the .935 power. In combining these results, the above empirical relation is obtained.

10. Discrepancies arise in the computation of a quantitative damping value. Presumably the failure evidenced here results from lack of exact knowledge concerning flow about the sides of the vane, the exact distribution of pressure along the advancing vane front, the effectiveness of the wipers at high pressures, the degree of turbulence in the fluid, the sealing abilities of the bypass valve in a closed condition, and the effects of rotation on the flow. Assumptions made concerning these unknowns in the derivation lead to inaccuracy.

11. The test Reynold's Number (2.13) places the flow in the laminar region in which the analysis is presumably correct. G.I. Taylor* indicates that while the critical Reynolds Number is a function of the radius of curvature of the cylinder, the effect is slight for the conditions concerned, i.e., the critical RN is reduced from the commonly accepted value of 2,000 to about 800. It is seen that the flow is laminar to a degree where local

---

* G.I. Taylor, "Fluid Friction Between Rotating Cylinder," Proc. of Royal Soc. Vol. A157, Nos. 892-893, 1936.

turbulence caused by sharp edges and the high constriction ratio still could not cause a shift into the turbulent range.

12. Actual pressure distribution is made difficult to evaluate by the complex flow pattern. Considering the flow two-dimensional in a circular cross-section the pattern is the following: the advancing vane front will displace a volume of fluid in a radial direction towards the orifice; as this unit volume approaches the orifice the flow area diminishes and the velocity rapidly increases. To this radial velocity must be added a tangential component provided by the velocity of the vane itself. As the flow moves inward, the tangential component diminishes to zero while the radial velocity increases to the value obtained at the orifice (about 400" / sec.) A vectorial addition of the components produces a slowly revolving resultant velocity, tangential at the cylinder wall and radial at the orifice. A rotating vector velocity of the type will bring about high circulatory and turbulent flows. It is, therefore, reasonable to assume a nearly constant velocity throughout the body with consequent uniform pressure distribution.

13. The flow through the side walls becomes important at small orifice openings. Preventing this flow with wipers would necessitate frequent adjustment and undesirable friction characteristics. The present wiper, spring-loaded, mounted in the moving vane edge, may possibly unseat under high body pressure; accurate determination has not been attempted. Similarly, although believed to function properly, the exact action of the bypass valve is unknown in the damping phase.

14. Experimental accuracy is not high, but is sufficient for test purposes. The dial markings can be read to ±5 intervals. For the majority of test results, this corresponds to a reading error of about ±20% for

individual instantaneous velocities. As the final velocity is obtained by averaging a great number of points, the scatter is reduced greatly and the final experimental accuracy considerably improved.

15. Test results (See Figure 5-16) indicate an attainable damping moment of about two hundred eighty in-lbs. with .0006 clearance. A desirable value is about 2,400 in-lbs.* To obtain this value the clearance would have to be approximately .0003 inches. A tolerance of as small a value as ±.0001 would exert large effects on the damping attained. Consequently it is not believed that the unit could be made commercially practical. A possible successful alternate procedure would be to employ an oil with a high viscosity, and a low viscosity temperature gradient. Such an oil was not available for these tests.

---

* University of California, Berkeley "Classification and Specification of Prosthetic Legs," Article 7, Draft Form.

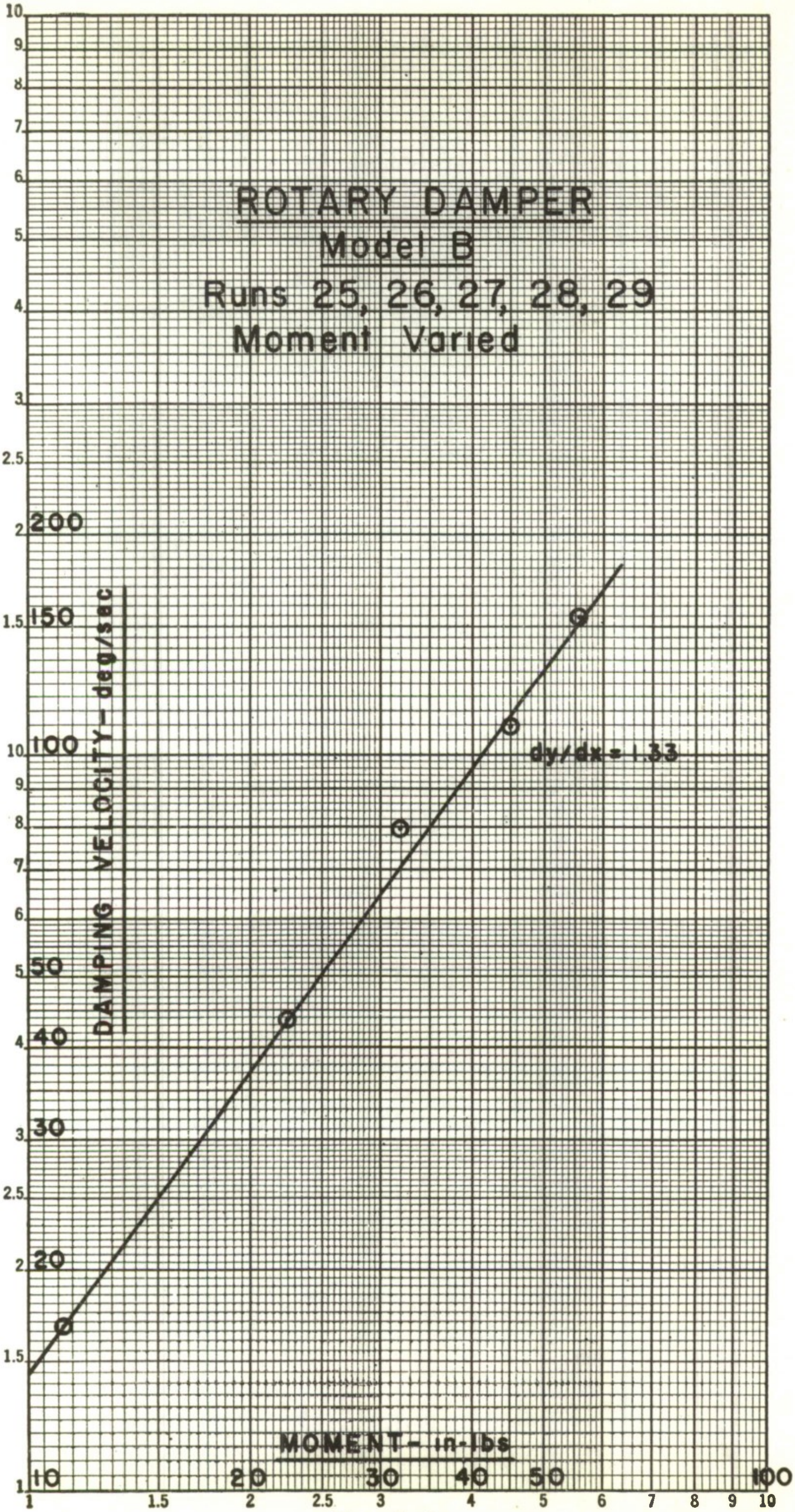

ROTARY DAMPER
Model B
Runs 25, 26, 27, 28, 29
Moment Varied
DAMPING VELOCITY - deg/sec
MOMENT - in-lbs
dy/dx = 1.33
10
20
30
40
50
100
150
200
10
20
30
40
50
100

