THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

THE DEVELOPMENT OF A PREDICTION MODEL FOR THE METABOLIC ENERGY EXPENDED DURING ARM ACTIVITIES

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
Department of Industrial Engineering
1967

August, 1967

IP-786

To Barbara Ann

ACKNOWLEDGEMENTS

At this time I wish to thank the many University staff members and fellow students who have given both encouragement and cooperation in this research endeavor.

In particular, I extend my deepest gratitude to all of the members of the Thesis Committee for their careful reading and editing of the manuscript. In addition, I wish to acknowledge my indebtedness to each of the Committee members for the following specific contributions: To Walton M. Hancock, Professor and Chairman of the Department of Industrial Engineering, for his continued, active, technical support and encouragement throughout the research. To Richard Carl Jelinek, Assistant Professor of Industrial Engineering, for his encouragement and consultation during the experimental design phase of the project. To Herbert P. Galliher, Professor of Industrial Engineering, for his perceptive ideas and assistance in analyzing the results of the experiments. To J. Raymond Pearson, Professor and Associate Chairman of Mechanical Engineering, for his technical assistance in resolving the biomechanical aspects of the arm. And to Harold J. Magnuson, M.D., Professor and Chairman of the Industrial Health Department, for his early and continued tutelage of the physiological

processes and medical aspects of the research.

My special thanks also is extended to the following persons: To Mr. Blake Fisher, Jr., Research Assistant in Industrial Engineering, for his invaluable assistance in performing the required experiments and analyzing the resulting data. To Tom Markham, M.D., Lieutenant Commander, U.S.N., for performing the medical examinations of the subjects, and for advising as to safe medical test procedures during the experiments. To John Faulkner, Associate Professor of Physical Education, for his early encouragement and technical consultation during the design of the experimental procedures. To James Foulke, Lecturer in Industrial Engineering, for his continued interest in the research and for designing the test equipment utilized during the experiments. And, to the four test subjects, James Kula, Jarl Johnsson, John Selecky, and Edward Harley, for their excellent cooperation without which the research could not have been completed.

Finally, my most sincere appreciation is extended to my wife for not only her patience, but also for her active support in editing and typing this manuscript.

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INTRODUCTION

One of the traditional interests of the industrial engineering profession has been the study and prediction of man's ability to alter his physical environment. Historically, the industrial engineer has employed the time required by man to perform a specific manual activity to indicate the level of his proficiency (42:3, 50:131-132). In recent years, however, the need to have better estimates of the stress imposed on a person when he performs a manual activity has been formally acknowledged (18:1-3,72:47-55). The need for this knowledge emanates from management's realization that in attempting to maximize the work output of manual activities, time must be allowed in certain types of activities to recover from the strain incurred by the body during the manual activity. The prediction of the duration of a recovery period which will allow a person to maximize his work output in a task without incurring injury to his health, has been the stated objective of researchers interested in manual labor since the beginning of the Twentieth Century (70:24,37:3).

The preceding statements rely on having quantified two types of knowledge: 1) the level of the physical stress, and 2) the physical capacity of an individual to recover from the strain resulting from that physical stress.

The research reported in this paper is directed towards the first point, that of developing a method for predicting the stress imposed primarily on the cardiovascular and respiratory systems by the resultant metabolic rate during manual activities. The latter point, which is concerned with methods for the determination of a person's physical work capacity will not be discussed in this paper, but excellent discussions are presented by Astrand, Brouha, Bink, and Robinson (6,15,18,64).

Scope of the Research Project

The research reported in this paper is based on the concept that the tension developed by a contracting muscle is the mechanical output of various metabolic processes (36:463). Therefore it was hypothesized that if the tension of various muscle contractions, or more specifically the effect of the muscle tensions (i.e. the torque at the various body articulations) could be characterized, the magnitude of the metabolic reactions could be predicted more accurately.

This thesis is a report of the research performed to quantify the relationship of a person's metabolic energy expenditure rate and the torque created at his wrists, elbows, and shoulders during various types of arm activities. Limiting the research to arm activities was found to be a practical necessity in order to determine the individual and combined effects of different physical conditions upon the proposed torque - metabolic energy relationship. The major physical conditions studied were: 1) the angle between the appendages which form an articulation, 2) whether one or both arms were active, and 3) whether the activity was static, e.g. holding or bracing an object, or dynamic, e.g. lifting an object.

The research reported in this thesis disclosed that all of these conditions altered the amount of metabolic energy expended by an individual who performed arm activities. Furthermore, it was disclosed that the effects of each of these factors could be combined into a metabolic energy prediction model, which in turn could be used to understand the stress of the activities on a person's respiratory and cardiovascular systems.

The arm activities to which the prediction model is applicable are confined to those meeting the following conditions:

1. Involves one arm, or uses both arms in a symmetric motion, i.e. both arms simultaneously perform the same motion pattern on their respective sides of the body

2. Be performed in a plane parallel to the sagittal plane of the body, which is the plane which defines the left and right sides of the body

3. Produce resultant torques at the wrists and elbows which tend to pull the hand or lower arm downward, of which some typical motions are:
    - A. Lifting the hand or an object in front of the body
    - B. Holding the hand or an object in front of the body
    - C. Moving an object away from or towards the body.

It was believed that the development of a metabolic prediction model for arm activities would entail the study of most of the general factors that would be contained in a metabolic prediction model for physical activities involving the whole body, thus giving a basic structure to the larger problem. The imposed restriction of confining the arm motions to the sagittal plane was founded on the desire to maintain a fairly simple, two dimensional, kinematic representation of the forces and moments created during arm activities. Also, there presently exists anthropometric data for kinematic analysis in the sagittal plane (78:129-138,62).

The arm activities studied in the research project were structured so that the net oxygen utilization rate never surpassed 0.6 liters per minute above a subject's resting rate (Chapter III explains the experiment procedure). Brouha and Radford have shown that below this limit the increase in the rate of oxygen uptake during a manual activity is due only to the metabolic activity of the skeletal muscles. In other words, the oxygen utilized by the cardiac and respiratory muscles, as well as the brain, skin, and other organs does not increase significantly above its normal resting level (18:11-13).

The level of arm activities studied ranged from "no activity" to levels that were 2.5 times greater than the eight hour work capacity level stated for arm activities (16). Because of this wide range of study, the results are applicable to levels of activity including heavy work with the arms.[1]

Research Approach

The research approach was to first characterize the physical aspects of the arm activities to be studied by extending existing biomechanical models (78,61). The output of these models are the resultant moments and forces at the body articulations of concern.

The metabolic rate was then measured as a single subject performed various manual activities with his arms. The activities were structured so as to allow the

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[1] Heavy work for eight hours has been defined as requiring an excess of 1.5 liters of oxygen to be utilized per minute if the whole skeletal muscle system is involved in the task (72:79). Boussett et al., have estimated that two arm activities require 30 percent of the total skeletal muscle system, thus giving a limit of 0.45 liters per minute for heavy arm work (16).

determination of regression equations of the metabolic rate for one and two arm activities in the sagittal plane within the following conditions:

1. Varying amounts of torque are incurred during static flexion and extension of the shoulders, and flexion of the elbows and wrists.
2. Different included angles exist between the appendages which form the shoulder and elbow articulations.
3. Different angular velocities are created at the shoulder and elbow articulations during dynamic flexions.

The resulting regression relationships of the subject's metabolic rate and the above factors were then combined into a model for prediction of the increase in the subject's metabolic energy expenditure for "whole arm" activities in the sagittal plane. The accuracy of this "single subject - whole arm model" was tested by comparing the predictions from it to measured metabolic energy expenditure rates produced by the subject during tasks involving the whole arm, such as holding and lifting objects in various positions.

The "single subject - whole arm model" was then used as the basis for a "general model" by introducing parameters to adjust for individual differences. The predictions from this "generalized - whole arm model" were compared to measured metabolic energy expenditures for static, "holding" activities for three additional persons.

The Contribution of a Metabolic Prediction Model

To be accurate, a prediction as to the level of a specific variable must be founded on all of the factors that are known to contribute to the level of that variable. The metabolic energy expenditure rate is influenced by many factors, as indicated by the past research summarized in the next section. Because of this, a metabolic prediction model will necessarily be complex. Since this is the case, one must ask, "What is gained by a prediction model as opposed to direct measurement of the metabolic rate?"

The following points are an attempt to state practical needs for developing a metabolic prediction model:

1. On the job measurement of the oxygen utilization is difficult, if not impossible to perform, due to the following conditions:
    - A. The job does not presently exist, as is the case in space research.
    - B. The confines of the work place are such that the measurement equipment would interfere with normal work methods.
    - C. The social environment is such in the work group that the addition of professional personnel and equipment would disrupt normal work methods.
2. With a prediction model it would be possible to simulate, on paper, various job conditions to determine the effects which the various alternatives would have on the metabolic energy

expenditure rate. The following are examples of such alternatives:

A. The addition of various types of mechanical assistors, such as powered conveyors, stock height regulators, and overhead tool supports.

B. The rearrangement of workplace layouts and work methods.

C. The inclusion of rest periods within present work periods.

D. The placement of anthropometrically different people into the task.

In addition, it is foreseen that a metabolic energy expenditure prediction model would allow a broad quantified understanding of the results of physical work. Such knowledge would serve as input information into present and future descriptive models of the short and long term effects of physical work on the human body (an example of an existing model that requires metabolic rate predictions is the Belding and Hatch Heat Stress Index Methodology (12:11-18).

Present Status of Studies to Determine the Metabolic Rate during Manual Activities

Many researchers have used the measurement of oxygen utilization rate to estimate the metabolic energy expenditure for various manual activities.[1] In general,

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[1] Metabolic energy expenditure rates for more than 1000 different types of activities, as measured by approximately 100 different researchers can be found in references (60,47,73).

their studies can be categorized into the following two groups, by referring to the objectives of each study: The first group, which will be referred to as "macro-studies", have as a common objective the determination of the metabolic energy expended by various people who are performing complex manual activities, such as mining coal, machining a work piece, or handling stock (60,21, 48,46,47,73,56). The second group of studies, which will be designated as "micro-studies", are attempts to relate the magnitude of the metabolic energy expended by a person to the magnitude of various common physical measures of his manual activity, such as the speed of walking or running, the amount of weight lifted, or the position of the body members during a manual activity (52,79,80,57,27,63,5,42).

The macro-studies have demonstrated that a large range of metabolic requirements exist in common manual labor. Based on these results, two researchers have estimated that approximately five percent of the present day industrial tasks produce physical stress to a high enough level that the total productivity of healthy acclimated workers is reduced (3). In addition, these studies have revealed that the combined stresses of manual activity and atmospheric heat are sufficient to severely limit the length of time that a person can perform many common industrial activities (41,35).

A major question is raised by the macro-study approach. This is, "What particular aspects of the total task produce the high physical stress?" The micro-study approach, which has recently become more prevalent in the literature, is an attempt to answer this question. Primarily through the use of analysis of variance models, statistically significant changes in metabolic energy expenditures have been demonstrated when the following physical conditions existed in the task:

1. The weight of a container, which was moved from a conveyor 23 inches high, to a table 33 inches high, and then to a second conveyor 43 inches high, was altered in five pound increments, from 10 to 25 pounds (42:60).
2. The rate of moving the container lifted in the task described in number one, was changed in increments of 6,9,12, and 15 times a minute (42:60).
3. Two arms were used, rather than one, in pulling down on a shoulder high lever with 10,20, and 30 pounds of force, and in cranking a hand ergometer at 10,20,30, and 40 watts (4).
4. The following factors involved in walking and running were changed:
    - A. Speed - in increments of approximately 0.5 miles per hour, over a two to six mile per hour range (52,79,27,26:332, 60).
    - B. Grade of hard walking surface - at levels of -10%, -5%, level, +5%, +10%, +15%, +25% (52,26:332).
    - C. Composition of walking surface - described as asphalt, grass track, tread mill, potato furrows, stubble field, and ploughed field (26:332).

   D. Weight of person's body - for a range of 80 to 200 pounds in increments of 20 pounds (26:332,60,79,27).

   E. Length of a person's legs - for a range of 32 to 39 inches, while walking at various speeds on a hard level surface (27).

5. The amount of acceleration and deceleration imparted to 22 and 17.5 pound containers when being lifted from the floor to a 66 inch high shelf was changed (89).

6. The horizontal velocity at which light and heavy blocks were moved, was altered over a range of 16 to 47 inches per second (57).

7. The height of a work surface for domestic tasks, such as beating, chopping, scrubbing, and turning was changed in an average of three inch increments over a range of 22 to 44 inches (63).

A general conclusion which is evident from the results of micro-studies is that relatively minor changes in the physical parameters that are commonly used to describe a person's manual activity result in significant changes in his metabolic energy expenditure. Dr. Brouha displayed the complexity of the problem when he stated, "Many industrial operations can be made easier if the position of the body (static contraction), the nature of motion (dynamic contraction), and the speed of motion (rate of contraction) are organized so that the physiological cost of the job is reduced to a minimum" (20). The metabolic energy prediction model developed in this paper is believed to present an understanding of the relative importance of each of these three general factors.

Metabolic Rate and Manual Activity

When a person performs a manual act, various skeletal muscles are stimulated into "contraction states" as dictated by the central nervous system requirements. Gemmill indicates that for a muscle to exert a force (i.e. contract) various metabolic processes breakdown already digested foodstuffs, and in so doing release kinetic and heat energy (36:463). Robinson has stated, "Since the ultimate source of the energy involved in all the metabolic processes is the oxidation of fuel, the tissues must be supplied with oxygen, and carbon dioxide must be removed, in amounts that are proportional to the man's energy requirements for the work" (64:494). Brouha reduces this thinking to practice when he concludes that the physical stress of manual activity is indicated by the amount of metabolic energy expended by a person, and that it can be estimated by measuring the amount of oxygen utilized by the person. This applies as long as the demand for oxygen is below the maximum rate at which the respiratory and cardiovascular systems can supply it to the active muscle tissue (19,18:4-7).

This research effort relies on the assumption that man's present and future advancement is dependent on his ability to perform manual tasks as well as mental tasks. In addition, it has been found that man's ability to continually perform a manual task is dependent on the maximum supply rate of various inputs into the metabolically active muscle tissue. It is therefore proposed that the demand (i.e. stress) placed on the supply systems by the metabolic rate must be characterized as a function of all of the parameters that can be shown to affect the metabolic rate and which are measurable in common manual activities.

General Problems Related to Manual Activity

Even though "heavy" manual labor in industry has been drastically reduced since the turn of the century, many problem areas still persist in our present society. These problems support the need for continual research into the effects of manual activity on the human body. Some of these problems will be presented in the following subsections.

Legal Responsibility

In the past two decades it has become more common for employers to be held legally responsible for the health of their workmen due to the increasing legal association between a man's job and certain types of injuries or disabilities. As an example of this trend, McNiece stated the following in referring to court decisions regarding heart diseases, "The inquiry of the courts is not into all the causative factors of the disease and the relative importance of each from the medical standpoint, but simply whether the work contributed, in the slightest, to the result" (55:2). Warshaw displayed the effect of heart disease on employment practices when he summarized the results of a survey of 119 Minnesota Companies by stating, "... nearly 60 percent of these companies reported that they seldom or never hired persons with known heart disease" (72:39-40). Yet there is growing medical evidence that many persons who have suffered cardiac problems can be returned to their previous levels of physical activity by a well supervised reorientation program (22,17:187-218). The cost of workmen's compensation reflects both the legal responsibility by employers for an employee's health, and the extent of various industrial medical problems. Example data for this representation is found in New York State where the cost of workmen's compensation for heart disease has increased from $1,023,561 for 167 cases in 1947, to $5,962,769 for 619 cases in 1956 (72:26). This increase is some justification for why management is becoming concerned with who they hire and what stresses their employees incur in their jobs.