Fig. 5-2

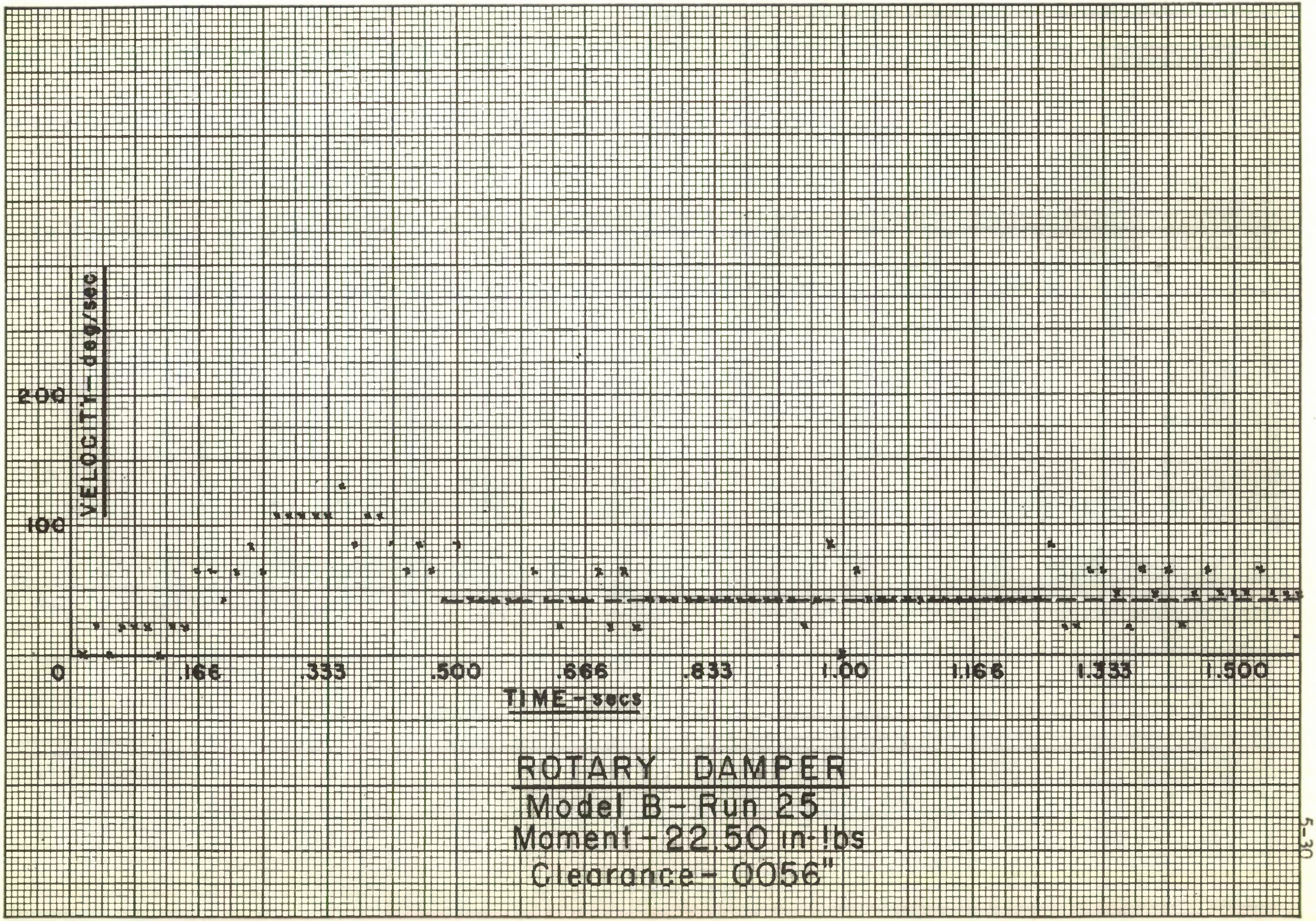
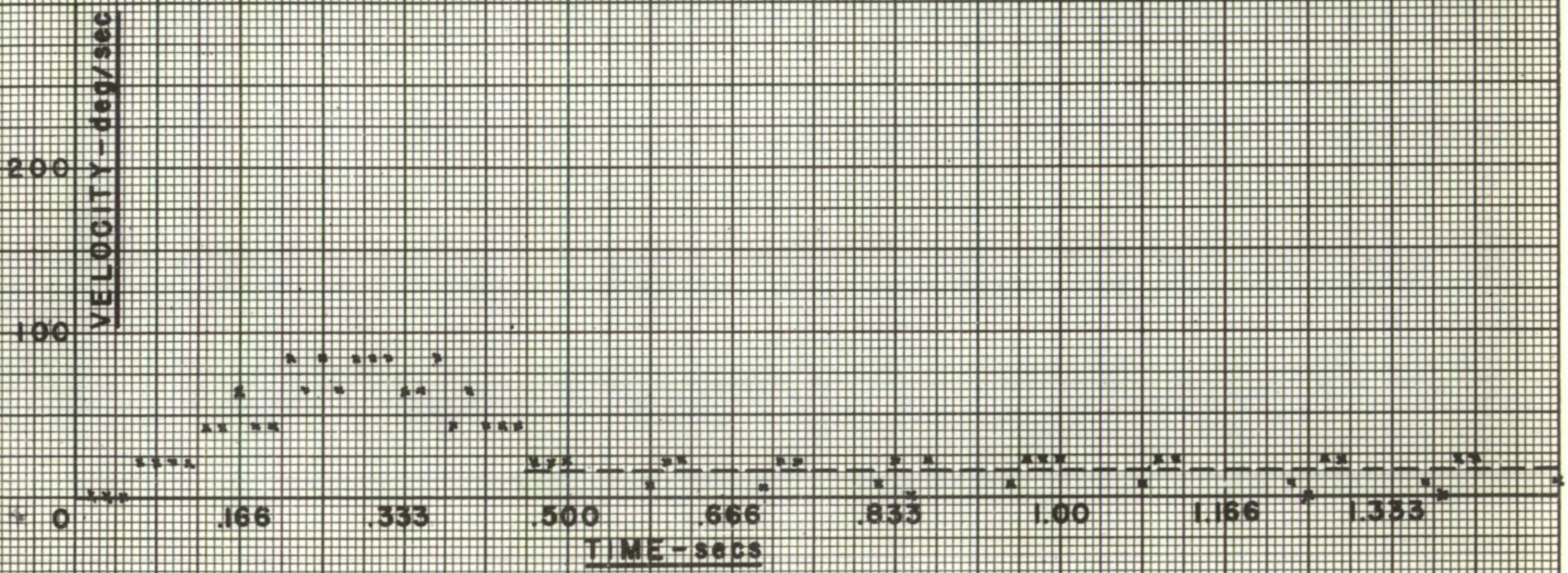

VELOCITY - deg/sec
200
100
0
.166
.333
.500
.666
.833
1.00
1.166
1.333
1.500
TIME - secs
ROTARY DAMPER
Model B - Run 25
Moment - 22.50 in-lbs
Clearance - .0056"

Fig. 5-3



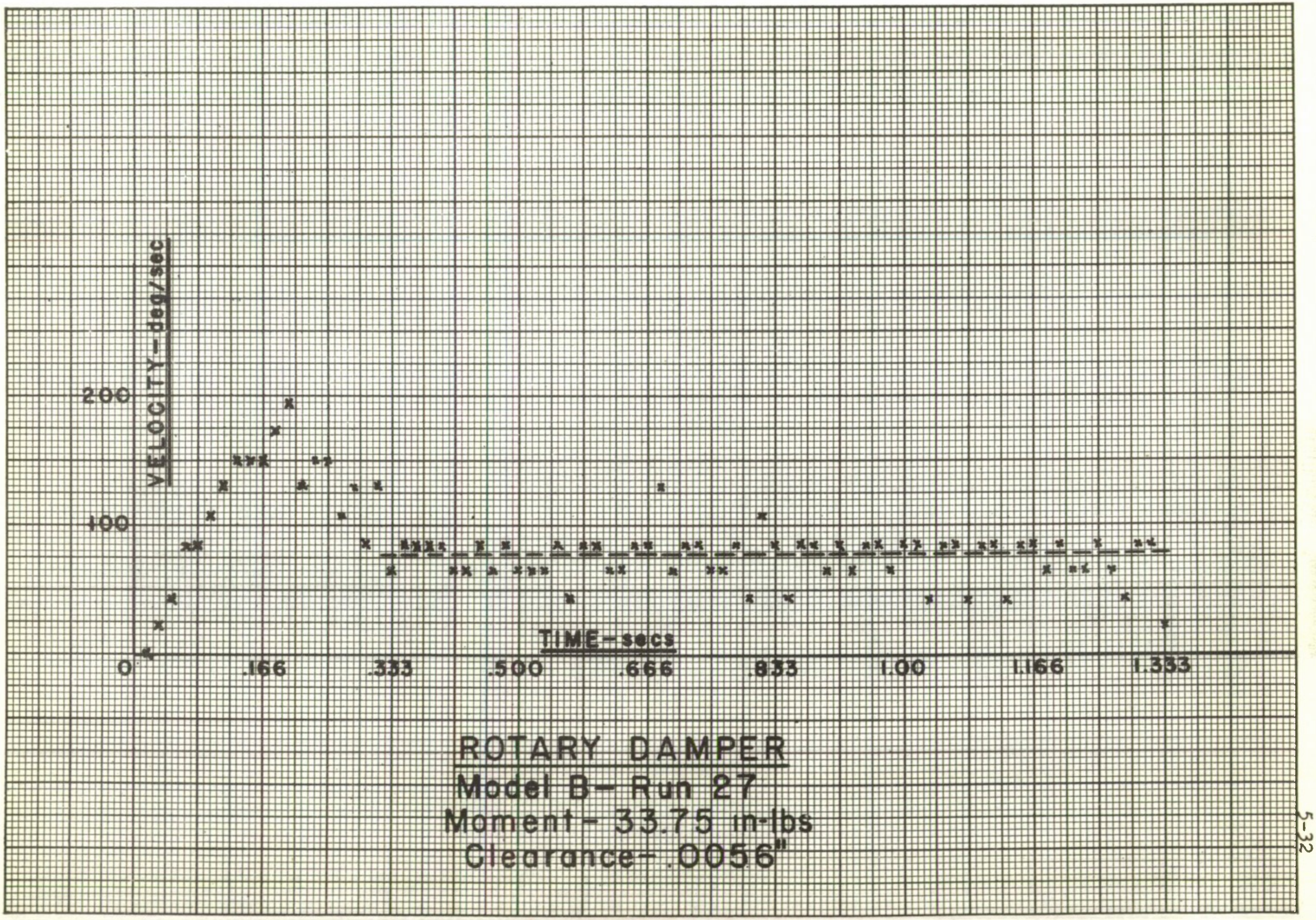
ROTARY DAMPER

Model B – Run 26

Moment – 11.25 in-lbs

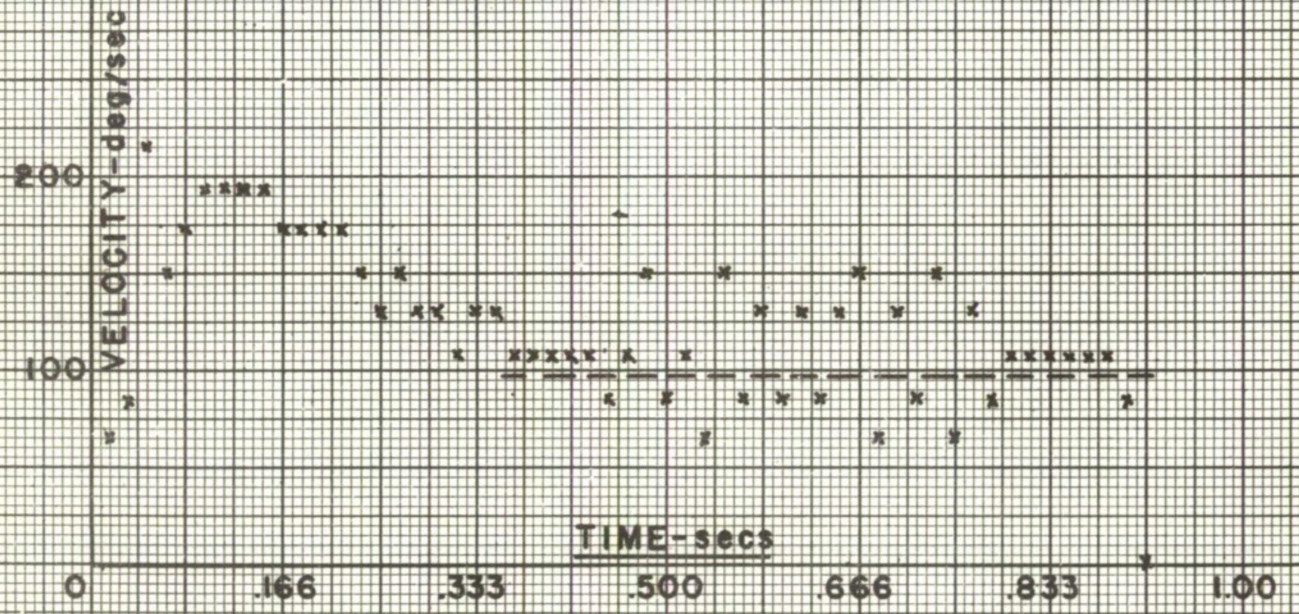
Clearance – .0056"

Fig. 5-4



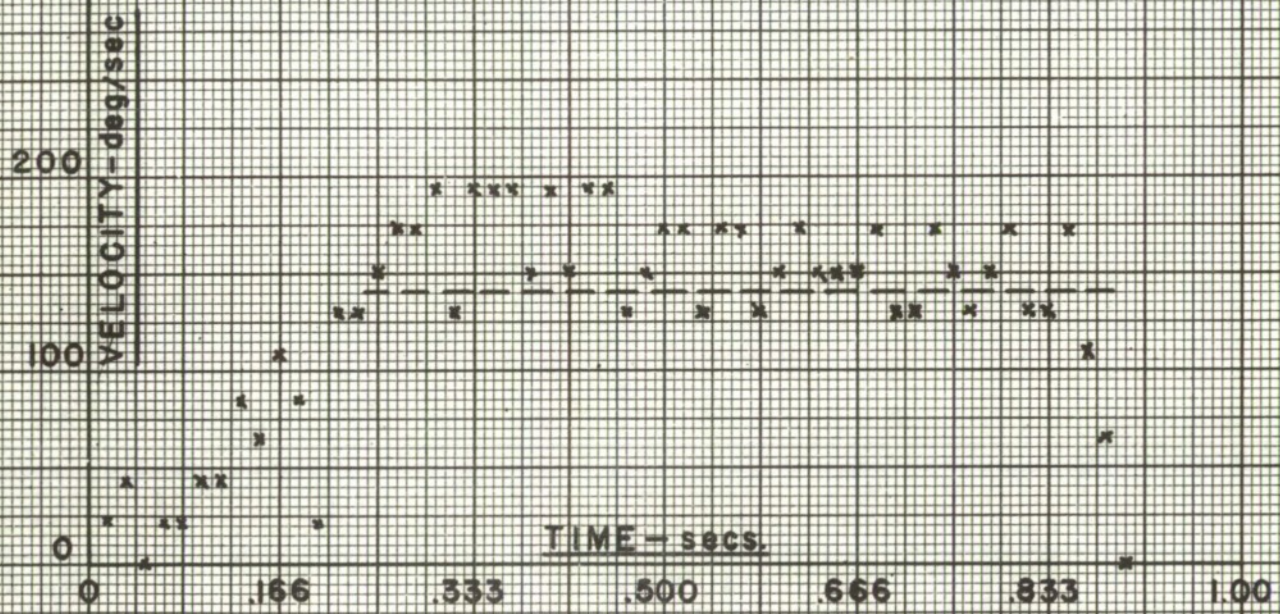
ROTARY DAMPER
Model B – Run 27
Moment – 33.75 in-lbs
Clearance – .0056"

Fig. 5-5



ROTARY DAMPER
Model B-Run 28
Moment- 45.00 in-lbs
Clearance- .0056"

Fig. 5-6



ROTARY DAMPER
Model B — Run 29
Clearance — .0056"
Moment — 56.25 in-lbs

Fig. 5-7

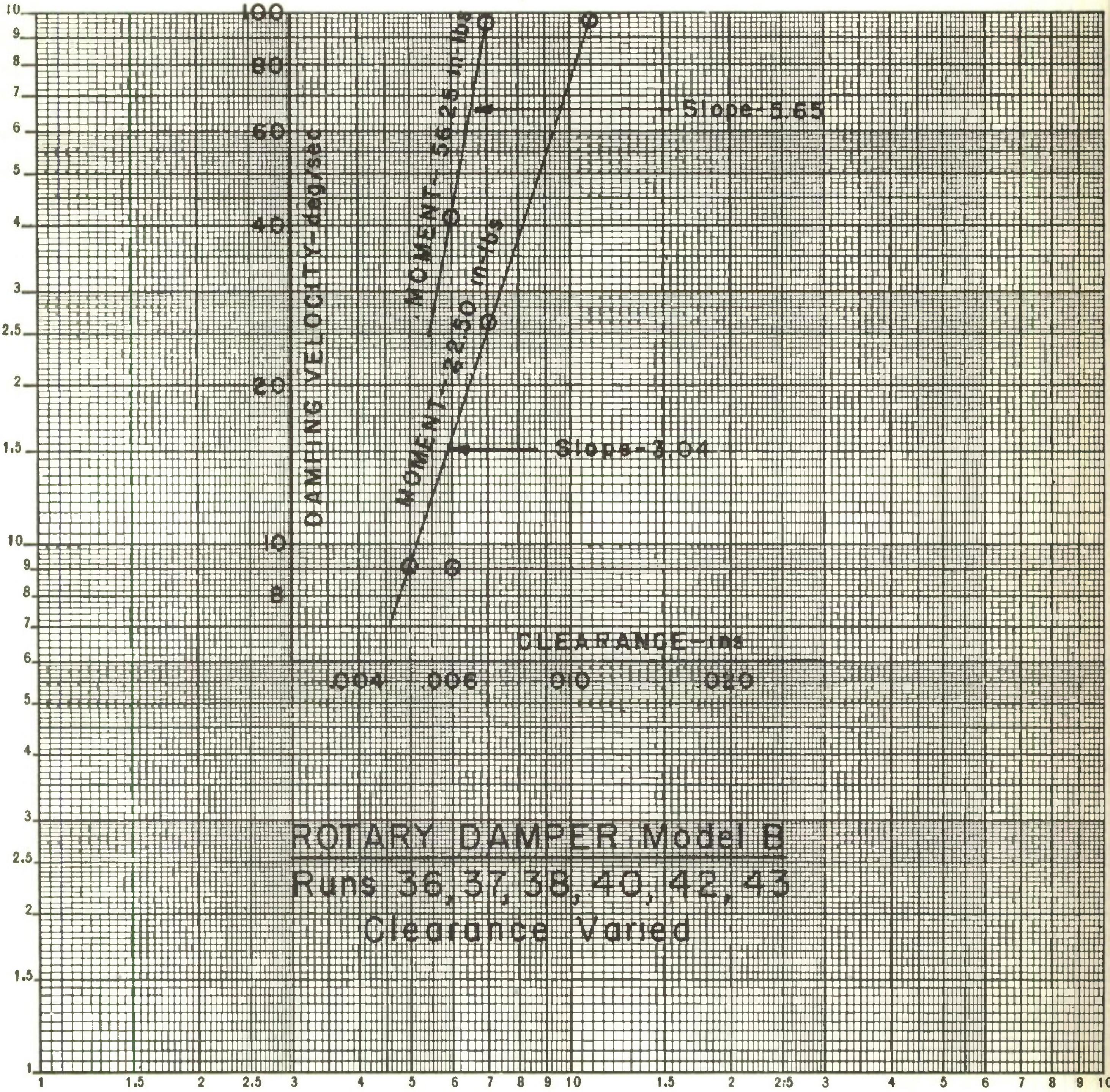
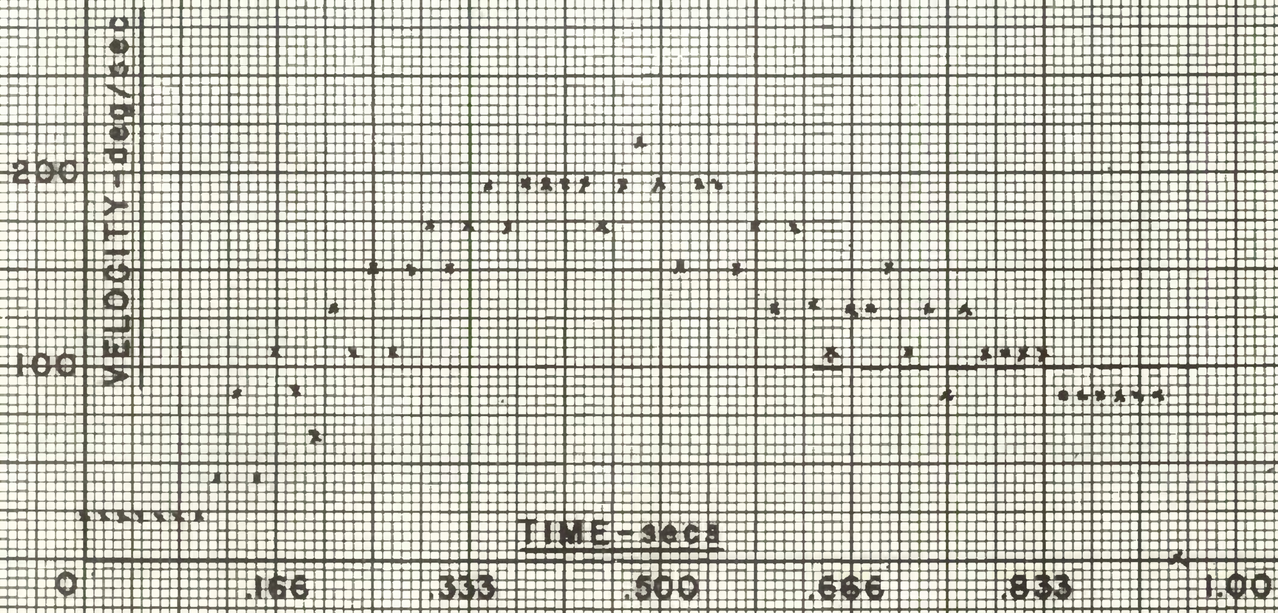