Utilization of Manual Resources

Though "heavy" manual labor is the exception rather than the rule today, management must operate within the constraint that portions of the working population have drastically reduced physical work capacities due to the following conditions: First are the effects of disease. Some indication of the magnitude of this loss is seen from the fact that the Social Security Administration has been adding 14,000 people, between 45 and 65 years of age, to their lists each year (for the last couple of years) who are in need of financial support due to chronic respiratory disease (58:112). In addition, during the Korean conflict 86,000 men were disqualified from active service due to cardiovascular disorders alone (72:4). Also, of the 400,100 deaths due to heart disease in 1955, 32 percent were between 25 and 64 years of age (72:3).

Secondly, the effects of aging have been shown to reduce the capacity to perform manual activity for prolonged periods of time (6). The average capacity for manual work at age 55 is 25 percent lower than at 19 years of age (15). One might assume that older workers have accumulated "senority rights" in various organizations, thus allowing them to migrate to "physically easy" jobs. Yet, Welford has stated that in an industry where it was easy for the workmen to choose their jobs, over 96 percent of the men who were found to be performing what he subjectively rated as very heavy manual labor were greater than 55 years old (76:122-126). Welford attributed this condition to the desire of older workmen to seek jobs with low mental and perceptual demands which often exist in jobs demanding high physical effort.

Labor-Management Agreements

Presently, the manual time required to manufacture a product is established by various time study or time prediction procedures, all of which require a subjective evaluation by an observer as to the rest time that should be incorporated into the standard production time. The inclusion of a completely subjective rating of physical stress in time study procedures has resulted in one labor spokesman stating that standard production times will always remain as part of the labor-management bargaining process until a more objective method of rating the physical stress of the work is available (38:71-94).

Exploration of Space

The Gemini space flights have disclosed that extravehicular activities can create high physical demands (34:54-113). These results have instigated many questions as to the type and amount of manual activity preferable for future space flights.

Order of Reporting

The order for the reporting of this research generally follows the research approach outlined at the beginning of this chapter. Chapter Two presents the various factors that could influence a person's metabolic energy expenditure during a given activity. Chapter Three of the report discusses the measurement techniques employed to quantify the metabolic energy required in a specific task. Chapter Four presents the results of experiments and the analysis which was performed to develop a "single subject" model for one and two arm static activities. Chapter Five develops a "general subject" model for static activities, and presents the results of validation experiments performed with three other subjects. Chapter Six reports the results of dynamic experiments and shows how these results are used to modify the "single subject - static model" of Chapter Four. Chapter Seven summarizes the metabolic prediction model research, discusses the relevance of the research to the broad objectives of work physiology, and recommends logical extensions for this type of work.

Chapter II

THE DEVELOPMENT OF A HYPOTHETICAL METABOLIC ENERGY PREDICTION MODEL

This chapter reports the development of a hypothetical metabolic prediction model for arm activities. The development of this model is based on a combination of literature concerning the following subjects: 1) the mechanics of manual activities, 2) the mechanics of the skeletal muscles, 3) the utilization of groups of muscles to perform a task, and 4) the physiology of individual muscles.

To be reported first are the biomechanical equations which combine into a single concept all of the physical factors that have been shown to affect a person's metabolic energy expenditure. This concept is represented by the resultant torques created by the external and inertial forces which act on the various body members during any manual activity. The second section of the chapter develops a list of variables that could intervene in any functional relationship between the resultant torque at an articulation and the metabolic energy expended by the skeletal muscles. This list of intervening variables is used as the basis for the experiments described in the next three chapters. The third section of this chapter combines the information of the first two sections into a hypothetical metabolic prediction model.

The Concept of Manual Activity

The term "manual activity" is many times used to indicate that some particular aspect of a person's physical action is under consideration. As an example, in each of the micro studies described in the Introduction some form of manual activity is used as the independent variable and is then related empirically to one or more person's metabolic energy expenditure rates. Examples of the different forms of manual activities used are: the speed of walking or running (52,79,27,60), the rate of moving objects (57,42), and the weight of objects that are lifted (42). Also, some researchers have indicated that the level of one person's manual activity is different from another's if their body dimensions vary (26,60,79,27). In addition, it becomes apparent from some of the micro studies that static activities are considered as forms of "manual activities" (4). Finally, one set of studies used the position of the body members during the performance of a task as a separate dimension of the manual activity (63).

In summary, the micro studies indicate that the development of a general prediction model would need to be based on the individual and combined effects of all of the preceding factors. It is estimated that such a development would entail many thousands of experiments. However, if a single concept could be referred to when describing any manual activity, then the metabolic prediction problem could become greatly simplified. In other words, any required metabolic experiments would only need to establish the relationship between the metabolic rate and the output of the general concept used to describe the activity. If the concept of manual activity encompassed all of the preceding physical dimensions commonly used to describe manual activity, generality in the prediction of the metabolic rate would be possible.

A general concept to characterize any manual activity was developed from the following facts. Metabolism in the skeletal muscles is initiated by the central nervous system stimulating the skeletal muscles to contraction states (36:463). The forces produced by the contracted skeletal muscles act at finite distances from the various bone articulations (78:35). Therefore, when a skeletal muscle contracts it results in a torque which, for this report, will be referred to as the reactive torque at each articulation. The logical implication being that if the resultant torques produced by external and inertial forces could be computed for at least the major body joints involved in a manual activity, they could serve as a basis for predicting the level of metabolism required of the contracted muscles which produce the reactive torques.

It was also realized that all of the factors listed in the micro studies which describe a particular manual activity are involved in the computation of the resultant torques produced at the major articulations of the body. Thus, it appeared that having knowledge of the resultant torques produced by external and inertial forces would allow a fuller understanding of the complete functions of the skeletal muscles and the metabolic rate which they must sustain for specific manual activities.

Biomechanics of Manual Activity

During the last two decades, anthropometric data has been developed to permit the construction of free body diagrams of the human body in the sagittal plane (62,61). These diagrams, and more recently their mathematical representations (referred to as "biomechanical models") have furnished a method by which the resultant torques at the major articulations of the body can be determined as a function of the direction and magnitude of any exterior or inertial forces (78:34-68). The assumptions under which these models operate are: 1) The skeletal joints are frictionless, single point articulations, and 2) The body can be segmented into solid links which do not deform during a motion (61:2-3). These assumptions are imposed on the development of the biomechanical model of the arm described in the following subsections. In view of the relatively large changes in the external and muscle forces that act to control a segment, these assumptions did not appear to restrict the generality or accuracy of the model employed in the research.

Introduction to Mechanics of Arm Activities. The Principle of Moments states: "The moment of a force about any point is equal to the magnitude of the force multiplied by the perpendicular distance from the action line of the force to that point" (78:35). It is clear from this statement that any factor that affects the magnitude of forces acting upon a body segment, or which affects the perpendicular distance from the line of action of the force to a body joint must be included in the computation of the resultant torque at the joint.

Mechanics of the Wrist. To illustrate the manner in which the resultant torque is computed for a single articulation, let us consider the following physical situation at the wrist. The lower arm is positioned upon a support so that the wrist is directly over the edge of the support with the hand extended into space in a semiprone position, i.e. thumb upward. To add a little realism, a handle which is attached to a container of known size and weight (this could represent a hand tool) is grasped and supported by the hand. The sagittal plane location of the center of gravity of the container is positioned so it coincides with the center of gravity of the hand, as defined by Dempster's anthropometric data (ref. Table A-1 in Appendix A). Figure 1 displays this situation (page 24).

The resultant torque about the wrist, due to the external and inertial forces exerted on the hand, is computed by the algorithm outlined in Figure 2 (page 25 The input information required for a numerical solution is essentially of two types. First, descriptive data of the hand and object, which includes the weight, size, and mass moment of inertia about the center of gravity of each is needed (Table A-1 describes how these are obtained). Second, a description of the motion is required. For our example this is accomplished by measuring the instantaneous horizontal and vertical (including gravity) acceleration components at the center of gravity of the hand throughout the motion. In addition, the initial angle α of the hand must be noted.

At this point it is necessary to define terminology for the direction of rotation of the various articulations. A tendency towards counter - clockwise rotation of the more distal body segment of an articulation will be called flexion at the articulation. An effort towards clockwise rotation is called extension. Therefore, the motion described in the preceding discussion and depicted in Figure 1 (page 24) is a

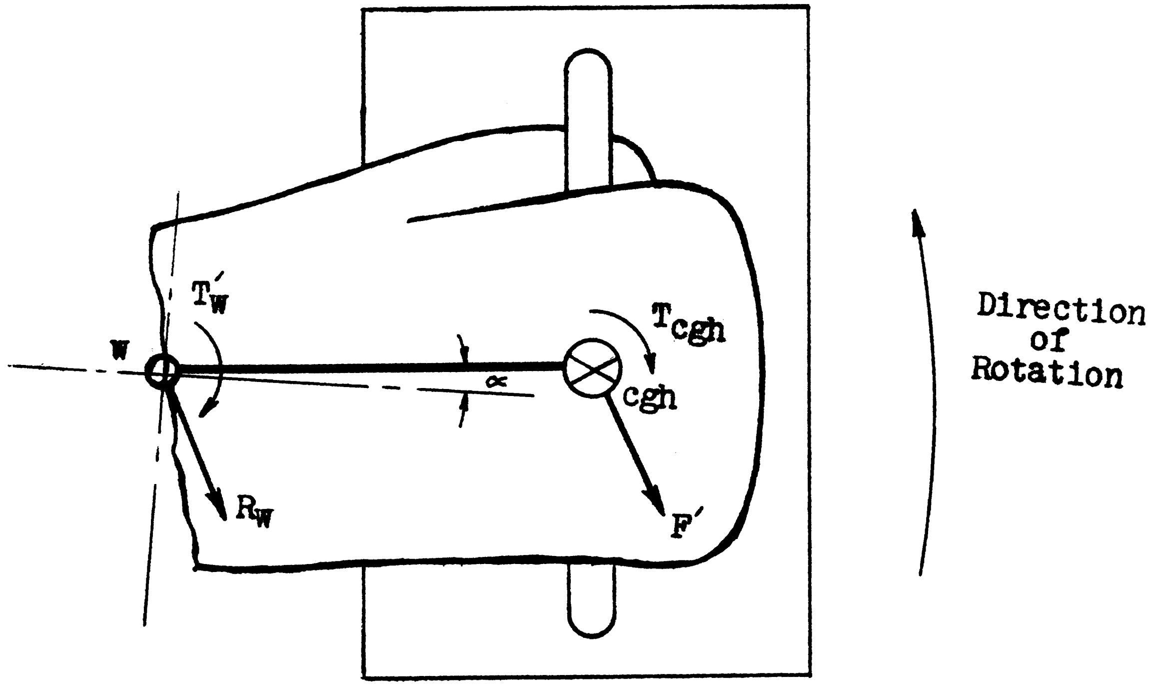

Figure 1

Object and Semiprone Hand Rotating
about Stationary Wrist

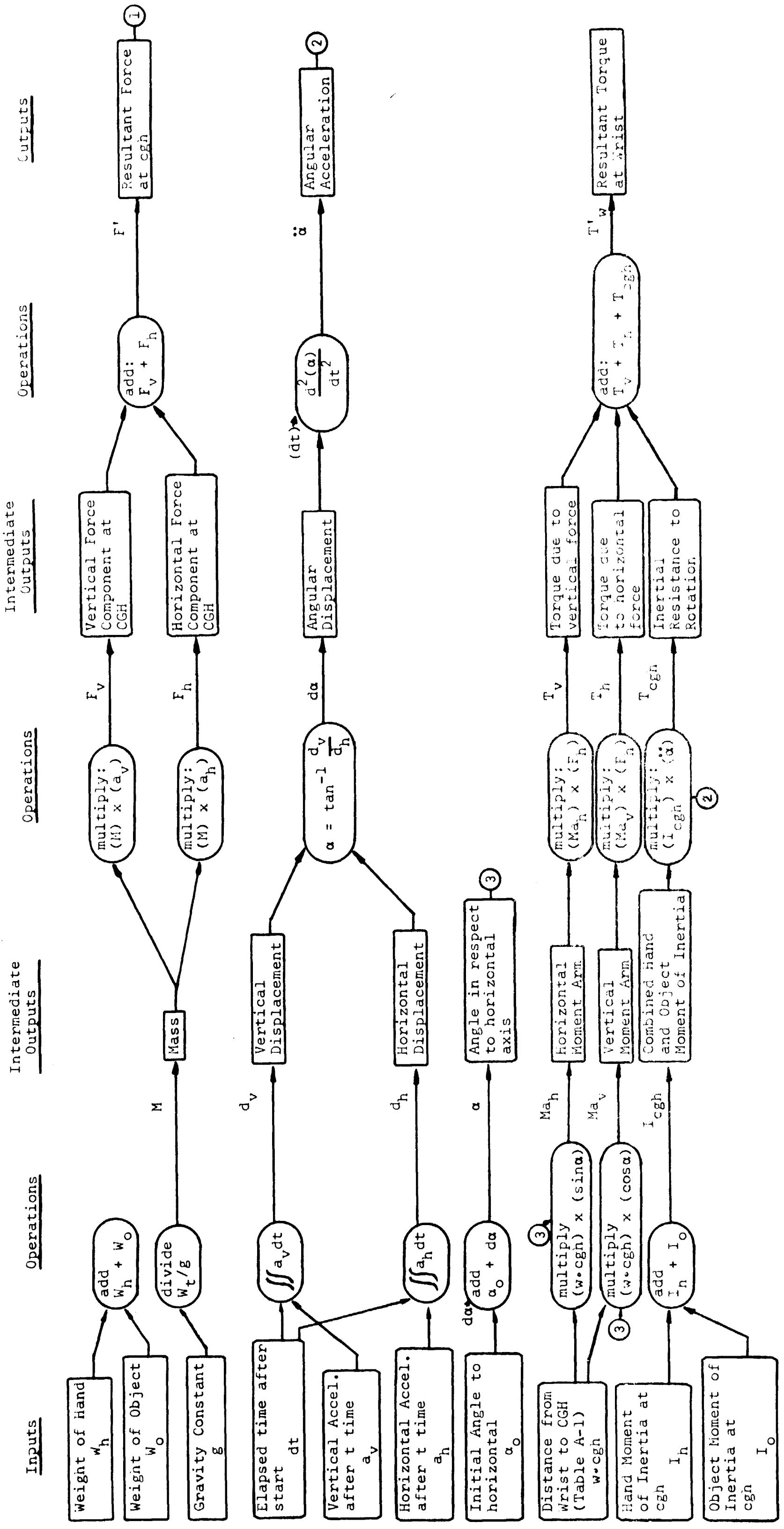

Figure 2

Algorithm for Computing Resultant Torque at Wrist

wrist flexion.[1]

Mechanics of the Arm. The preceding example is abstract in the sense that the lower arm is stationary. A more realistic situation occurs when the arm segments are allowed to rotate about the shoulder and elbow, thus imparting a plane motion to the wrist joint. This results in the acceleration characteristics of the hand and object becoming a function of the lower arm accelerations, which in turn are dependent upon the upper arm accelerations, etc., until a stationary articulation is defined. As stated earlier, this report concerns only arm motions, thus the shoulder joint is considered to be the stationary reference point for the acceleration computations.

A second problem arises during a motion of the whole arm, in that the resultant torque created by the forces acting on a particular body segment e.g. the lower arm, must include the reactive torque created by the more distal body segment, e.g. the hand. In other words, the torques accumulate, by vector addition, from the distal to the proximal segments. The equations for computing the torques and forces created at the shoulder,

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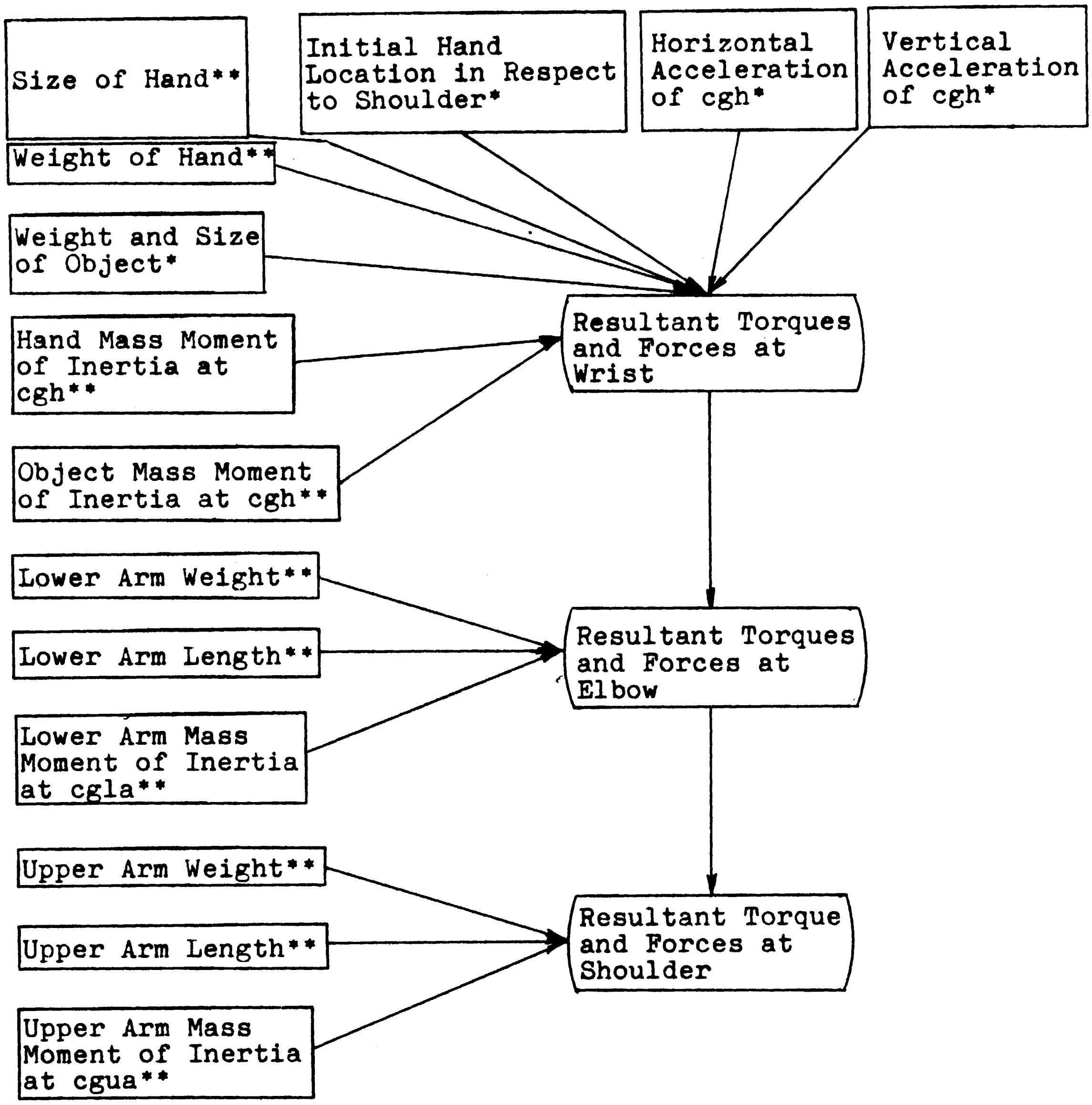
[1] The term wrist flexion is adopted in this report due to the motion of the semiprone hand being in the sagittal plane, rather than in the more typically depicted frontal plane where the motion is called wrist adduction.



* Directly measured

** Described in Table A-1, page 217

Figure 3

<u>Arm Articulation Torques due to External and Inertial Forces on Arm</u>

elbow, and wrist by the external and inertial forces which act on each arm segment during an arm motion in the sagittal plane are presented in Appendix A. Figure 3 is a representation of the biomechanical equations described in Appendix A.

Summary of Mechanics of Arm Activities

The preceding subsections have developed the mechanics equations for arm activities under these assumptions: 1) The joints are frictionless, single point articulations, 2) The arm is composed of three solid links that do not deform, and 3) The motions are within the sagittal plane. The computed torques at the shoulder, elbow, and wrist articulations represent the effects of only external and inertial forces acting on each body segment. The next section of this chapter presents the variables from the literature that were recognized as possibly intervening in a relationship between the resultant torques computed by the preceding algorithm and the metabolic energy expended by the muscles to create equal reactive torques.

The Intervening Variables between the Resultant Torque at an Articulation and the Metabolic Energy Expended by the Articulation Muscles

The preceding biomechanical model provides a mechanism by which the resultant torques due to external and inertial forces can be characterized. The question which now arises is, "What is the relationship between the computed resultant torques at each articulation and the metabolic energy expended by the muscles to produce equal reactive torques?" A literature search disclosed no empirical research on this question. Because of this and the apparent complexity of the metabolic prediction problem (as displayed by the results of the various micro-studies reported in the Introduction), it was deemed necessary to perform experiments to gain quantified information as to the existence and possible form of this relationship.

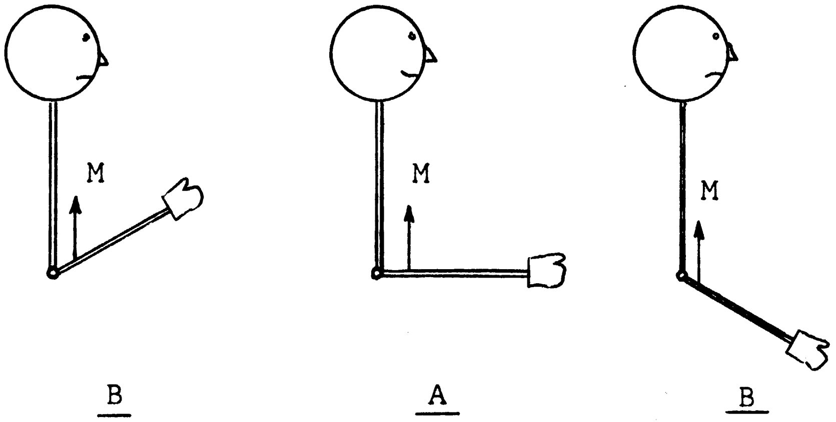
This section presents a discussion of some of the major factors foreseen to be possible sources of error in the establishment of an empirical relationship between the metabolic energy expenditure and the muscle reactive torques at the shoulder, elbow, and wrist. Muscle mechanics, recruitment, and physiology are discussed in the context of their expected individual and combined effects on a torque - metabolic energy relationship. The expected effects of these concepts on a person's metabolic energy expenditure are stated in the form of questions which are answered by the results of metabolic experiments reported in later chapters.

Muscle Mechanics

As stated earlier, when a person contracts a skeletal muscle it produces torque about one or more articulations by acting at finite moment arms from the articulations. To produce a given level of torque, the required muscle tension varies inversely as the length of its moment arm (78:35). Since the metabolic energy expenditure rate is related to the muscle tension (36:463), it was expected that the expenditure was also inversely related to the muscle moment arm length.

The Angle of an Articulation.

What influences the moment arm length in an individual? One factor is the angle of the articulation at which the torque is being produced. Williams and Lissner (78:72) have graphically demonstrated this effect, and their representation is duplicated in Figure 4. It should be noted, however, that the muscle tension may not vary directly with the size of the flexion angle. This is due to the muscle's moment arm length being a function of not only the angle but also any restraining tissue through, or by which, the muscle's tendons must pass. Since there does not exist, at present, any practical means by which to determine the change in the moment arm lengths of the individual muscles at different angles of an articulation, an empirical definition



"In A, the forces [M] applied are fully effective in rotating the segment, while in B a portion is lost." from Williams and Lissner (78:72)

Figure 4

Representation of Muscle Moment Arm Effect on Elbow Flexion appeared to be necessary to account for any change in the torque to metabolic energy relationship. Thus, the following question:

> Question 1 to be Answered by Experiments - What is the effect on an individual's metabolic energy expenditure rate when a constant level of torque is created by the muscles but at varying angles of the articulation?

Anatomical Differences between Subjects. It was also speculated that anatomical differences between individuals would alter the muscle moment arms, thus possibly affecting any metabolic energy to torque relationship. This propogated the following question:

> Question 2 to be Answered by Experiments - What is the effect of individual differences on the metabolic energy expenditure rates for specific torque levels and articulation angles?

Muscle Recruitment

The variables discussed in this subsection are those which influence the recruitment of specific muscles at an articulation. From the literature describing muscle functions in the arm, it becomes evident that many variables can influence the relative utilization of specific skeletal muscles, and thus the amount of metabolic energy expended by each. Figures 5,6, and 7 summarize the results of electromyographic analyses