ROTARY DAMPER Model B
Runs 36, 37, 38, 40, 42, 43
Clearance Varied
DAMPING VELOCITY-deg/sec
CLEARANCE-ins
.004
.006
.010
.020
100
80
60
40
20
10
8
MOMENT-56.25 in-lbs
MOMENT-22.50 in-lbs
Slope-5.65
Slope-3.04

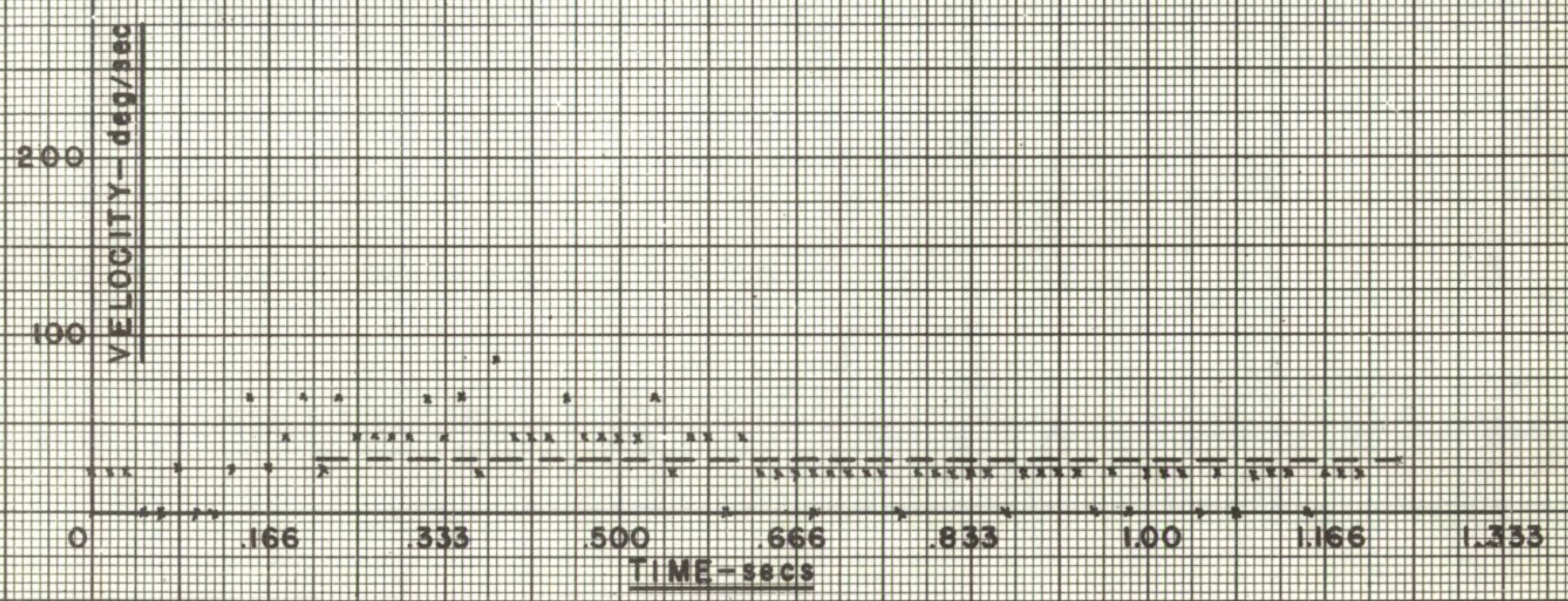
Fig. 5-8



ROTARY DAMPER

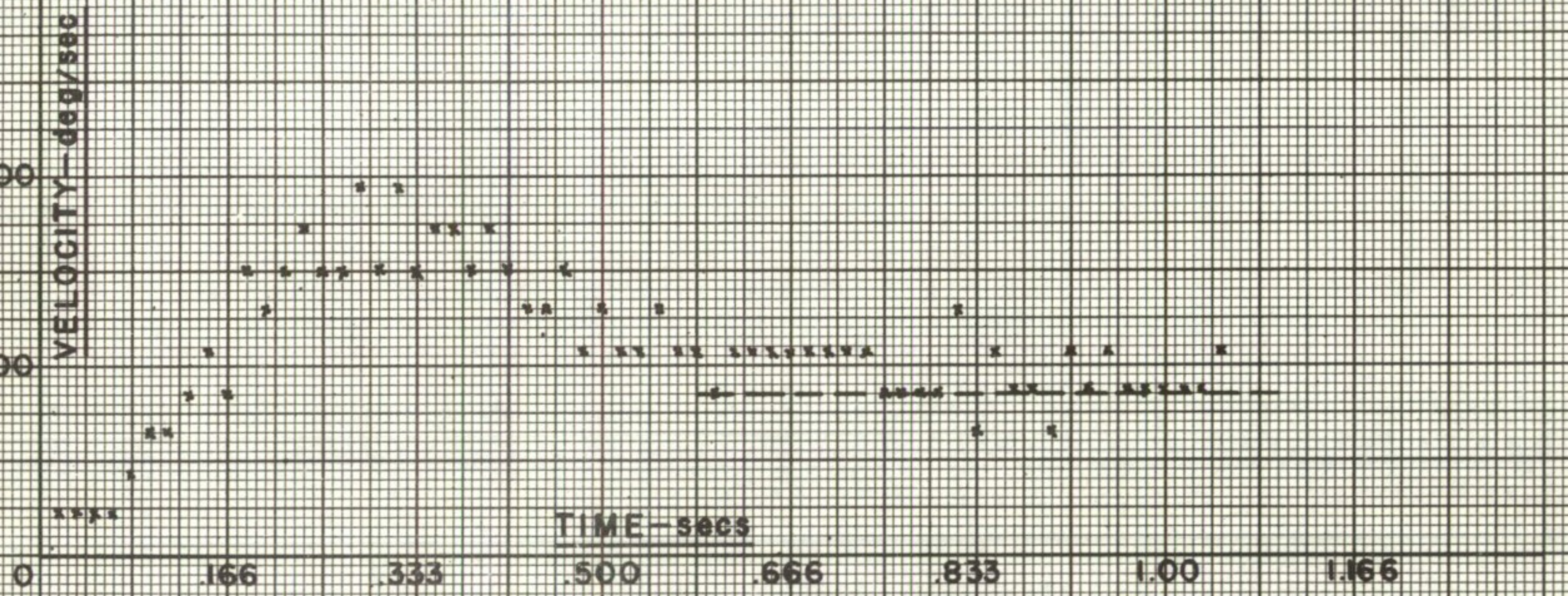
Model B—Run 36
Clearance-.011"
Moment-22.50 in-lbs

Fig. 5-9



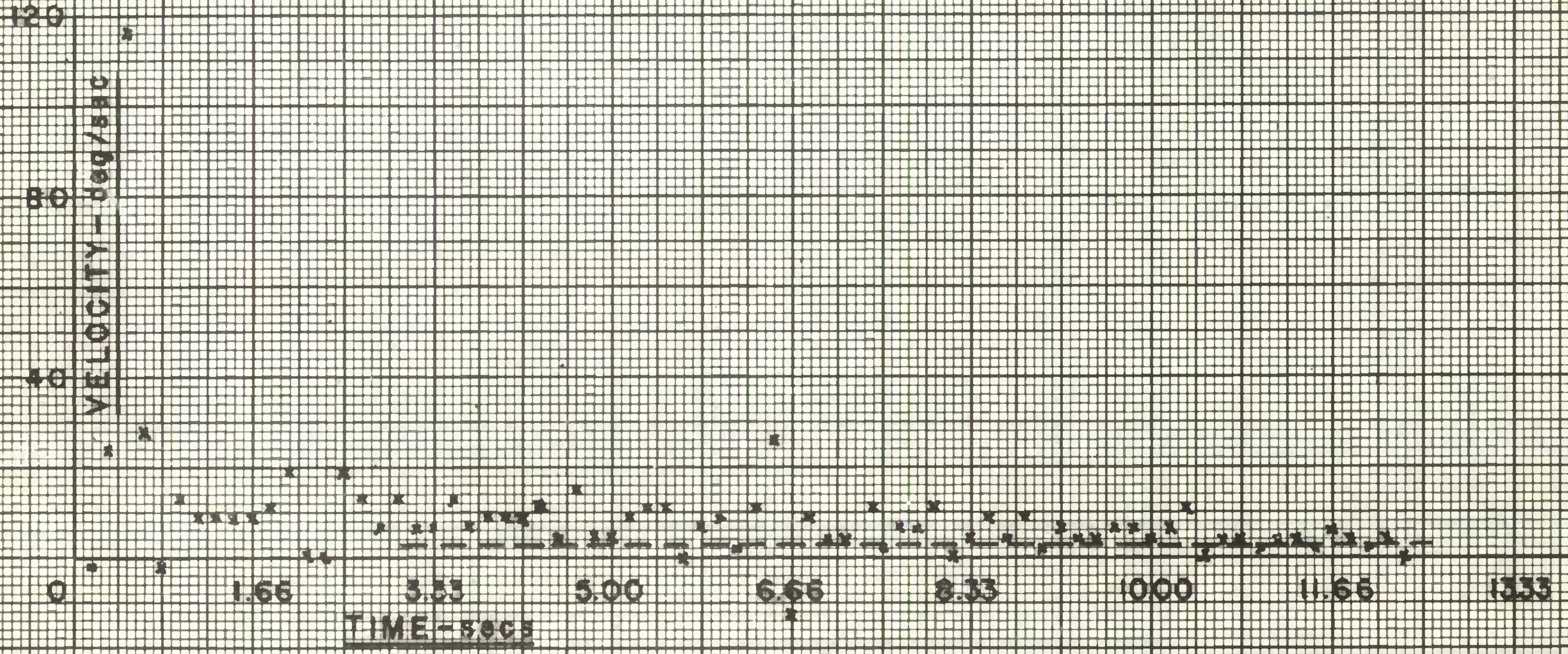
ROTARY DAMPER
Model B – Run 37
Clearance – .007"
Moment – 22.50 in-lbs