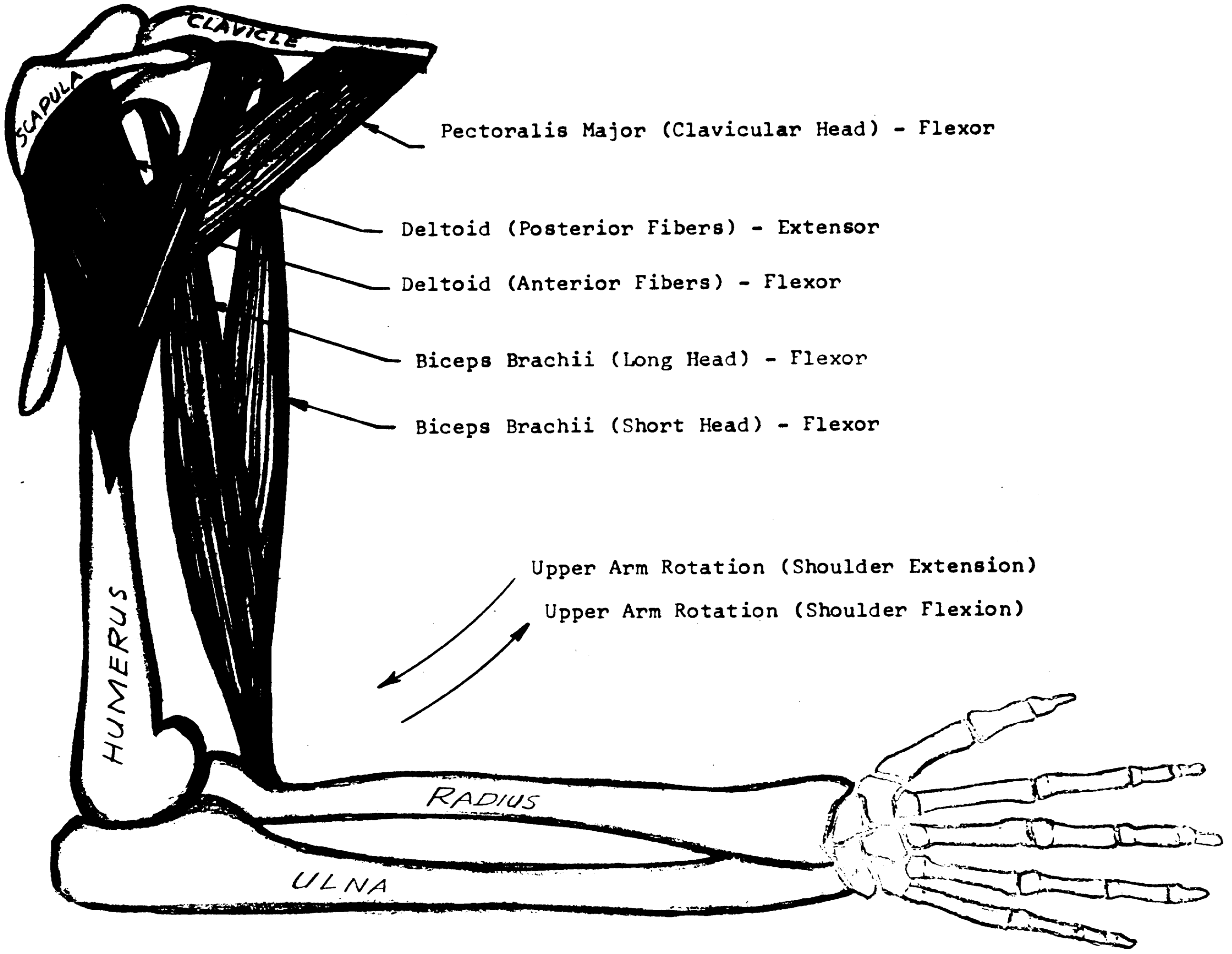


Figure 5

<u>Major Shoulder Flexors and Extensors (11:106-112)</u>

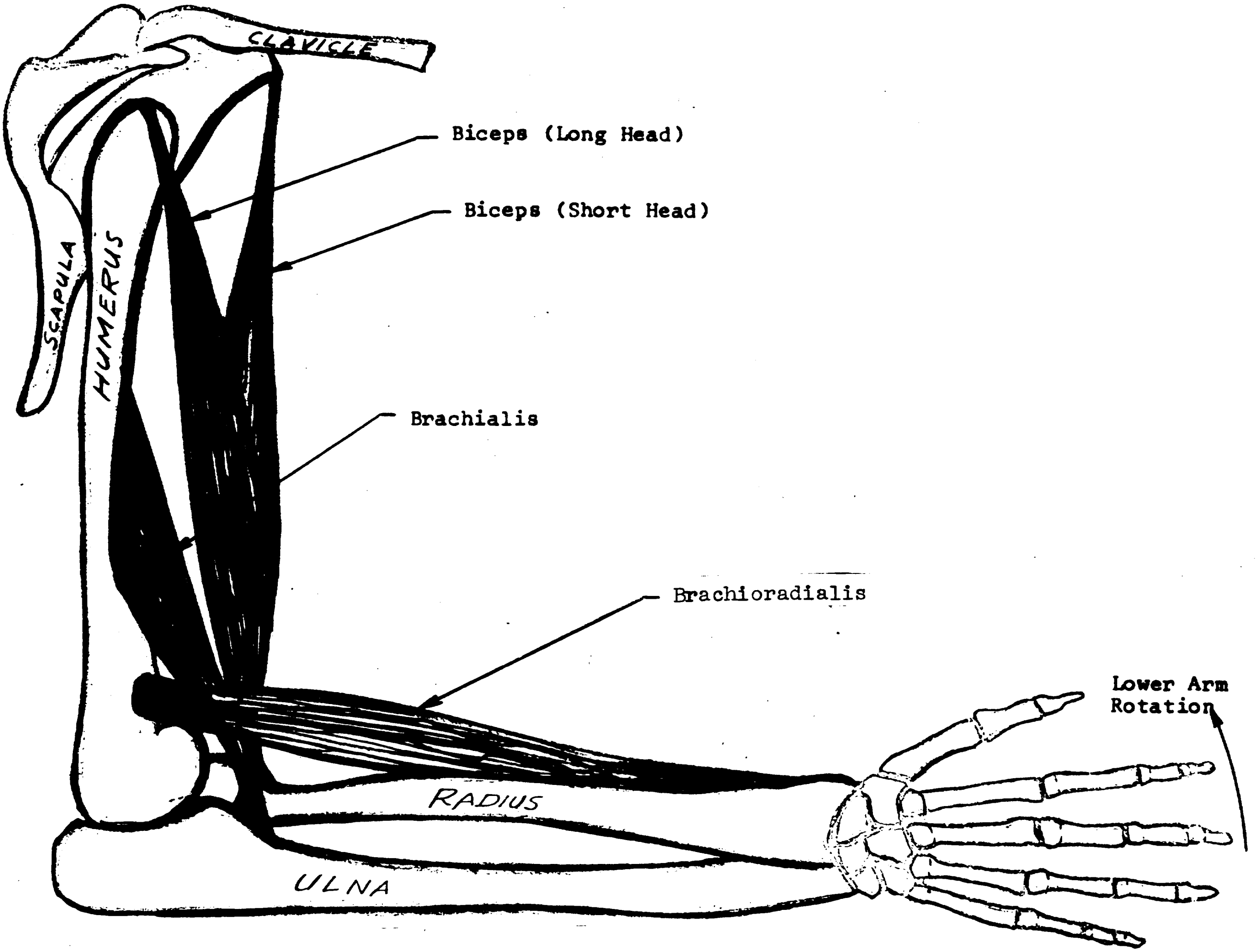
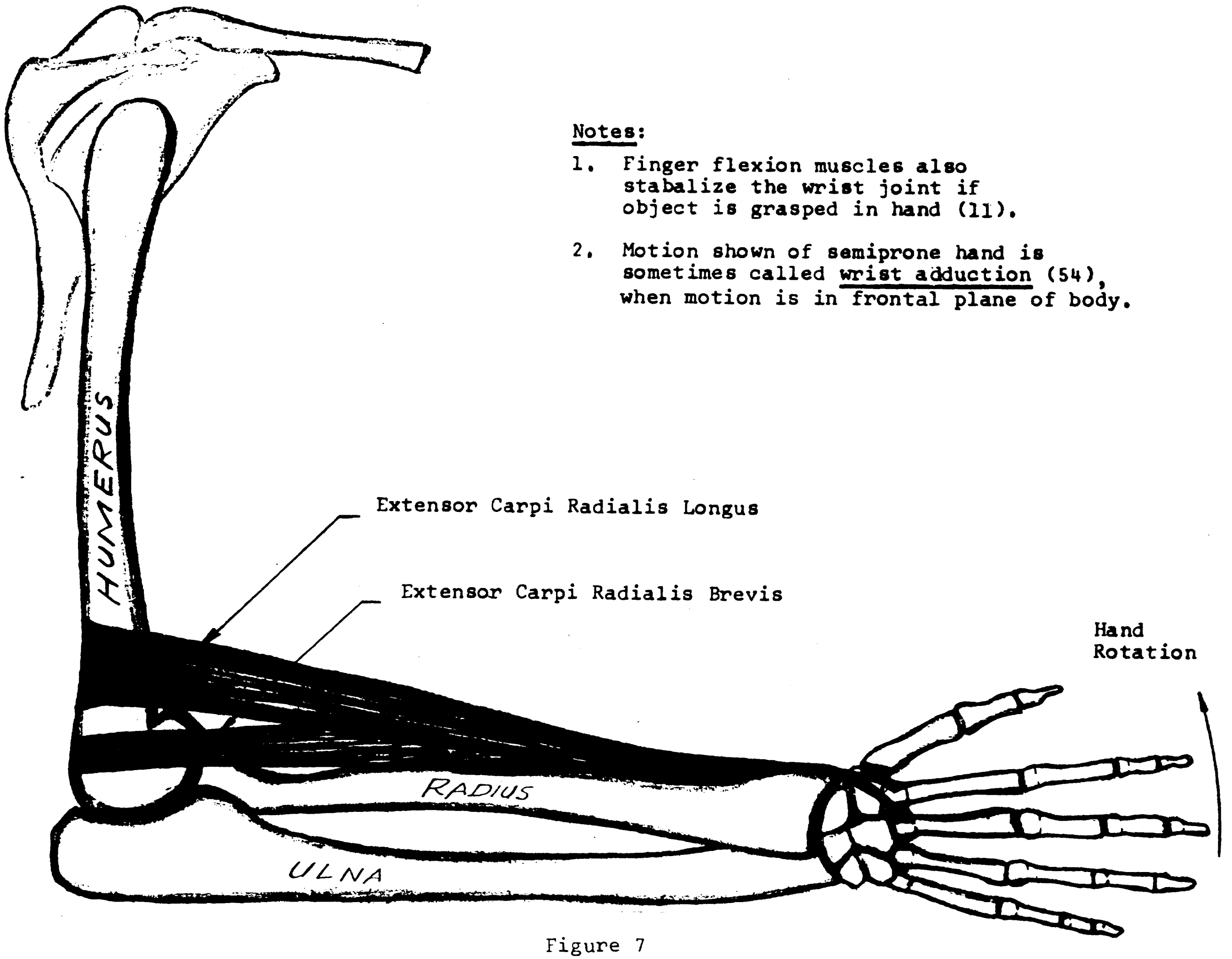


Figure 6

Major Elbow Flexor Muscles (11:106-112)



Notes:

1. Finger flexion muscles also stabalize the wrist joint if object is grasped in hand (11).
2. Motion shown of semiprone hand is sometimes called wrist adduction (54), when motion is in frontal plane of body.

Figure 7

Major Wrist Flexor Muscles (29)

reported by Basmajian (11:97-124) for the arm actions included in the scope of this project.

The Direction of the Resultant Torque. As may be noted in Figure 5, two separate muscle groups are usually stimulated by an individual to extend and flex the shoulder joint, i.e. rotate the arm clockwise and counter clockwise respectively. Because of the possibility that each of these two groups of muscles could have a different mechanical advantage when rotating the arm, the following question appeared to be appropriate:

> Question 3 to be Answered by Experiments - Is there a significant difference in an individual's metabolic energy expenditure rate for shoulder flexion activities as opposed to shoulder extension activities?

One Arm versus Two Arm Activities. Since the scope of the project also includes the study of symmetric two arm activities, i.e. activities where both arms are simultaneously performing the same action, a question arises as to whether the metabolic energy expended in two arm activities is twice that of one arm activities. Basmajian has concluded that there is no appreciable muscle activity in a resting limb while the opposite limb is active (11:57-58). Thus from a neurological view the metabolic energies expended by the muscles of each arm should be additive.

However, the proximal side of the shoulder joint, i.e. the scapula and clavical in Figure 5, are supported by the trapezius, the levator scaulae, and the upper digits of the serratus anterior muscles (11:99), which exert forces across the upper trunk and neck when contracted. Therefore, the possibility of a conservation of metabolic energy when the external loads on both ends of these muscles are balanced, which occurs in the two arm symmetric motions, appeared to substantiate the following question:

> Question 4 to be Answered by Experiments - What is the difference between a person's metabolic energy expenditure for one arm as opposed to two arm flexion and extension activities involving the shoulder and elbow joints under equal loads?

The Resultant Torque. Figures 5,6, and 7 are representations of the "usual" muscles involved in arm activities. However, differences between individuals exist in the recruitment of specific muscles. As an example, Basmajian measured the action potential levels in twenty persons while they flexed their elbow with a two pound weight held in their hand. The results of these experiments are summarized in Table 1. The differences between individuals substantiated the need for empirical research of individual differences under Question 2 on page 32.

The level of torque itself can change the

Muscle Used:	Percent of Individuals Classified as having Activity Levels of:				
	None	Slight	Moderate	Marked	Very Marked
Biceps - short head	5% -0-	40% 5%	20% 25%	35% 50%	-0- 45%
Biceps - long head	-0- -0-	20% 5%	30% 5%	40% 40%	10% 50%
Brachialis	-0- -0-	20% 5%	25% -0-	45% 40%	10% 55%
Brachioradialis	-0- -0-	25% -0-	45% 10%	30% 25%	-0- 65%

Upper percents represent slow flexions - Lower percents represent fast flexions (Data from Basmajian,(11) pages 1108-1109) Hand semiprone with two pound weight on hand.

Table 1

<u>Differences between Individuals in Muscle Recruitment for Elbow Flexion</u>

recruitment of specific muscles. Basmajian has stated, for example, that the biceps and brachioradialis usually do not act in elbow flexion with just the weight of the lower arm and hand. However, with an extra load of just two pounds held in the hand they both can become quite active, as depicted in Table 1 (11:106-112). Thus the following question appeared to be in order:

> Question 5 to be Answered by Experiments - How does the metabolic energy expenditure rate change with different torques at each articulation, given the angle of the articulation and direction of the torque (i.e. flexion or extension)?

The Angular Velocity. The speed of an isotonic contraction, which is reflected by the angular velocity of the appendages that form an articulation, was also shown to influence which muscles are used (Table 1 also depicts this effect). In a situation where fast flexions are required, those muscles that act along the moving bone are contracted to provide a centripetal force. These are called the shunt muscles. The brachioradialis has been classified as belonging to this class (11:64). In contrast, a slow flexion instigates activity in spurt muscles, of which the brachialis and biceps brachii are examples (51).

The preceding results provoked the following question:

Question 6 to be Answered by Experiments - In an isotonic muscle contraction, what is the effect of the rate of angular change (i.e. angular velocity) at an articulation on the metabolic energy expenditure rate under constant torque conditions?

The Conditions that Exist at Two Adjacent Articulations. Additional electromyographic muscle studies disclosed that some major muscles span two articulations. The short head of the biceps (Figure 6) and the extensor carpii longus and brevis (Figure 7) are examples of this configuration. These muscles produce torques at both of the articulations that they span (11:68-72). Theoretically then, if the torques desired in two adjacent articulations are compatible, i.e. their directions are the same, then use of these muscles could result in a reduction in the metabolic energy required as compared to the energy required by two single articulation muscles.

However, the torques at two articulations can be incompatible, which is often the situation in lifting and moving an object towards the body. This action requires the shoulder to be rotated clockwise, i.e. extended, while the elbow rotates counter clockwise, i.e. flexed. In this case, the use of a two-articulation muscle would theoretically hinder the desired motion at one of the two articulations. In other words, it could be said that it was functioning as an agonist at one joint and an antagonist at the other.[1] If this muscle action could occur (and quantified evidence is not obvious to either prove or disprove this possibility), then an additional metabolic energy expenditure would probably be required of the person to overcome the torque created by the antagonistic muscle action at one of the two joints.

Because of the existence of two articulation muscles in the arm, the possibility that they could influence the relationship of metabolic energy expenditure to the torques at the shoulder, elbow, and wrist was perceived to be great enough to warrant the performance of torque interaction experiments, to answer the following question:

> Question 7 to be Answered by Experiments - What is the effect on a person's metabolic energy expenditure rate when different levels of compatible and incompatible torques are created at adjacent articulations?

When an object is held in the hand, such as in the situation depicted by Figure 1 on page 24, the

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[1] An agonist is a muscle which assists in the performance of a particular action as opposed to an antagonist which inhibits a desired motion.

muscles that flex the fingers have been shown to also assist in stabilizing the wrist joint against rotation (29).[1] This latter function of the finger flexion muscles could, therefore, assist or hinder the desired action at the wrist joint. Because of this, any relationship between the resultant torque computed at the wrist and the metabolic energy expended by the muscles that span the wrist would be dependent on what external forces were acting on the fingers. Therefore, the experiments to define the wrist torque to metabolic energy expenditure relationship would need to contain a control over the actions of the fingers.

Muscle Physiology

This subsection is based on the empirically proven relationship that the energy stored in the foodstuffs metabolized by the human body is expended as heat and kinetic energy (45:987). The significance of this concept to the design of metabolic experiments is realized when one poses the question of how much heat is liberated for a given amount of useful work done.

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[1] Dempster has referred to this joint stabilizing function of some muscles as a synergistic action (29).

Dr. A. V. Hill has studied this muscle physiology problem in detail, and has recently proposed the following hypothetical energy model for the case of an isoloated muscle which is being forcibly stretched (45:897-898):

$$E_T = A + ax + W$$

Where:

E_T - total energy expended by a muscle

A - heat energy expended to maintain a contraction state

a - parameter representing energy required per unit distance of stretch

x - distance that muscle is stretched while in a contraction state

W - mechanical work done on the muscle to stretch it.

Hill does not present values for A and a, but shows that when an isolated stimulated muscle is stretched, i.e. work W is done on it, its total heat output does not increase above the initial heat created when it changes from the resting to the active state. This provides indication of a reversible reaction during muscle stretching, in which the mechanical work W done on the muscle provides the energy to resist the stretching action with no additional energy loss in the form of heat a above the heat A required to transform the muscle from rest to a contraction state.

This concept, which has been referred to as "negative work", i.e. work input effect on a muscle, was empirically displayed by Abbott (2). By measuring the oxygen utilized by persons who maintained a constant resistive load against the motion of the pedals on a motor driven bicycle ergometer, he was able to show that the speed of "back pedalling" did not increase the oxygen utilization significantly above that required to maintain a static position. The oxygen uptake that he found to be required for the static loads increased as a positively increasing function of only the loads. This oxygen uptake, under static conditions, represents the metabolic energy which would be equivalent to the energy A in Hill's formulation, since no mechanical work W or displacement x occurs in the static activities.

The contribution of Hill's and Abbott's research to the present project is as follows. If the metabolic energy required to maintain an isometric contraction could be predicted for different torque levels, then the metabolic energy expenditure for performing negative work would be the same as the predicted static energy. This realization placed an extra emphasis on being able to predict the metabolic energy expended for the static situation where isometric muscle contractions are involved. This is stated in Questions 1 thru 5 (pages 32-39).

Non-Isometric Contraction Effects on E_{inc}. The prediction of the metabolic energy expended by a muscle when it is creating a tension and shortening, i.e. when it is performing mechanical work during an isotonic contraction, appears to be more complicated.

Hill formulated an empirical equation to represent the tension-velocity relationship of a fully stimulated muscle. His equation is (44):

$$(P + a)(V + b) = (P_o + a)b$$

which rearranges to:

$$P = \frac{P_o b - aV}{V + b}$$

Where:

P - average isotonic tension developed during shortening

a and b - empirically derived constants with a in force units and b in velocity units

V - average velocity of shortening muscle

P_o - average tension developed by muscle during isometric contraction when it is at its "resting" length.

Various researchers have empirically determined values for P_o, a, and b for different muscle tissue (1). The effect of increasing velocity on the tension producing capability of an isolated muscle of a frog's leg (the sartorii of the Rana temporaria), is depicted in Figure 8, as determined by Abbott and Wilkie (1). As may be noted in Figure 8, the empirical measures correspond closely to Hill's model and clearly indicate a large reduction in muscle tension capability when a high shortening velocity occurs. Karpovich has summarized Hill's and Fenn's thinking on this phenomenon as follows: "Contraction of a muscle depends on energy liberated during certain chemical reactions in the muscle. These reactions are characterized by the constancy of the rate, which means that the rate of liberation of energy necessary for contraction is also constant" (47:17). This restriction on the rate of availability of energy in a specific muscle could explain the electromyographic observations presented in the preceding section, Table 1. As is displayed in Table 1, if the "prime mover" muscle (which is the brachialis at the elbow) cannot produce tension at a high enough rate to achieve a desired shortening velocity, additional muscles (the biceps and brachioradialis) are stimulated to assist the initial "prime mover".

The "accumulation" of muscles to achieve speed could affect the metabolic energy expenditure due to the "secondary" muscle moment arms being different than the initial "prime mover" muscle. Therefore, the overall effect of the speed of contraction on a torque-metabolic energy relationship could be to increase the

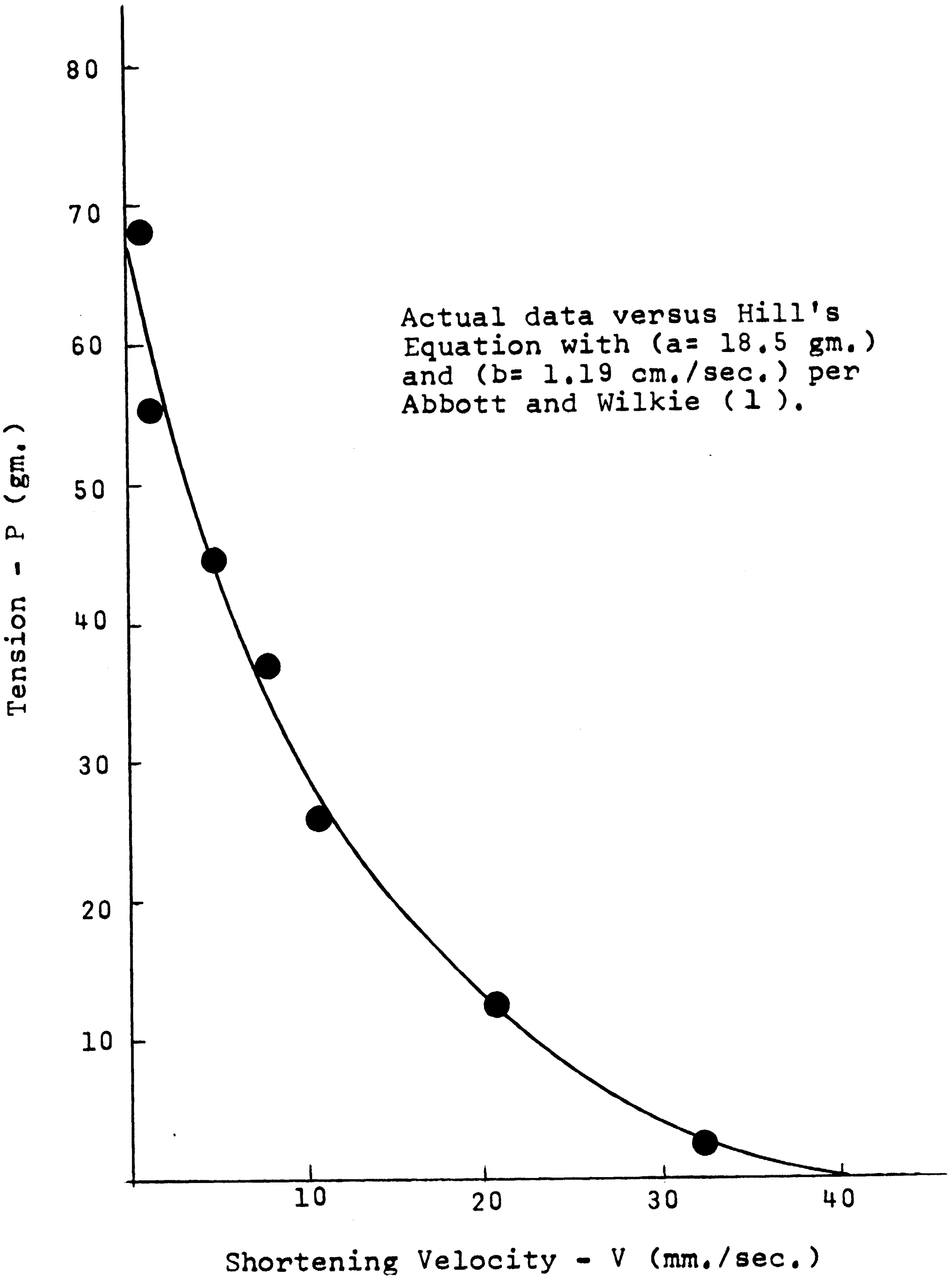


Figure 8

Tension - Velocity Relationship

metabolic energy expenditure for a fast flexion over that expended for a slower flexion under equal torques. This possibility placed an additional emphasis on the quantification of the speed of isotonic contraction effect discussed under Question 6 (page 40).

The Length of the Muscle when Contracted. A second functional aspect of skeletal muscle tissue is that the isometric tension it produces under a constant level of stimulation is dependent on the length of the muscle. When a muscle is shorter than its normal "resting" length in the body, the tension that it produces decreases steadily until at 60 percent of its resting length it completely loses its ability to produce tension (33). At this point the muscle is called "actively insufficient". Conversely, when a muscle is stretched beyond its resting length and then stimulated, the tension produced by the chemical reactions is lower than at the resting length, but the resilience of the connective tissue of each muscle fiber contributes a passive tension, thus raising the total muscle tension. The effects of these processes were depicted by Elftman (33) and are presented graphically in Figure 9. As may be noted in Figure 9, the metabolic energy expenditure for a given tension level is highly sensitive to the length of the muscle. The result of this tension-length relationship on the total metabolic energy expenditure required to produce a given level

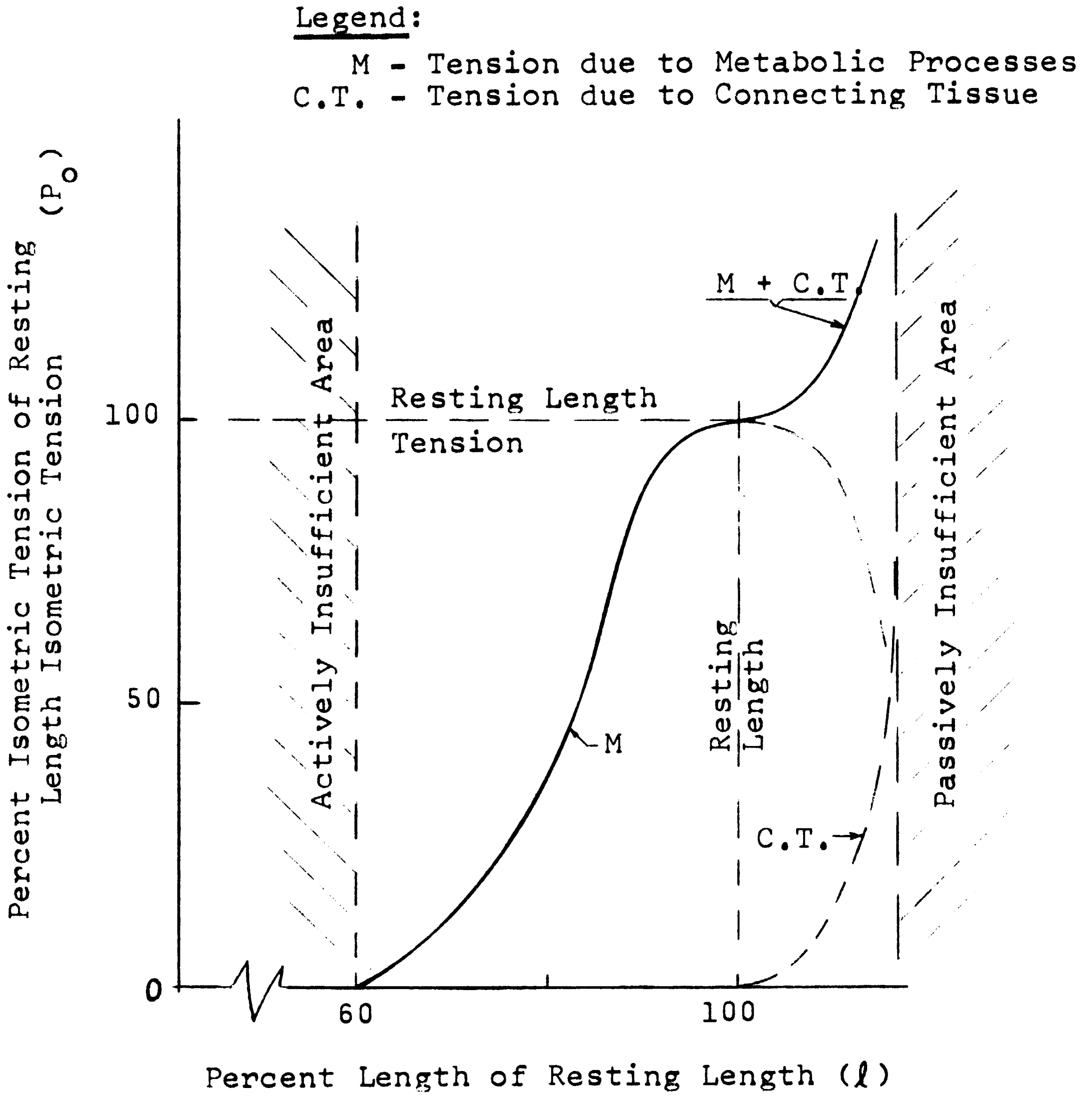


Figure 9

Isometric Tension versus Muscle Length per Elftman (33) of torque at an articulation, could be to require additional muscles to be stimulated to assist the "prime mover" due to it being too short to exert the required tension. Since muscle resting lengths and length changes cannot practically be measured in a person but have been qualitatively related to the angle of the articulation which they cross, further substantiation was given for an empirical definition of the articulation angle effect on the torque-metabolic energy relationship posed in Question 1 (page 32).

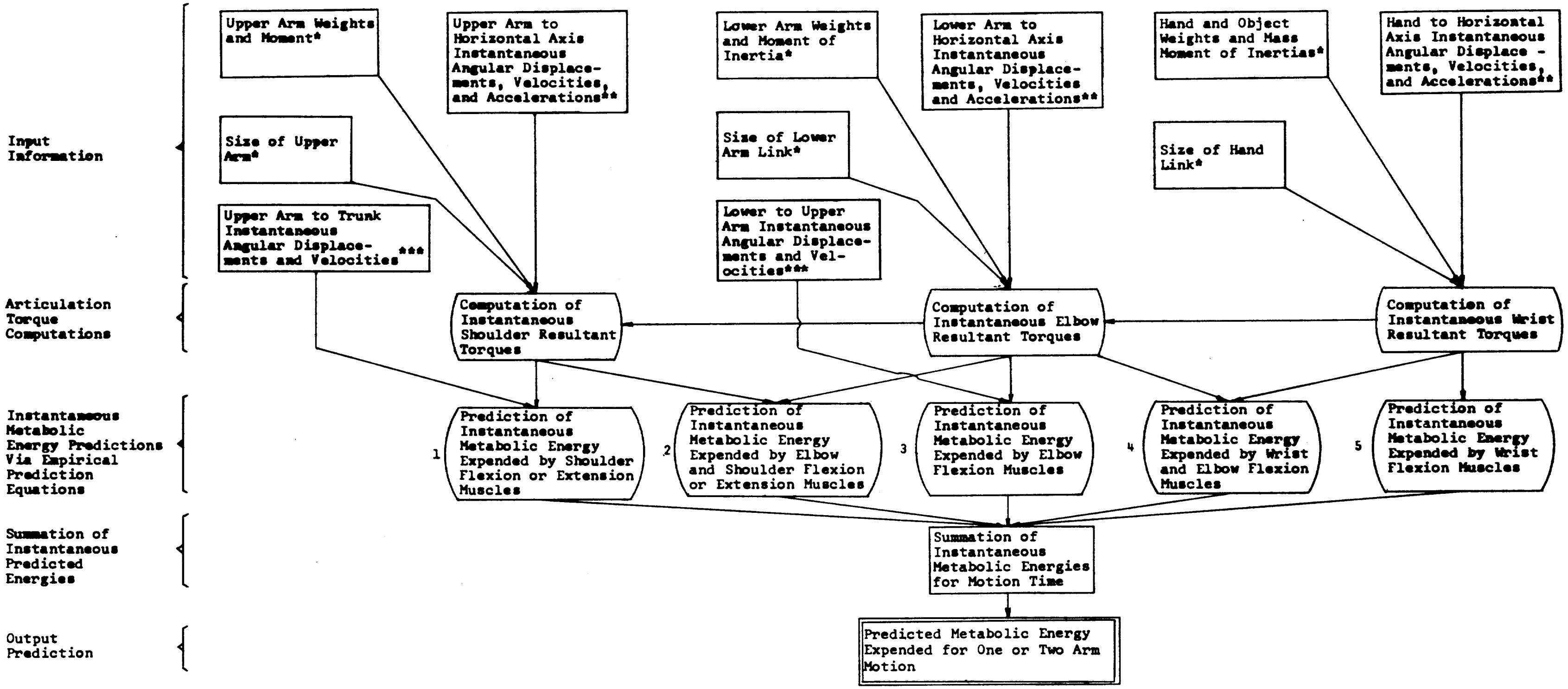
A Hypothetical Metabolic Energy Prediction Model for Arm Activities

The physical factors which have been used to describe manual activity involving the arm can be represented by a single concept, i.e. the torques that they produce at the shoulder, elbow, and wrist joints. However, the literature on muscle mechanics, recruitment, and physiology indicates that the following factors could influence any relationship between these computed articulation torques and the metabolic energy expended by the muscles to produce equal-in-magnitude but opposite-in-direction reactive torques:

1. The included angle between two appendages that form an articulation (page 32).

2. The anthropometric and muscle recruitment differences between individuals (page 32)
3. The direction that a resultant torque is acting at an articulation (page 36)
4. Whether an activity is being performed by one arm or both arms (page 37)
5. The magnitude of the torque at an articulation (page 39)
6. The magnitude of the angular velocity at an articulation during dynamic activities (page 40)
7. The magnitude and direction of the torque at an articulation which is adjacent to the one under consideration (page 41)

The intervening factors when combined with the torque computation algorithm presented in Appendix A, resulted in the formulation of the hypothetical metabolic prediction model diagrammed in Figure 10 on the next page. This hypothetical model has served as the basis for the design of the metabolic experiments described in the next four chapters.



Legend:

* Described in Table A-1
** Output of Equations A-7 through A-21 in Appendix A
*** Trigonometrically related to output of Equations A-7 through A-21 in Appendix A

General Notes:

It is expected that the empirical prediction equations used may be different in form and parameter values for:

A. An individual (eq. 1 thru 5)
B. The direction of torque (eq. 1 thru 2)
C. One arm or symmetric two arm activities (eq. 1 thru 5)

Figure 10

Hypothetical Metabolic Energy Prediction Model

Chapter III

METABOLIC ENERGY EXPERIMENT METHODOLOGY

This chapter presents the procedures employed to empirically answer the questions stated in the preceding chapter. The first section reports the controls and procedures developed to determine a person's metabolic energy expenditure rate. The next section presents the procedure used to create the resultant torques which are required in the experiments described in the later chapters.

Measurement of Metabolic Energy Expenditure

This section is divided into two subsections. The first discusses the biochemical factors involved in muscular contraction. The second subsection presents the methods utilized to obtain empirical relationships between resultant torques at an articulation and the metabolic energy being expended by a person's skeletal muscles to produce equal reactive torques.

Biochemical Factors in Muscle Contractions

As mentioned previously, the ability of the human body to produce muscle tension is dependent on the metabolism of various foodstuffs. This subsection briefly describes the development of the technique utilized to estimate the amount of energy liberated from food metabolism.