Fig. 5-10



ROTARY DAMPER
Model B– Run 38
Clearance– .007"
Moment— 56.25 in-lbs

Fig. 5-11



ROTARY DAMPER

Model B - Run 40
Clearance - .006"
Moment - 22.50 in-lbs

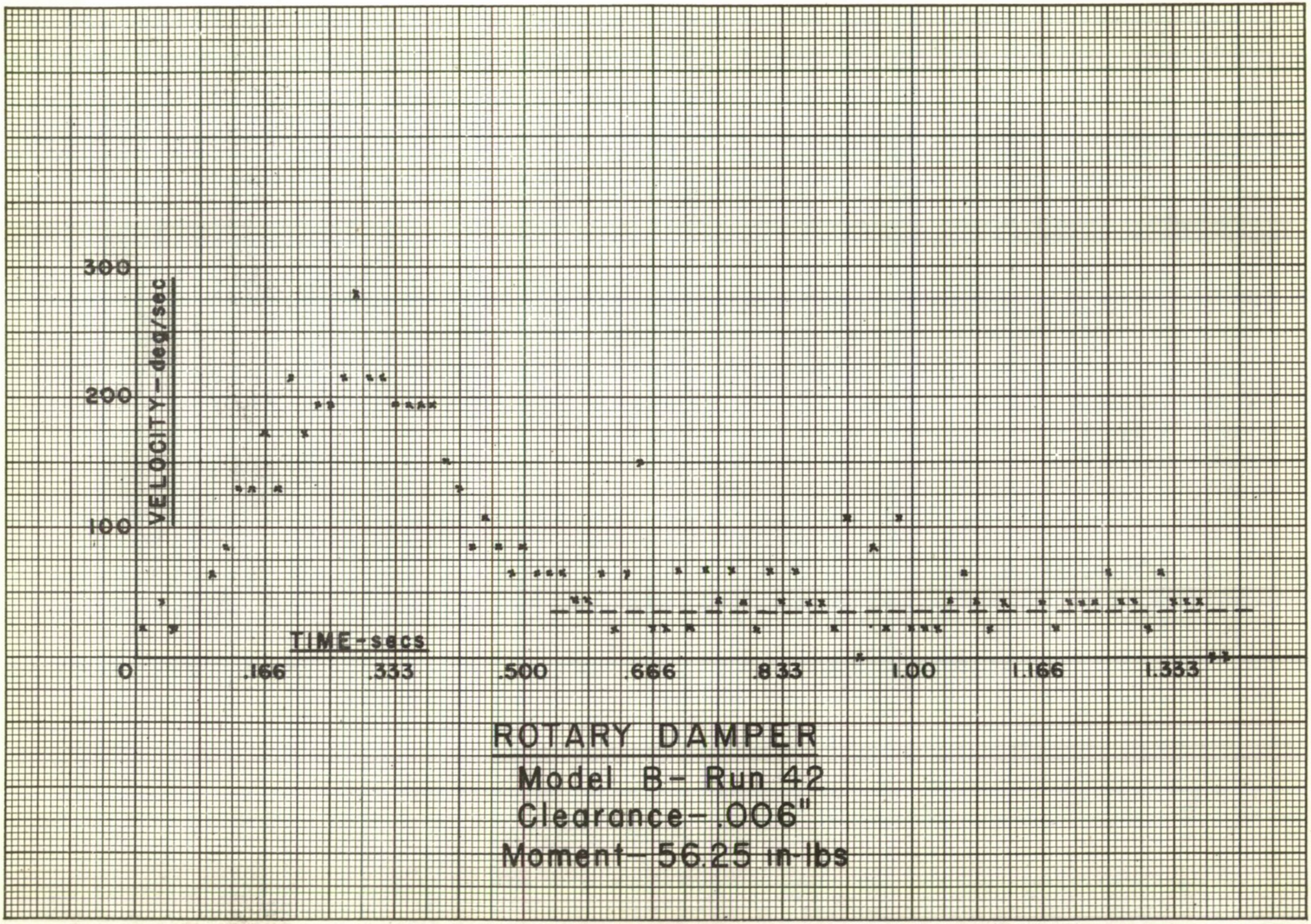

300
200
100
0
VELOCITY – deg/sec
TIME-secs
.166
.333
.500
.666
.833
1.00
1.166
1.333
ROTARY DAMPER
Model B- Run 42
Clearance- .006"
Moment- 56.25 in-lbs