When various foodstuffs are burned in oxygen, which is known as <u>direct calorimetry</u>, the amount of chemical energy stored in the foodstuffs can be obtained for given amounts of oxygen utilized, and free carbon dioxide and water liberated. Two representative reactions are (71:637):

Carbohydrate (glucose): $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Heat}$

Fat (tristeran): $C_{57}H_{110}O_6 + 81.5O_2 \rightarrow 57CO_2$ $55H_2O + \text{Heat}$

With this knowledge in mind, a theory was proposed by early 20th Century biochemists. They theorized that the human body obeys the law of conservation of energy and that animal metabolism is an oxidation process (36:467). If true, the energy expended by animal metabolism could be estimated by measuring the amount of oxygen utilized and carbon dioxide expelled, since the liberated energy would be equal to that available in the foodstuffs eaten by the animal. The results of the investigation of this theory are summarized by Consolazio et al. (26:5):

> "Atwater and Benedict (1903) and their group applied the modern-day techniques of direct and indirect calorimetry to the demonstration of the validity of the law of conservation of energy for the human organism by first using carbon dioxide production as a measure of gaseous exchange and later using oxygen consumption [Benedict and Milner (1907)]. In their experiments they showed that the energy intake balanced the energy expenditure within 0.1 per cent. The confirmation of the law of conservation of energy placed calorimetry upon a secure basis.
>
> Because of the difficulty of performing direct calorimetry, it was important to show that indirect calorimetry was as accurate as the direct method. Comparative studies were performed on both animals and man. For example, in one series of experiments comparing both methods, there was agreement within 0.17 per cent of each method over a range of RQ, [i.e. Vol. CO_2 expired/Vol. O_2 utilized] between 0.77 and 0.97 [Gephart and Du Bois] (1915).
>
> Following the confirmation of results showing the validity and accuracy of calorimetry, studies were performed in two areas, the measurement of metabolic rate in health and disease and the measurement of energy expenditure."

The above reported experiments were based on subjects eating a controlled diet. In a more recent study, Weir formulated the relationship of metabolic energy expenditure rate (with the single assumption that 12 1/2 percent of the diet was protein) as a function of the percent of oxygen used and carbon dioxide expired (75). His reported coefficient of variation for the values predicted, as compared to the actual measured heat and kinetic energy liberated, was 1.5 percent. The form of this relationship, as presented by Liddell, is (49):

$$K = 1.0324 - 0.049327(O_E) + 0.000673(C_E)$$

Where:

K - Kilogram calories/liter of expired air

O_E - Percent of oxygen in expired air (percent inspired was 20.93%)

C_E - Percent of carbon dioxide in expired air (percent inspired was 0.03%)

The use of the above relationship negates the need to know the specific type of foodstuff that is being metabolized by a person during continuous, sub-maximal activity. (Table 2 on page 57 displays the range of energy expenditure rates for various foodstuffs.)

A further refinement was made by Liddell when he performed 335 separate studies with 14 different subjects who performed dynamic and static tasks with their arms and legs. These tasks required energy expenditure rates from two to eight Kilogram-calories/minute. The results of these studies showed that the percent of carbon dioxide in the expelled air could be estimated as a function of the percent of oxygen in that air. His regression is depicted in the following expression (49):

$$\%CO_2 \text{ expelled} = 15.60 - 0.7051(\%O_2 \text{ expelled}).$$

This regression has an estimated standard deviation of the data about the regression line equal to 0.15 percent CO_2 (49):

Nonprotein RQ= $\left[\frac{CO_2 \text{ Expired}}{O_2 \text{ Used}}\right]$	Fuel		Energy (Kcal/Liter O_2)
	Carbohydrate grams	Fat grams	Kcal.
0.718	0.000	0.516	4.735
0.72	0.009	0.512	4.737
0.73	0.052	0.494	4.748
0.74	0.096	0.476	4.759
0.75	0.140	0.457	4.770
0.76	0.183	0.439	4.781
0.77	0.227	0.421	4.793
0.78	0.271	0.403	4.804
0.79	0.315	0.384	4.815
0.80	0.358	0.366	4.826
0.81	0.402	0.348	4.837
0.82	0.446	0.329	4.848
0.83	0.489	0.311	4.859
0.84	0.533	0.293	4.870
0.85	0.577	0.274	4.881
0.86	0.620	0.256	4.892
0.87	0.664	0.238	4.903
0.88	0.708	0.220	4.914
0.89	0.751	0.201	4.925
0.90	0.795	0.183	4.936
0.91	0.839	0.165	4.947
0.92	0.882	0.146	4.958
0.93	0.926	0.128	4.970
0.94	0.970	0.110	4.981
0.95	1.104	0.091	4.992
0.96	1.057	0.073	5.003
0.97	1.101	0.055	5.014
0.98	1.145	0.037	5.025
0.99	1.188	0.018	5.036
1.00	1.232	0.000	5.047

Table 2

Energy Equivalents for Various Basic Foods (71: 641)

Liddell then combined his equation with Weir's under the assumption that the percent of oxygen in the inspired air is constant at 20.93 percent, and produced:

$$K = 1.0429 - 0.0498 \times O_E$$

Referring to this simplified equation, Liddell states (49):

> "The standard deviation of an estimate based on this formula (due to the substitution for C_E) is (0.000673) x (0.15) or 0.0001 Kilogram calories per liter of air, so that the error is less than 0.1 percent [coefficient of variation] and completely negligible in practice."

Thus it appears from the preceding discussion that an estimate of a person's metabolic energy expenditure rate, from a measurement of his oxygen utilization rate alone, will have a coefficient of variation of 1.6 percent. This error is considered to be the accuracy of indirect calorimetry without a CO_2 measurement, because it reflects the difference between the estimated metabolic energy expenditure rate as determined by a person's oxygen utilization rate, and the actual energy liberated by the person.

Determination of Incremental Metabolic Energy Expenditure

It has been empirically substantiated that when a person performs a manual activity, his metabolic energy expenditure increases above that required to maintain the vital functions of the body (64:494). The magnitude of this increase in metabolic energy expenditure has been referred to as the incremental metabolic energy expenditure (5:21). The rationale for the concern with this incremental quantity rather than the absolute metabolic energy expenditure is presented in the following subsection, along with a procedure developed to estimate its magnitude.

Why Incremental Metabolic Energy Expenditure?

Many factors have been empirically shown to affect a person's metabolic energy expenditure rate while they are not manually active, i.e. when there are no resultant torques about the major body articulations. Gemmill discusses the following factors as being the major contributors to a change in the "resting" metabolic energy expenditure rate (36:478-485): 1) age, 2) sex, 3) body surface area, 4) extremes of thermal stress, 5) prior ingestion of food, 6) strong emotional stress, and 7) disease.

The first three factors have been studied, and their effects on the resting metabolic rate are presented by Consolazio et al. (42:22-32). Average effects reported are:

1. A 10 year old boy expends approximately 25 percent more metabolic energy while resting than a 45 year old man.
2. A female expends about five percent less energy than a male while resting.

3. A person who is 5'3" and weighs 140 pounds will average 19 percent less metabolic energy expenditure while resting than a person who is 6'0" and weighs 180 pounds.

It can be seem that a large variation in the resting metabolic energy expenditure rates occurs between individuals.

The thermal stress has been shown to be insignificant in changing a person's metabolic rate if the environmental conditions remain between 70 and 85 degrees fahrenheit with a 30 percent relative humidity (25). However, an average increase in the metabolic rate of nine percent has been reported when the external thermal conditions vary from 70 to 85 degrees fahrenheit with a relative humidity of 86 percent (68). This latter study also showed that the metabolic energy expenditure change with temperature and relative humidity was statistically independent (at a statistical confidence level of 90 percent) of the physical activity level. Thus the temperature and humidity could affect the absolute metabolic energy expenditure but would not be expected to affect the incremental energy expenditure at different levels of manual activity.

The fifth factor affecting the resting metabolic energy expenditure rate is that of ingestion of food. The food ingestion effect occurs in two ways: 1) due to the energy required in the digestion processes, and 2) by altering the foodstuffs that are being metabolized, thus changing the thermal efficiencies of the biochemical processes. These effects usually increase the resting metabolic rate by six percent above that of the fasting level (71:669). The effect decreases slowly after the first hour following ingestion, and is negligible after the sixth hour (9:142-151, 71:668). Because of this, the time between a meal and testing has become a necessary control procedure in metabolic experiments, with limits from one to four hours having been reported (5:106,42:40).

The last two factors listed as having an effect on a person's resting metabolic energy expenditure are disease and severe emotional stresses acting on an individual. The effect of emotional stress has been investigated in three different settings, all of which showed no statistically significant effects on the subjects' metabolic rates. One of these studies used vocal reprimands and/or praise for the subjects (53). Another study employed various types of background music varying from marches to slow classical music (83). The third study compared students while in the contrasting activities of answering questions orally and resting quietly (84). These experiments do not negate the possibility of an emotional effect on the metabolic rate, however. Mental anxiety, if sufficient, will many times arouse overt muscle responses, such as finger or foot tapping. It has been stated that these actions will increase the metabolic energy expenditure and therefore the experiment setting should be such as to discourage severe changes in sensory input information (36:482).

The effect of a disease which raises the body temperature can increase the resting metabolic rate by 13 percent for each centigrade degree (36:482). Thus, a control in the experiments is necessitated to prohibit the testing of a subject with an elevated body temperature. Also, various thyroid gland conditions (particularly hyperthyroidism) are related to the resting metabolic rate. The possible effects of these conditions required that the resting metabolic rate be measured prior to the commencement of each activity to be studied.

It seems evident then, that many factors can affect the absolute level of an individual's metabolic energy expenditure. The next logical question appeared to be, "What is the minimum day-to-day variance in the metabolic energy expenditure of a group of resting people in a controlled experiment?"

One recent study by Andrews resulted in an estimated standard deviation of the day-to-day error in the observations (averaged for six subjects) equal to 0.086 Kilogram-calories per minute (5:102-152). The experiment controls were:

1. Oxygen volume-measuring equipment -- calibrated each day
2. Subjects -- six male students in good health

3. Timing -- three observations each day; the first after eating, the second between one and four hours after eating, and the third at least four hours after eating.
4. Instructions -- told to relax completely in a sitting position
5. Measurement period -- observations initiated after heart rate achieved a steady state for two minutes and then measurement taken for six minute period
6. Environment -- comfortable temperature and humidity

As will be shown in the results of this report, some of the metabolic energy expenditures for the lightest torque levels studied average less than Andrew's day-to-day error in the resting activities. Therefore, in addition to test controls, a test procedure was also adopted which it was hoped would further eliminate some of the previously listed expected effects. This test procedure was developed from the concept that the effects of most of the factors discussed do *not* vary greatly over a half-hour period. Therefore, if the *resting* metabolic energy expenditure was estimated by measuring the oxygen utilization rate of the test subject *immediately* prior to estimating it while he was performing a manual activity, it was believed that the incremental metabolic energy expenditure would be more apt to reflect *only* the effects of the manual activity. From this belief a test procedure was developed which *required the estimation of each subject's metabolic* load for a ten minute "resting" period prior to each ten minute "active" period.

Incremental Metabolic Energy Estimating Procedure. The following procedure was adopted to estimate the magnitude of the increase in a person's rate of metabolic energy expenditure when he uses his arms to perform a manual activity. The experiment controls, oxygen measuring procedure, and equipment design are discussed below.

The controls adopted during each study were as follows:

1. Each of the four subjects was judged as being in "good" physical condition with reference to individual medical examinations, including the following special aspects:
   a. Lung Vital Capacity Test (7:243-278)
   b. Time Rate Expiration Volume (7:243-278)
   c. New Modified Step Test (40)
   d. Medical History - (similar to U.S. Government Form 89 - Medical History)
2. Anthropometric dimensions were obtained as described in Table A-1 in Appendix A. (Subject data is summarized in Table B-1 in Appendix B.)
3. The subject was instructed not to eat or drink more than 10 fluid ounces of liquid for four hours before each study.
4. The room temperature was maintained between 70 and 80 degrees fahrenheit with the relative humidity between 30 and 85 percent.
5. During the test sessions any outside disturbances were discouraged, and soft "background" music was played to mask low random noises.

6. During the last five minutes of each ten minute test period, the percent of oxygen in the expired air was measured each minute and compared to the previous minute. If more than 0.4 percent variation occured from one minute to the next, it was noted on the data sheet. This limit was set because past experience showed inconsistencies in the estimates of the metabolic rates due to the subject apparently not achieving a steady-state oxygen withdrawal rate. If over 0.4 percent per minute variation was noted, the study was usually repeated at a later date.

7. The subject was instructed to refrain from any body motions besides those involved in the experimental task while being tested.

In addition to the above controls, the incremental metabolic energy expenditure rate was determined by first estimating the "resting" metabolic energy immediately prior to estimating the "active" energy, and then subtracting the two energy estimates. The procedure for this is as follows:

1. The "resting" period was established as ten minutes, of which the last five minutes were used to determine the average steady-state metabolic energy expenditures.[1] During this "resting" period the subject lifted his arm(s) into the position to be used during the active portion and then immediately relaxed. He repeated this procedure at equal intervals of time for the same number of times that the

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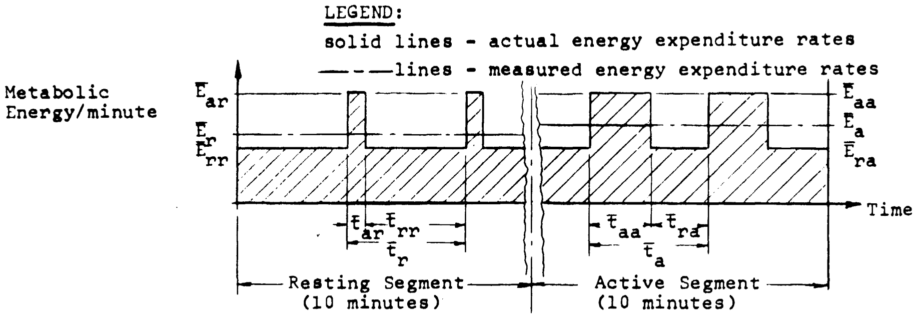
[1] Steady-state oxygen uptakes during submaximal activities have been reported to occur from one to five minutes after the onset of the activity by nine different researchers (5:100).

experiment task was to be performed in the next "active" portion of the total test. (The usual experiment conditions required this "move to position and relax" cycle to be performed every 15 seconds.)

2. The "active" period, which directly followed the "resting" period, also lasted ten minutes. Again the first five minutes of the cycle were used to acclimate the subject to the task as well as to allow his oxygen uptake to achieve a steady-state. During the "active" period, the subject performed the experimental tasks for a specified period, rested for a controlled period, and then repeated the task, etc., for the total ten minute segment. This alternating of work and rest during the "active" period was required to alleviate local muscle fatigue due to poor circulation in the contracted muscle tissue. It was also necessary to keep the cardiovascular and respiratory muscle actions small to avoid any significant increase in the total metabolic energy expenditure due to the required actions of these supporting systems (See discussion on page 4 for background on this latter point).

A diagram of the above test procedure is outlined in Figure 11. To test the additivity of the energies expended during the "resting" and "active" portions of a study, an experiment was performed which utilized different length active and resting periods. If the energies expended in the two periods were independent, the computed E_{inc} (incremental metabolic energy expenditure rate) should be equal for the different time intervals. The results of this experiment are contained in Table B-2, in Appendix B. The conclusion was that the computed E_{inc}'s did not differ significantly for the various time intervals. In other words, the test



Where:

$\bar{E}_r$ - Average measured steady state metabolic energy expenditure rate for "rest" segment (based on last 5 minutes)

$\bar{E}_a$ - Average measured steady state metabolic energy expenditure rate for "active" segment (based on last 5 minutes)

$\bar{E}_{ar}$ - Average metabolic energy expenditure rate for moving arms to active position in rest segment

$\bar{E}_{rr}$ - Average metabolic energy expenditure rate for subject at rest during resting segment

$\bar{E}_{aa}$ - Average metabolic energy expenditure rate for moving arms to active position and performing experimental task during active segment

$\bar{E}_{ra}$ - Average metabolic energy expenditure rate for subject at rest during active segment

Assumption:

$\bar{E}_{rr} = \bar{E}_{ra}$ (Discussed in preceding subsection on factors that effect resting metabolic energy expenditures.)