Fig. 5-13

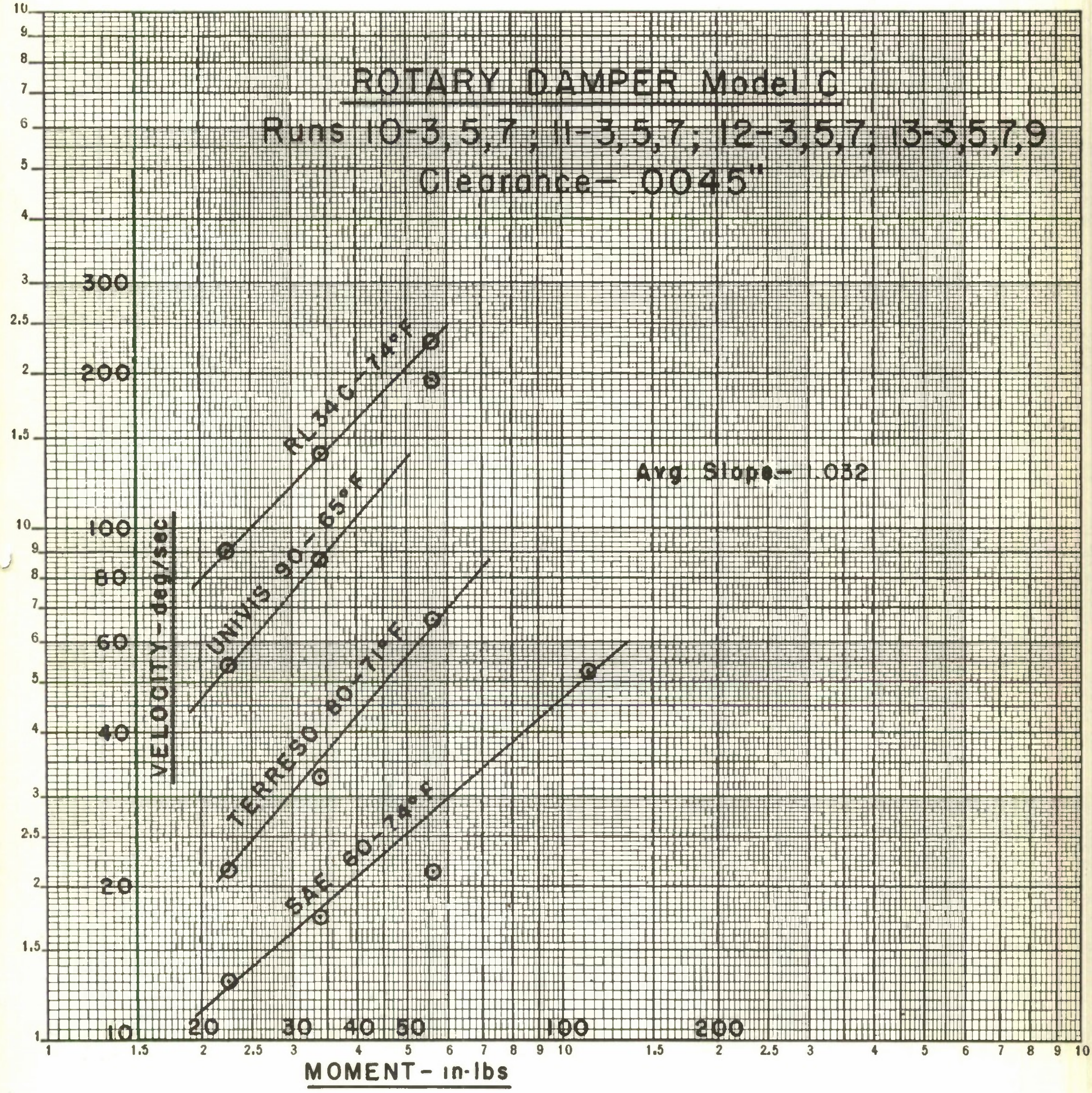
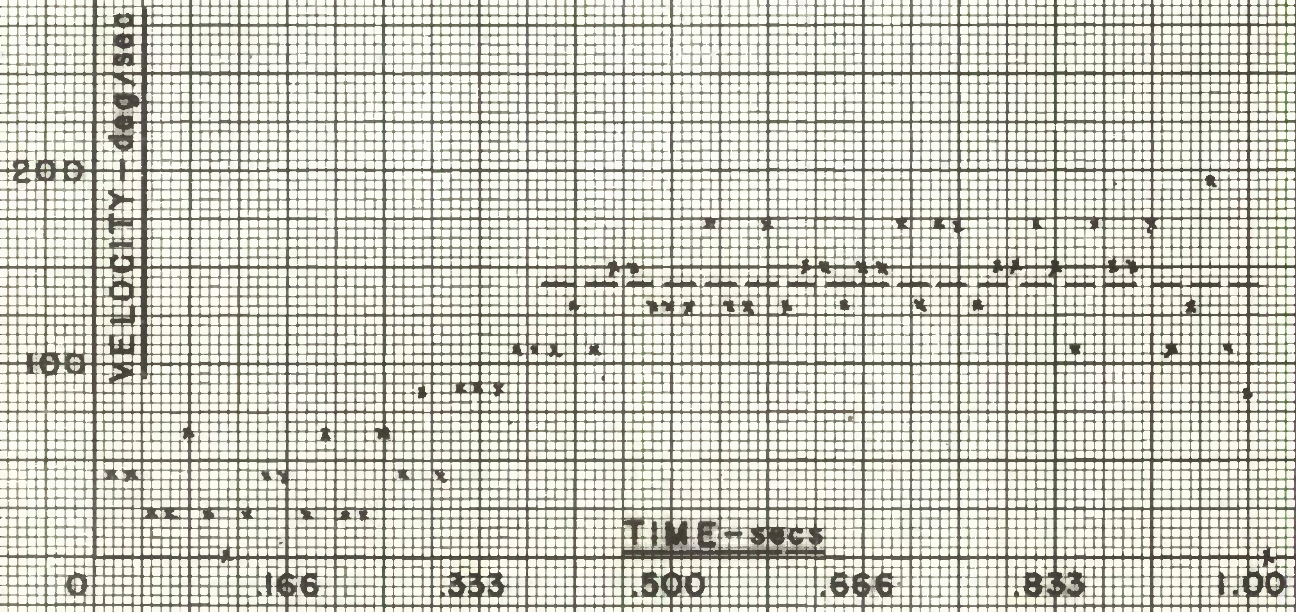
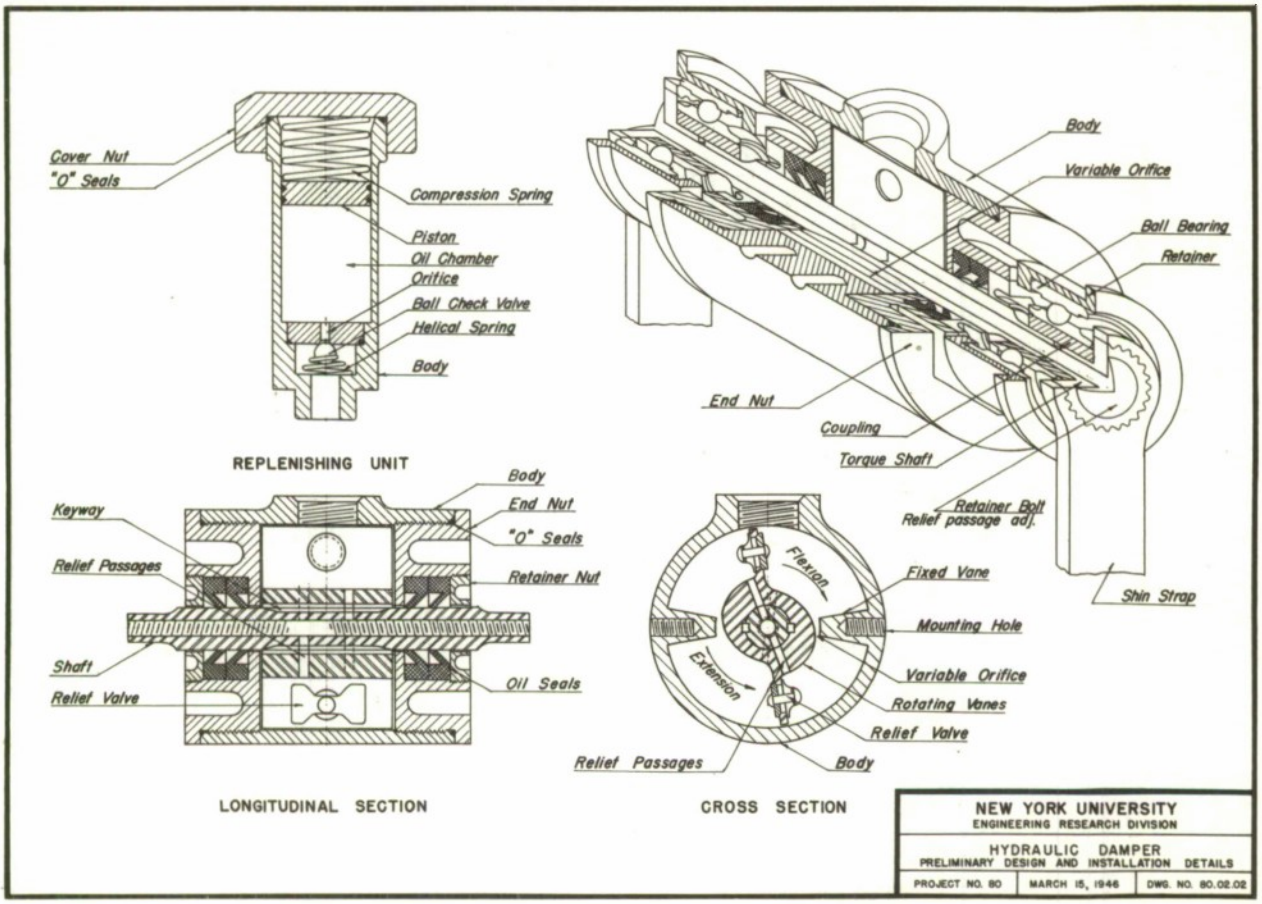

ROTARY DAMPER Model C
Runs 10-3,5,7; 11-3,5,7; 12-3,5,7; 13-3,5,7,9
Clearance - .0045"
Avg. Slope - 1.032
RL 34 G - 74°F
UNIVIS 90 - 65°F
TERRESO 60 - 71°F
SAE 60 - 74°F
VELOCITY - deg/sec
MOMENT - in-lbs
300
200
100
80
60
40
20
10
20
30
40
50
100
200

Fig. 5-14



ROTARY DAMPER
Model D - RUN 133-25
Clearance - .0006"
Moment - 281.25 in-lbs

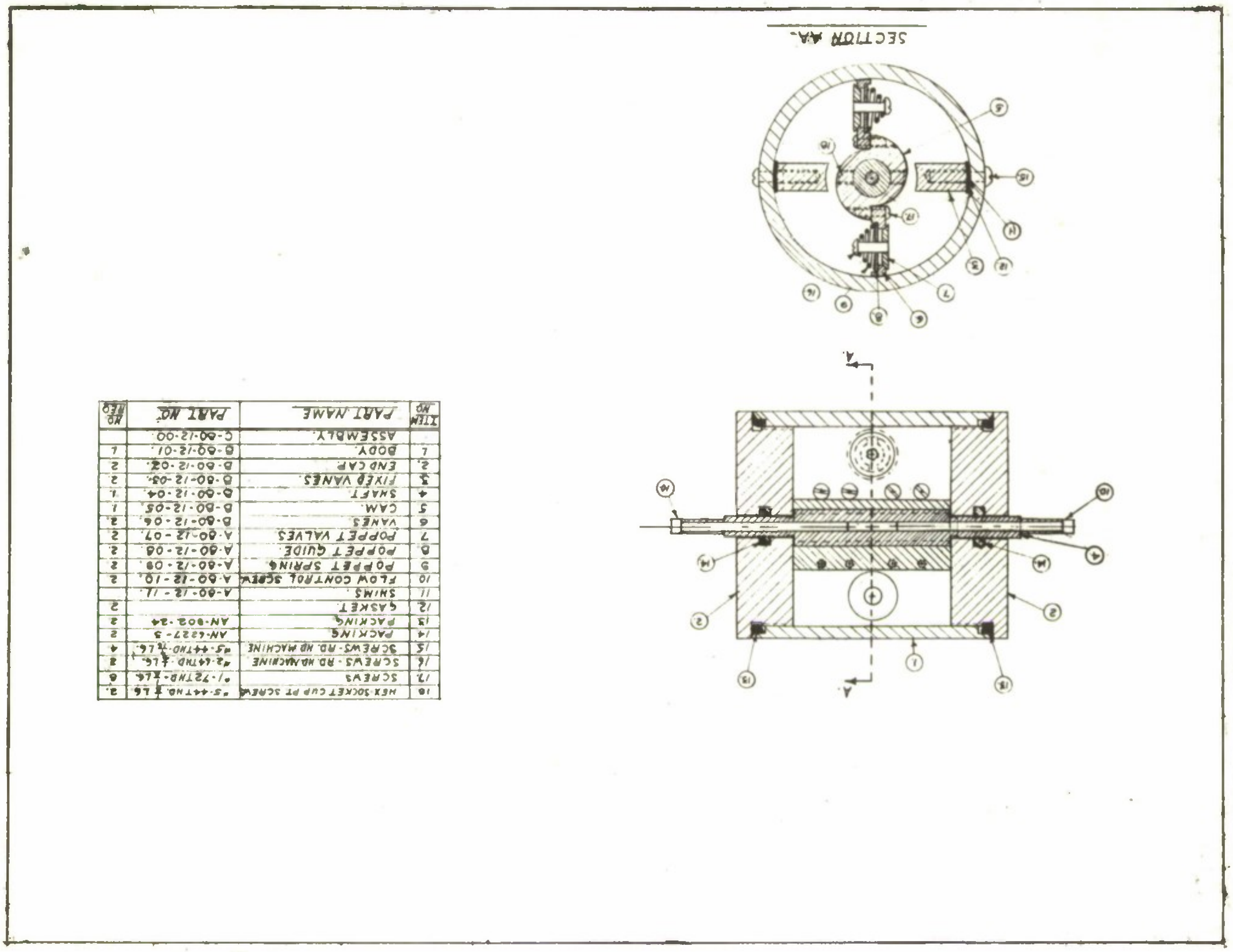
Fig. 5-16



IDEALIZED ROTARY DAMPER

To fit in distal space of AK socket. Provides for a variable high resistance in flexion, low resistance to extension.