Measured Average Variables: (Discussed in next subsection on measuring procedure.)

$\bar{E}_r$, $\bar{E}_a$, $\bar{t}_{ar}$, $\bar{t}_{rr}$, $\bar{t}_{aa}$, $\bar{t}_{ra}$, with condition $\bar{t}_r = \bar{t}_a$

By definition, the average incremental metabolic energy expenditure rate for just the experimental task can then be expressed as:

$$E_{inc} = \frac{\left\{(\bar{E}_{aa} \times \bar{t}_{aa}) - \left[(\bar{E}_{ar} \times \bar{t}_{ar}) + \bar{E}_{rr} \times (\bar{t}_{aa} - \bar{t}_{ar})\right]\right\}}{(\bar{t}_{aa} - \bar{t}_{ar})}$$

Substitution of:

$$\bar{E}_r = \frac{\left[(\bar{E}_{ar} \times \bar{t}_{ar}) + (\bar{E}_{ra} \times \bar{t}_{rr})\right]}{\bar{t}_r}$$

and:

$$\bar{E}_a = \frac{\left[(\bar{E}_{aa} \times \bar{t}_{aa}) + (\bar{E}_{ra} \times \bar{t}_{ra})\right]}{\bar{t}_a}$$

Results in:

$$\boxed{E_{inc} = \frac{\left[\bar{E}_a \times (\bar{t}_a)\right] - \left[\bar{E}_r \times (\bar{t}_r)\right]}{(\bar{t}_{aa} - \bar{t}_{ar})}}$$

Figure 11

Computation of E_{inc}

procedure appeared to give an unbiased estimate of the incremental metabolic energy expenditure rate E_{inc} in respect to the resting and active times.

It was noted in the preceding test, however, that the variance in E_{inc} increases slightly as the ratio of active time $\bar{t}_{aa}$ to resting time $\bar{t}_{ra}$ decreases. Because of this the largest ratio of $\bar{t}_{aa}/\bar{t}_{ra}$ was sought during the tests, under the following conditions: 1) the test would not cause local muscle pain in succeeding days, and 2) it would not require the average oxygen uptake in the active segment to exceed 0.6 liters per minute above the rate of uptake in the resting segment. This is equivalent to approximately three kilogram-calories per minute difference between the average resting metabolic energy expenditure rate $\bar{E}_r$ and the average active metabolic energy expenditure rate $\bar{E}_a$. Since both of these conditions could not be evaluated until after a given test, the experience gained from the results of previous tests was used to derive the test time limits presented in Table B-3 in Appendix B. These limits were used as a reference throughout the 400 tests described in this paper.

<u>The oxygen measurement procedure</u> adopted was as follows:

1. Prior to each test, a nose and mouth mask was fitted to each subject's facial contours so that under forced exhalation no leaks could be detected by the subject or the experimenters.

2. During the initial experiments with each subject, electrodes were taped to the skin over what was expected to be the most active muscle group for a particular experimental task. These were attached to a differential amplifier which drove an oscilloscope within the subject's sight. By setting the horizontal sweep trigger on the oscilloscope to a level that would synchronize the scope sweep and the onset of the muscle action potentials, both the subject and the experimenters could time the duration of the activity by a muscle group.

3. The subject was informed of the average time that his muscles should be contracted (i.e. $\bar{t}_{aa}$ in Figure 11) during the last 10 minute "active" segment. For static activities typical cycles were composed of 5.0 or 7.5 seconds contracted followed by a rest period of 10 or 7.5 seconds respectively. To provide this information a timer with a 15 second per revolution sweep hand and a dial marked "active" and "rest" was placed so as to be easily viewed by the subject.[1]

4. The subject was carefully instructed on the type of activity to be performed by him during the "active" segment. Usually a few pretest "active" cycles were then performed to assist in establishing the details of the designated experiment task.

5. The average metabolic energy expenditure rate $\bar{E}_r$ was estimated for the first 10 minute "resting" segment by measuring the volume of oxygen utilized by the subject at one minute intervals during the last five minutes (see discussion on page 65 for a more detailed

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[1] After the subjects had practiced with the timer, it was found that they did not require the electromyographic information gathered from Step 2, preceding, to repeatedly contract a muscle group for the specified average period. This occurred usually after no more than ten test sessions, each of which required 40 individual "contraction-rest" cycles. After this "learning" period only occasional monitoring by E.M.G. analysis was utilized.

description of the "resting" segment).[2]

6. The average metabolic energy expenditure rate $\bar{E}_a$ was then estimated for the 10th and 20th minutes, which has been designated the "active" segment of a study. This was accomplished by measuring the volume of oxygen utilized by the subject each minute during the last five minutes, while he repeatedly relaxed, performed the experiment task, and relaxed, etc. for the ten minute period (see discussion on page 66 for a more detailed description of the "active" segment).

7. The incremental metabolic energy expenditure rate E_{inc} was then computed from the procedure presented in Figure 11 (page 67).

Consistency of E_{inc} Estimations for a Single Subject.

As was hypothesized in Question 2 for Experiments, individual differences in both muscle recruitment and mechanics were expected to affect the metabolic energy expended by various people performing the same task (page 32). Unfortunately, the published metabolic energy expenditure studies reviewed by this author did not separate this source of variation from the variations due to measurement and subject acclimatizations to the different test situations. Since the metabolic energy expenditure estimations in this research project were to be made with only four subjects tested over a one and one half year period, the question of how much variation

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[2] Appendix C describes the format of the oxygen data, equipment used, and calculations for estimating the average metabolic energy expenditure rates.

in the estimation of E_{inc} would be due to each experimental task configuration and how much would be caused by day-to-day variation in a subject, as well as the measurement technique, required evaluation.

In testing for the consistency of the estimates of E_{inc} the following concepts appeared to be relevant:

1. The learning process required to activate only the mechanically efficient muscles to perform a specific task could take longer than the five minute adjustment period allowed in each "active" test period.
2. The strength in more mechanically efficient muscles may be developed slowly by the repeated use of these muscles during the testing program.

Both of the above ideas posed the possibility of long term acclimatizations of the subjects which could result in a gradual decrease in the metabolic energy being expended to produce a given torque at a specific articulation. Therefore, the following repeatability analysis was included in the experiments to be performed by the subject who was to be involved in the majority of the metabolic experiments reported in this paper. The analysis was based on the following concept which has been displayed empirically by Basmajian. This concept is that specific muscle activation is sensitive to: 1) the level of the total torque required (page 39) 2) the direction of the torque (page 36), and 3) the articulation involved (page 39). The repeatability procedure employed required three or more identical static studies to be repeated at different times during each of the test periods required for the experiment conditions displayed in Table 3.[1]

The objective of the repeatability analysis was to determine the expected "long term" variation in E_{inc} throughout each test period. By comparing the average $\bar{E}_{inc}$'s computed from the E_{inc}'s obtained at the beginning, middle, and end of each test period, confidence could be gained as to the long term effect of the experiment tasks on the incremental metabolic energy expended by the subjects. Replication of experiments on one day were not performed because of local muscle fatigue at the higher torque levels which created the possibility that other "supporting" muscles would be used rather than the "normal" muscles. Thus, an estimate of the variance within each day was not possible.

As is displayed in the three average $\bar{E}_{inc}$ values in Table 3, no consistent long term trend in the estimates appeared to be present. Because of this, the three individual observations of E_{inc} for each experiment condition were pooled to derive an estimate of the means

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[1] A test period for a particular set of experiment conditions usually ran from three to six months, as can be seen from the earliest and latest test dates for each set of conditions described in Table 3.

Experiment Condition	Date	E_{inc} (Kcal/min)	Expected Value $E(E_{inc})$ (Kcal/min)	Est. Var. σ_e^2 (Kcal/min)^2	Est. Std. Dev. σ_e (Kcal/min)	Log E_{inc}	Est. Var. in Log E_{inc} **	
Elbow Flexion - 80° EFT1 = 175 Kgm-cm.*	7-22-66 8-10-66 6-27-66	0.21 0.24 0.28	0.243	0.0012	0.035	9.322-10 9.380-10 9.447-10	0.0039	Average $\bar{E}_{inc}$ for all Experiment Conditions at Different Times During Test Periods: $\bar{E}_{inc}$ (Early in Periods) = <u>0.69</u> Kcal/min $\bar{E}_{inc}$ (Middle of Periods) = <u>0.75</u> " " $\bar{E}_{inc}$ (Late in Periods) = <u>0.72</u> " "
Elbow Flexion - 80° EFT1 = 325 Kgm-cm.	7-25-66 8- 3-66 10-17-66	0.80 0.97 0.82	0.863	0.0086	0.093	9.903-10 9.987-10 9.914-10	0.0020	
Wrist Flexion WFT1 = 40 Kgm-cm.	6-23-66 7-28-66 9-10-66	0.20 0.25 0.17	0.207	0.0016	0.041	9.301-10 9.398-10 9.230-10	0.0071	
Wrist Flexion WFT1 = 55 Kgm-cm.	8- 3-66 7-11-66 10-13-66	0.38 0.48 0.43	0.430	0.0025	0.050	9.570-10 9.681-10 9.634-10	0.0031	
Shoulder Flexion SF1 = 140 Kgm-cm.	6-14-66 7-23-66 8- 4-66	0.10 0.13 0.15	0.125	0.0007	0.026	9.000-10 9.114-10 9.176-10	0.0079	
Shoulder Flexion SFT1 = 280 Kgm-cm.	6-28-66 8- 2-66 10-13-66	1.00 0.89 0.80	0.897	0.0100	0.100	10.000-10 9.949-10 9.903-10	0.0023	
Shoulder Extension SET1 = 140 Kgm-cm.	10-15-66 8- 4-66 9-13-66	0.06 0.07 0.08	0.070	0.0001	0.010	8.778-10 8.844-10 8.903-10	0.0033	
Shoulder Extension SET1 = 280 Kgm-cm.	6-22-66 7-19-66 9-29-66	0.86 0.98 0.78	0.873	0.0101	0.100	9.934-10 9.991-10 9.892-10	0.0023	
Shoulder Extension SET1 = 350 Kgm-cm.	7-21-66 1-24-67 10-28-66	2.80 3.31 3.10	3.070	0.0657	0.257	10.447-10 10.519-10 10.491-10	0.0013	
Elbow Flexion - 80° EFT2 = 325 Kgm-cm.	7-19-66 6-30-66 8- 2-66	0.34 0.40 0.43	0.395	0.0021	0.046	9.532-10 9.602-10 9.633-10	0.0021	

Subject: J.K.

*These numbers are resultant torques

** Bartlett Homogeneity Test disclosed logarithmic variances to be equal at α=0.05 level.

Table 3

Repeatability Data

and variances in E_{inc} for the different experiment conditions. The results of this analysis showed that the standard deviation of the error, σ_e, increased as the expected value $E\{E_{inc}\}$ increased. A linear least squares regression of this effect resulted in the following formulation (the variables are in units of Kilogram-calories per minute, abreviated Kcal/min.):

$$\sigma_e = 0.021 + 0.07963 \ E\{E_{inc}\}$$

which was found to have a correlation coefficient of 0.96.

A speculative interpretation of this regression relationship is as follows: If the subject continued performing the "resting" activity during the "active" segment of the study, the standard deviation of the error (0.021 Kcal/min.) could be contributed to measurement error and the lack of a true steady state during the last 15 minutes of each study period. In addition, if the subject is required to perform a task which requires a significant increase in muscle involvement during the "active" segment of the study (which in turn raises the expected value of E_{inc}), the standard deviation of the error increases with E_{inc}. This could possibly be attributed to the larger number of alternative muscle motor unit recruitment possibilities becoming available as a larger number of muscles are involved in the task. Or, possibly it could be due to a change in the day-to-day muscle efficiency which would be magnified by the amount of metabolism required to perform the task. Whatever the rational, the implication of this relationship for subsequent experiments is that the confidence in a point estimate of a low value of E_{inc} for a person is much higher than if the point estimate of E_{inc} has a large value. This concept is used in the analysis of data described in the next chapters.

Creating Resultant Torques

The first part of this section presents the methods used to establish a static resultant torque, while the latter part discusses the method used to maintain a constant torque during dynamic flexions of the elbow and shoulder.

Static Resultant Torque Procedure

The concept employed to create a static resultant torque at an articulation was simply to support the proximal appendage of the articulation while exerting a known load at a finite distance from the articulation on the distal segment. The procedure used for this is as follows:

1. With reference to the following data, the resultant torque at an articulation, due to

the weight of the distal segments, was estimated by equations A-1 through A-6 in Appendix A:

   a. Subject's weight
   b. Subject's radius length
   c. Subject's hand length
   d. Angles formed by body segments and the horizontal axis.

2. The resultant torques due to the body segment weights were subtracted from the resultant torques desired at the body articulations under study.

3. A force was applied to the distal body segment by weights acting at a measured distance from the articulations under consideration. The magnitude of the weights and the direction of their actions were selected to produce the difference between the desired resultant torque and the torque already produced by the body segment weights as computed in steps one and two.

The following special test conditions were evoked in creating resultant torques at each articulation:

1. The *single wrist flexion torques*, designated (WFT1), were produced by having the subject grasp a roughly finished handle of 1.5 inch diameter to which a specific weight was attached (Figure 12 depicts the test setup).

2. The *two wrist flexion torques*, designated (WFT2), were produced by having the subject grasp a roughly finished handle of 1.5 inch diameter in each hand. These were attached to the ends of a 14 inch long by 12 inch square container of a known weight (Figure 12 depicts the test setup).

3. The *one and two elbow flexion torques*, designated (EFT1 and EFT2), were created by applying loads at the wrist joint while supporting the upper arms and shoulders. (Figure C-1 in Appendix C depicts this test setup).

THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

THE DEVELOPMENT OF A PREDICTION MODEL FOR THE METABOLIC ENERGY EXPENDED DURING ARM ACTIVITIES

Don B. Chaffin

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
Department of Industrial Engineering
1967

August, 1967

IP-786

4. The production of one and two shoulder flexion torques, designated (SFT1 and SFT2), required the following procedure. First, the arms were placed in plastic half-casts of known weights and center of gravity locations. The purpose of the casts was to support the lower arm and hand so the resultant torque at the elbow due to the weight of these appendages was zero. The required torques were then produced by applying forces by means of weights attached to straps which were centered over each elbow joint (Figure 13 displays a typical test setup).

5. The one and two shoulder extension torques, designated (SET1 and SET2), were produced in the same manner as the shoulder flexion torques, but the load was applied in the opposite direction (Figure 13 also depicts this test setup).

The maximum deviation of the weights used in the study was measured and found to be ± 1.8 percent of the stated weight. In addition, a series of X-rays were taken of the major subject used in the experiments. These disclosed that the body segment lengths, as determined by the procedure described in the first part of Appendix A, were within ± 2.0 percent of the measured segment lengths.