Fig. 5-17



ITEM NO	PART NAME	PART NO.	NO. REQ.
18	HEX SOCKET CUP PT SCREW	#5-44THD. 1/4 LG.	2.
17.	SCREWS	#1-72THD-1/4 LG.	8
16	SCREWS-RD. HD MACHINE	#2-64THD-1/4 LG.	8
15	SCREWS-RD. HD MACHINE	#5-44THD-5/16 LG.	4
14	PACKING	AN-6227-3	2
13	PACKING	AN-802-24	2
12.	GASKET.		2
11.	SHIMS.	A-80-12-11.	
10	FLOW CONTROL SCREW	A-80-12-10.	2
9	POPPET SPRING	A-80-12-09.	2
8.	POPPET GUIDE.	A-80-12-08.	2.
7	POPPET VALVES	A-80-12-07.	2.
6	VANES.	B-80-12-06.	2.
5	CAM.	B-80-12-05.	1.
4	SHAFT.	B-80-12-04.	1.
3.	FIXED VANES.	B-80-12-03.	2.
2.	END CAP.	B-80-12-02.	2
1.	BODY.	B-80-12-01.	1.
	ASSEMBLY.	C-80-12-00.	

ASSEMBLY DRAWING, ROTARY DAMPER

MODEL 'A'

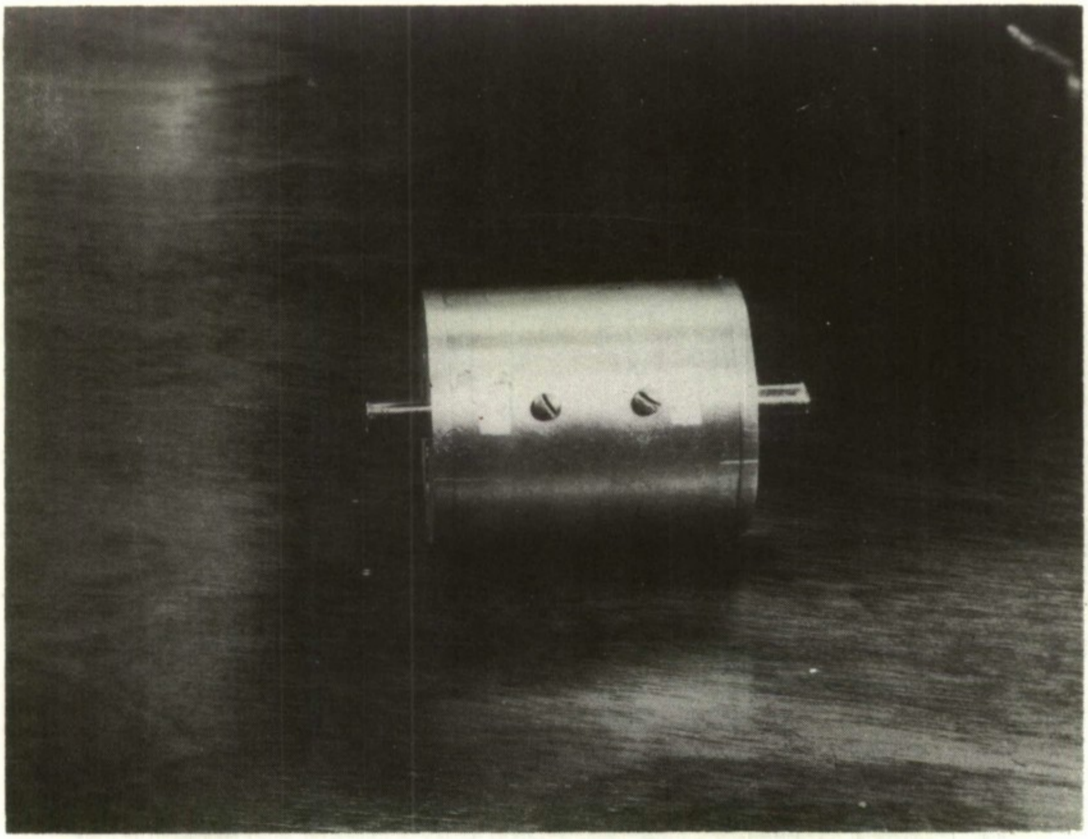
First tested version of the rotary damper; revealing weakness in torsion and sealing ability, it was redesigned.

Fig. 5-18

EXPLODED VIEW, ROTARY DAMPER MODEL 'B'

Filling accomplished through the tapped holes in the left end cap. Cam and shaft machined integrally. Note bypass poppet valves in cam vane. Construction of aluminum.

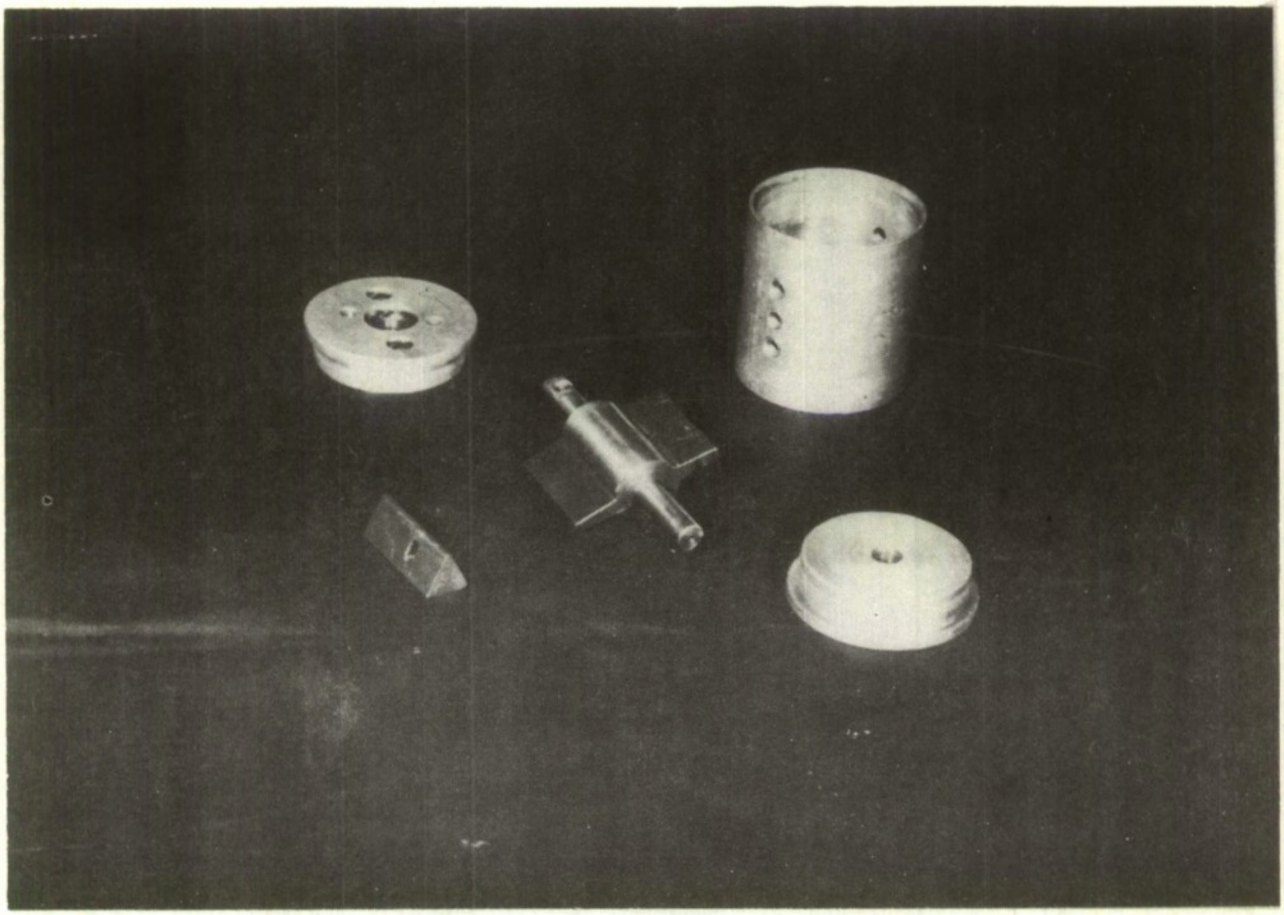
Fig. 5-19



ROTARY DAMPER MODEL 'B', AS ASSEMBLED

Round head screws allow insertion of shims between fixed vane and cylinder wall to decrease flow clearance.

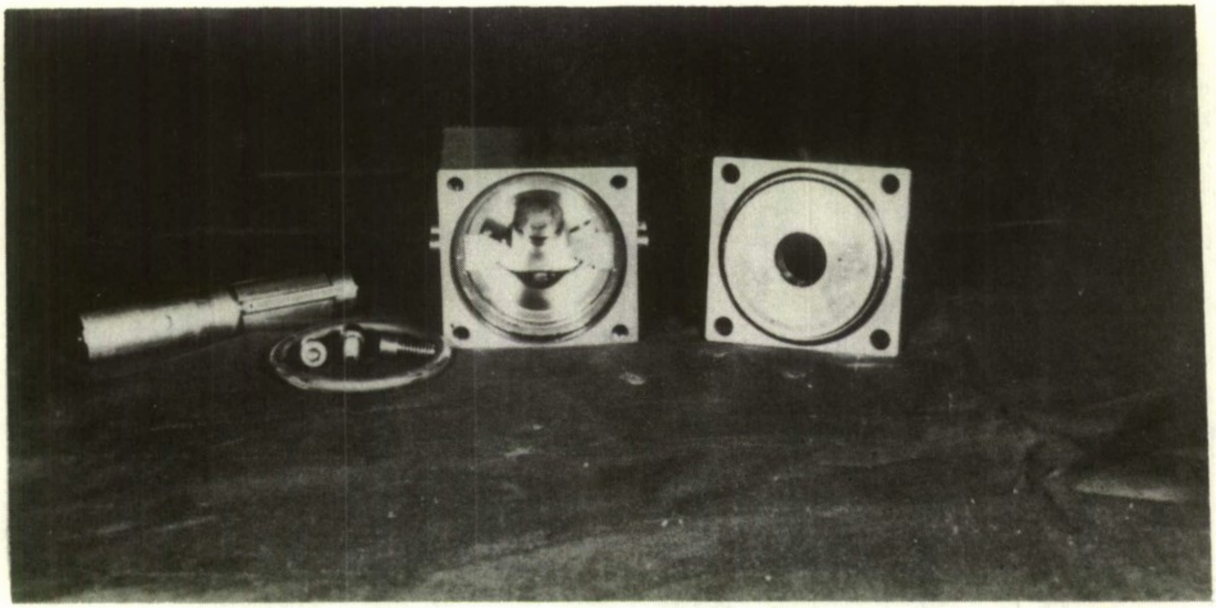
Fig. 5-20



ROTARY DAMPER MODEL 'C'

Leaf-spring valves replaced the poppet valves. New stationary vanes allowed smaller clearances with greater stability. Provision for shim insertion is superior.

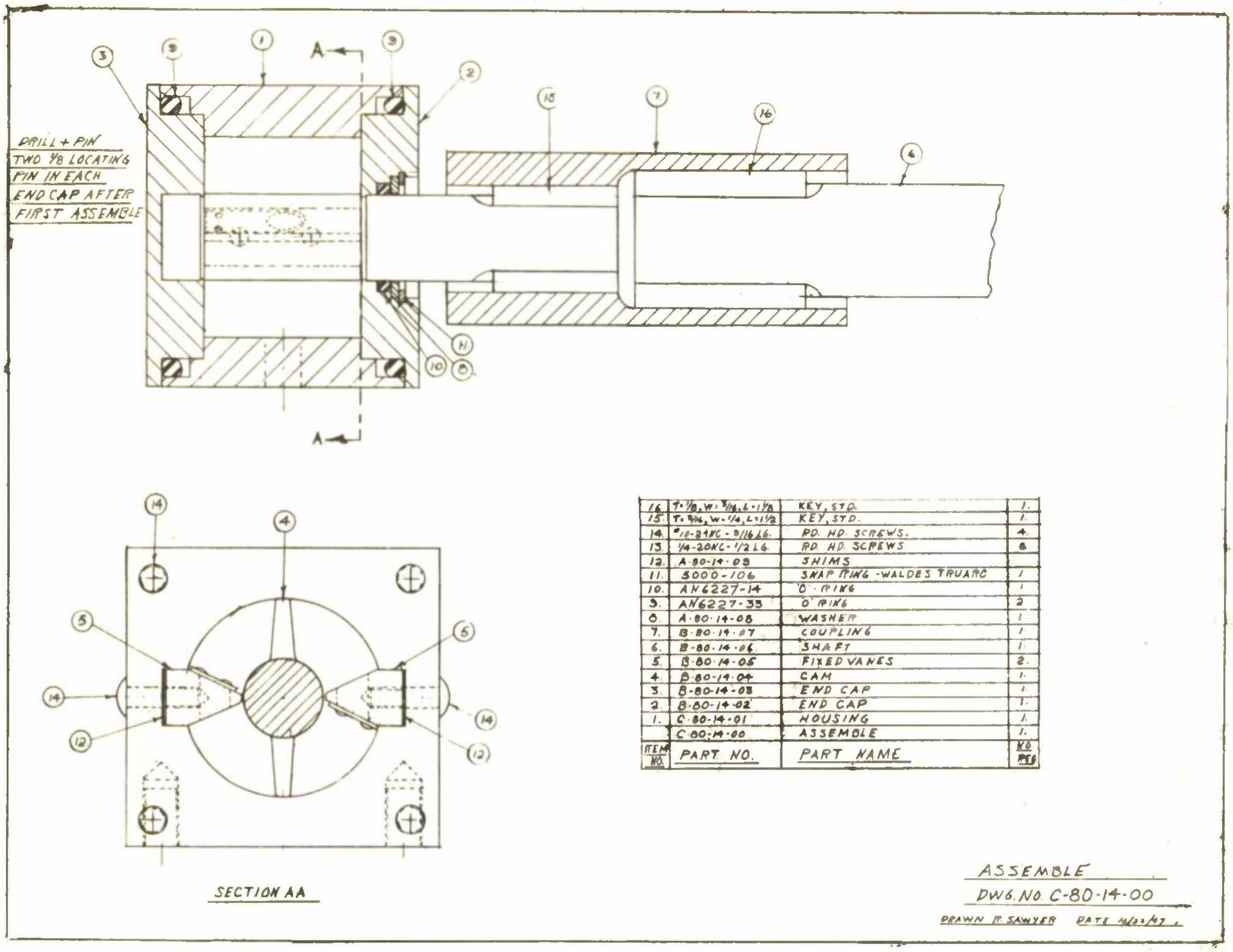
Fig. 5-21



ROTARY DAMPER MODEL 'D'

The construction of this steel version of the damper permitted smaller clearances, minimized deflection and distortion, and provided a wiper contact with the cylinder wall.

Fig. 5-22

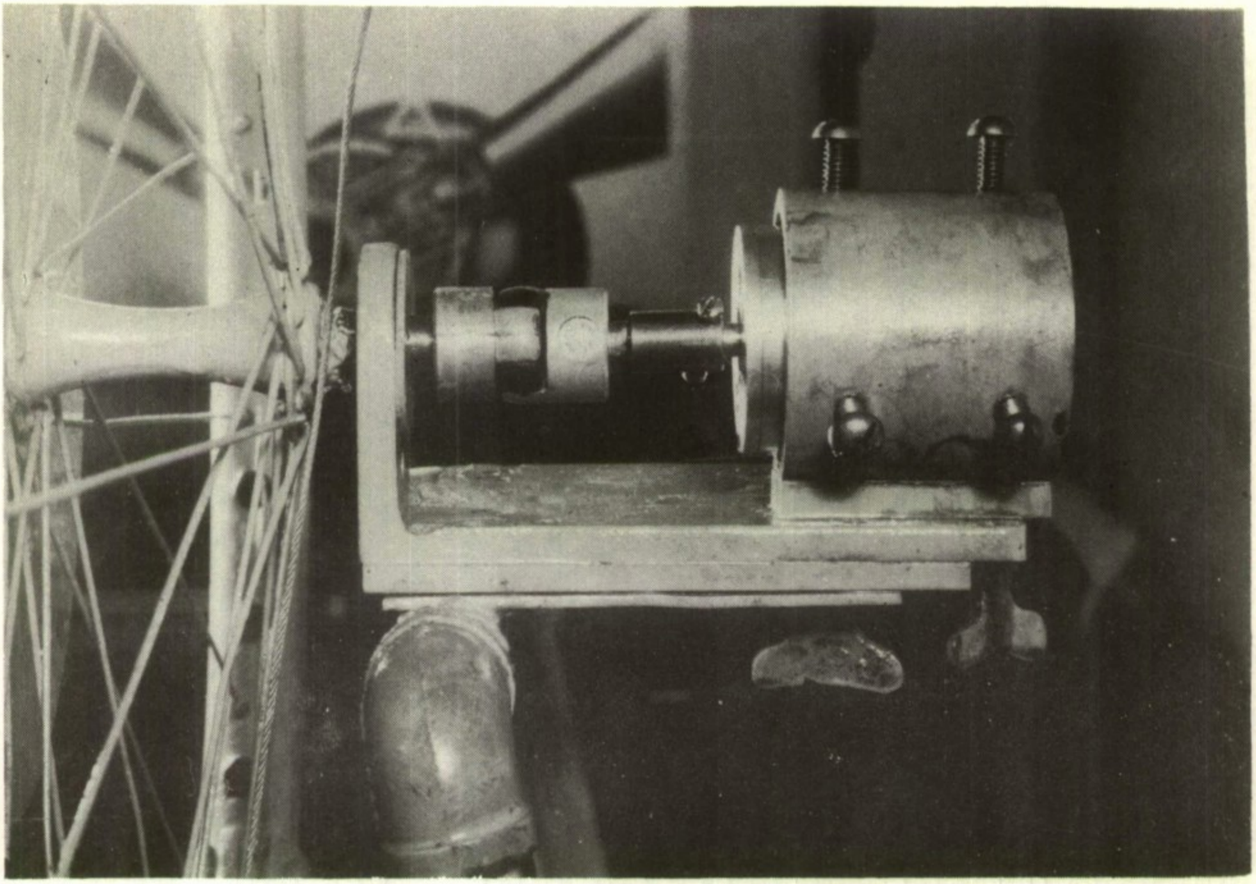


ITEM NO.	PART NO.	PART NAME	NO. REQ.
16.	T-1/8, W-3/16, L-1 1/8	KEY, STD.	1.
15.	T-3/16, W-1/4, L-1 1/2	KEY, STD.	1.
14.	#10-24NC-9/16 LG.	RD. HD. SCREWS.	4.
13.	1/4-20NC-1/2 LG.	RD. HD. SCREWS	8.
12.	A-80-14-09	SHIMS	
11.	5000-106	SNAP RING - WALDES TRUARC	1
10.	AN6227-14	'O' RING	1
9.	AN6227-33	'O' RING	2
8.	A-80-14-08	WASHER	1
7.	B-80-14-07	COUPLING	1
6.	B-80-14-06	SHAFT	1.
5.	B-80-14-05	FIXED VANES	2.
4.	B-80-14-04	CAM	1.
3.	B-80-14-03	END CAP	1
2.	B-80-14-02	END CAP	1.
1.	C-80-14-01	HOUSING	1.
	C-80-14-00	ASSEMBLE	1.

ASSEMBLY DRAWING, ROTARY DAMPER MODEL 'D'

Essentially a strengthened version of Model 'C', modifications include a blind hole in the left end-cap and a one piece $\frac{3}{4}$" shaft.

Fig. 5-23



TEST STAND MOUNT. MODEL 'B' IN POSITION

Alignment is obtained by the sets of mounting screws at the right. Supporting the torque wheel, the pillow block (left center) absorbs loads other than torsion.

Fig. 5-25