Dynamic Resultant Torque Procedure

The following is a method employed to produce a relatively constant resultant torque during dynamic flexions of the shoulder and elbow articulations. It is based on the concept that at a constant angular velocity the inertial forces (with the exception of the segment weight) are zero. This idea is consistent with a

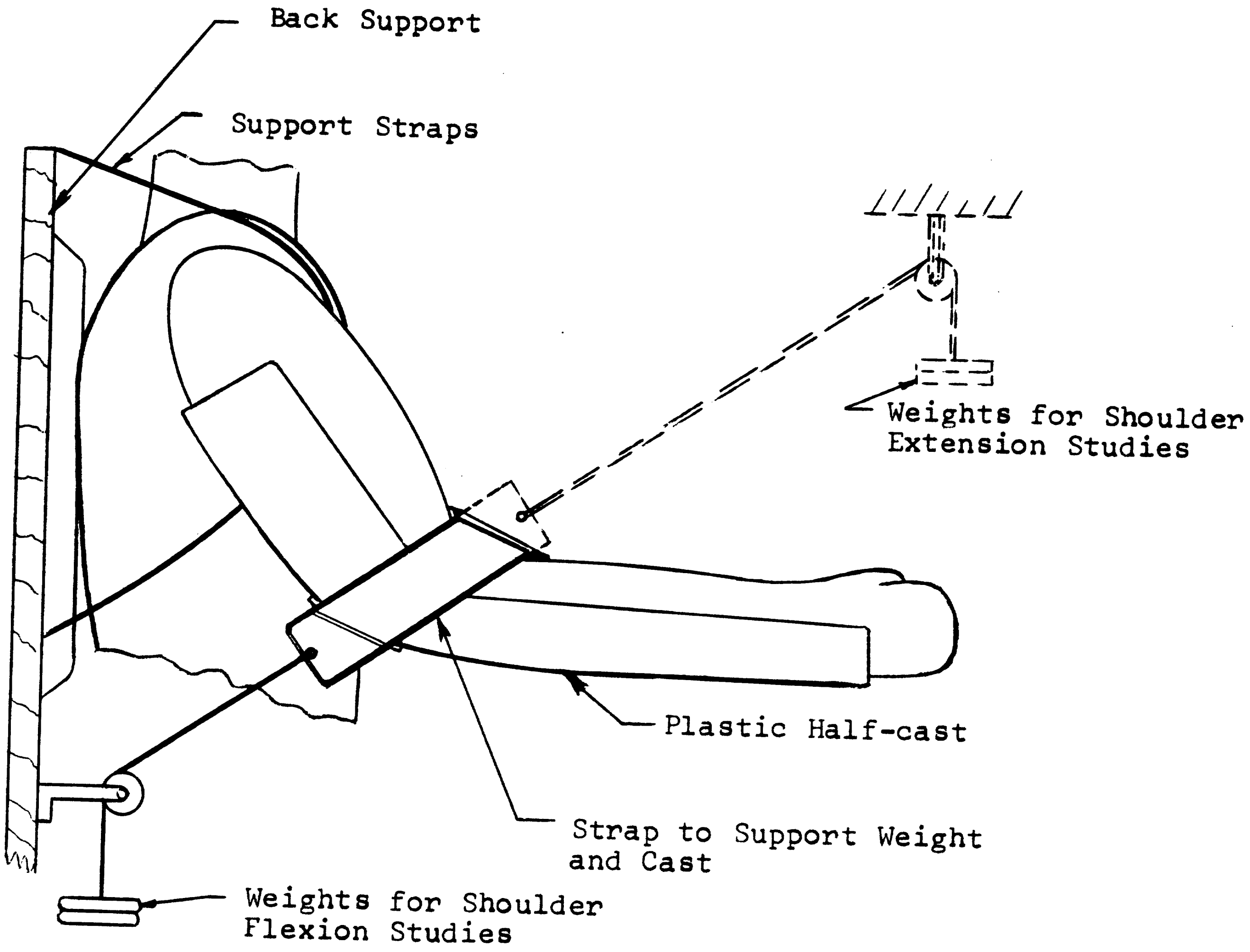


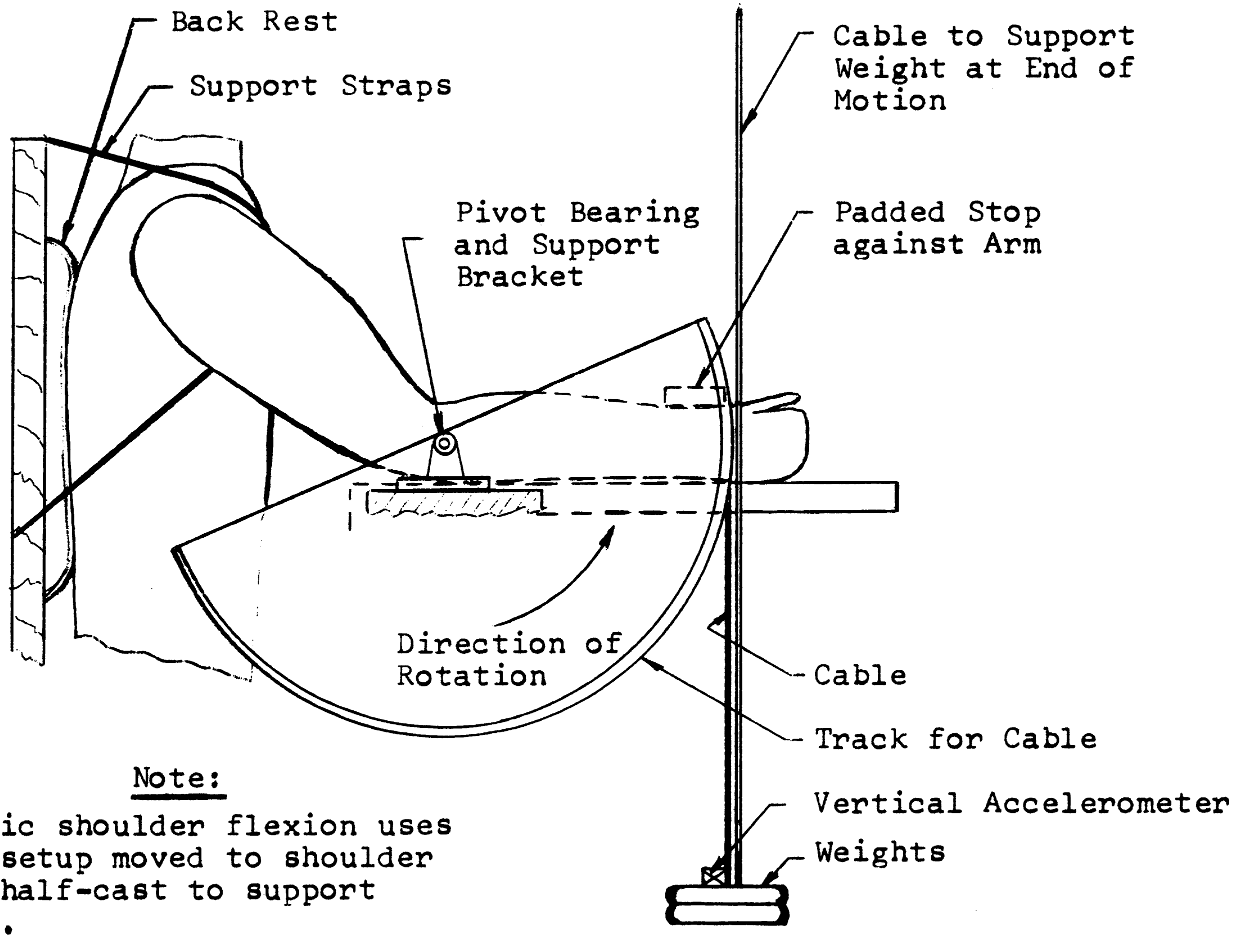
Figure 13

Shoulder Static Task Test Setup

question posed in Chapter II in which the effect on E_{inc} by different magnitudes of angular velocity at an articulation are desired (page 40). In the experiments discussed in Chapter VI, it will be seen that the different angular velocities were created by the following procedure and equipment:

1. The articulation under consideration was positioned opposite the center of rotation of a "half-wheel" having a 10 inch radius (Figure 14 depicts the test setup for the dynamic elbow flexion study).
2. A padded stop at the periphery of the "half-wheel" was positioned against the forearm to apply the desired load to the arm.
3. The load creating weight was supported from a cable, the other end of which was attached at the periphery of the "half-wheel".
4. A linear accelerometer was attached to the weight to detect its vertical acceleration which was used to compute the angular velocity and acceleration of the lower arm.
5. The subject was instructed to repeatedly jerk against the weight but not move it significantly. This was the activity of the first 10 minute "rest" segment of a study.
6. During the next "active" 10 minute segment, the subject was instructed to jerk the weight into motion and keep it in motion at a constant speed through the required flexion angle, which was determined by the point at which the experimenter pulled the weight away.

With repeated practice of the preceding steps five and six, the subject was able to maintain a constant angular velocity for speeds of up to 3.5 radians per second throughout a 100 degree flexion angle. By



Note:

Dynamic shoulder flexion uses same setup moved to shoulder with half-cast to support elbow.

Figure 14

Elbow Flexion Dynamic Task Test Setup

requiring the amount of weight moved to be much greater than the arm and hand weight, the total torque variation due to the angular change effect of the arm and hand weights was minimized. Because the effect of the arm and hand weight was still present, however, two different external loads were used in the dynamic studies discussed in Chapter VI.

Summary of Chapter

This chapter has attempted to present the technical background and procedures used to estimate the incremental metabolic energy expenditure rates. It briefly reviews the biochemical aspects of metabolism, followed by a more detailed discussion of actual measurement problems, and why the incremental metabolic energy expenditure rate is more applicable to the objectives of the research project than the gross metabolic energy expenditure rate. The experiment controls and procedures are then presented. The chapter concludes with a description of the methods employed to create the resultant torques which are utilized throughout the experiments discussed in the next few chapters.

Chapter IV

THE DEVELOPMENT OF A SINGLE-SUBJECT METABOLIC PREDICTION MODEL FOR STATIC ARM ACTIVITIES

This chapter describes the static activity experiments which were performed with one subject (designated J. K. in Table B-1 in Appendix B). The general objective of these experiments was to quantify the change in the incremental metabolic energy expenditure rate of the subject for the types of static arm activities contained within the scope of this research project, as delineated on pages 2 and 3 of the Introductory section of this paper.

The experiments performed were attempts to answer the questions presented in Chapter II. The order of reporting in this chapter is as follows: The first section describes the experiments that were performed in order to determine the variation in E_{inc} at different levels of torque for the following major factors: 1) the articulation involved, 2) whether the action was a flexion or extension, 3) the articulation angle, and 4) whether one or two arms were active. The next section presents the interaction effects on E_{inc}, i.e. the change in E_{inc} when two adjacent articulation angles and torques were varied simultaneously. The Chapter concludes by combining the results of these experiments into a metabolic prediction model for static activities. The predictions from this single subject model were then compared to E_{inc} data obtained while the subject held weights of various magnitudes in different positions with one and both arms.

The Experiments to Determine the Effects of the Major Factors

In summary, Questions 1,3,4, and 5 in Chapter II presented the concept that any relationship between the resultant torque at a single articulation and the level of E_{inc} resulting from the creation of a reactive torque by the muscles at that articulation could be dependent upon the following factors:

1. Which particular muscle group was involved (i.e. which articulation and what was the direction of the action)?
2. What was the angle between the appendages which formed the articulation being used?

Because of their direct relationship to the conditions involved in this research project, these factors will be referred to as major factors.

The objective of the research reported in this section is to quantify the effects of these major factors on the previously implied relationship between E_{inc} and resultant torque.

The Experiment Design for Determining the Effects of the Major Factors on E_{inc}

It was hypothesized (based on the concepts of Question 5, Chapter II) that the increase in E_{inc} for increased resultant torques could probably be depicted by a monotonic continuous function. The basis for this is that skeletal muscle actions are smoothly integrated into the total action required, i.e. one muscle does not become highly active with a small change in load, and for that matter no single muscle decreases in activity as the total load increases. Based on this hypothesis, which was empirically displayed in earlier reported research (24:10), the decision was made to study the change in E_{inc} for four different resultant torques created within each experiment condition selected to test the effects of the major factors.

The selection of the four torques (within each set of experiment conditions) was accomplished by a preliminary analysis of the maximum torque which the subject was willing to sustain for the required twenty minute study periods.[1] Once the maximum torques were estab-

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[1] It was later disclosed that the incremental metabolic energy rates found for these maximum torques would categorize them as heavy work with the arms (page 5).

lished, the three remaining torque levels were equally spaced between the maximum torque and a minimum torque. The minimum torque was approximately double the torque created by just the weight of the body segments.

The possible effects of the torque and the angle of an articulation on the metabolic energy expended by each muscle group considered in this project resulted in the establishment of the following experiment conditions:

1. Both shoulders perform static flexions (i.e. they sustain resultant torques in the c. w. direction), at angles of 0°, +30°, +60°, +90°, and +110 degrees.[1]
2. Both shoulders perform static extensions (i.e. they sustain resultant torques in the c. c. w. direction), at angles of -30°, 0°, +30°, +60°, +90°, and +110 degrees.
3. One shoulder performs static flexions with angles set at -30°, 0°, +30°, +60°, +90°, and +110 degrees.[2]

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[1] Angle measured with a goniometer from trunk to upper arm, with counter-clockwise direction being positive. The range of angles studied was chosen to characterize what was intuitively believed to represent a typical working range.

[2] Preliminary experiments showed no significant difference in the subject's left and right arm E_{inc} values. Therefore, when only one arm was studied in an experiment, no specific distinction was made between arms. This permitted additional experiments to be performed, because the one arm experiments could generally not be repeated with the same arm in one day.

4. One shoulder performs static extensions with angles of -30°, 0°, +30°, +60°, +90°, and +110 degrees.

5. Both elbows perform static flexions with the angles between the upper and lower arms at 55°, 80°, 110°, 140°, and 170 degrees.

6. One elbow performs static flexions with the angles between the upper and lower arms at 55°, 80°, 110°, 140°, and 170 degrees.

7. Both wrists perform static flexions with the hand and lower arm center axes in line.

8. One wrist performs static flexions with the hand and lower arm center axes in line.

It was recognized in designing the above described experiments, that the angle and torque at an adjacent articulation to the one being studied could interact with the effects of the experiment conditions on E_{inc}. To avoid this possibility the adjacent articulation angles were held constant for all of the listed test conditions. Also, the resultant torques at the adjacent articulations were minimized by supports. (The adjacent articulation interaction analysis described in the next section of this report (page 127), was also performed to determine the extent of these possible effects.)

A summary of the test conditions for determining the effects of the major factors on E_{inc} is presented in

Table 4, as well as the resulting E_{inc} value determined when the subject sustained the torque designated by each test condition. The E_{inc} values were obtained by the procedure outlined in Figure 11, and discussed on page 67.

The Analysis of the Major Effects

The objective of the preceding experiments was to determine how the value of E_{inc} changes for different resultant torques when these torques are produced within the stated test conditions for the major factors. This objective required the hypothesized torque-E_{inc} relationship to be quantified for each test condition. An analysis of these relationships was made to determine if the various test conditions (such as changing the angles, or using one arm or both arms), significantly altered the torque-E_{inc} relationships.

The Quantification of Torque-E_{inc} Relationships.

It was speculated in Question 5 of Chapter II that any torque-E_{inc} relationship need not be linear. Because of this speculation, a regression model which could be linear or non-linear was selected to be fit to the resultant torques and corresponding E_{inc} values for each of the major factor test conditions listed in Table 4. The procedure employed in estimating the value of the parameters in the model was to produce the smallest sum

E_{inc} Response in Experiments of Major Factors One Arm:				E_{inc} Values(Kcal/min) for:				
Sights of Activity (Articulations)	Direction of Action	Shoulder Angles (γ)	Adjacent Elbow Angles	One Shoulder Torque(S-T1) in Kgm. - cm. 140	210	280	350	
Shoulder	Flexion	-30°	140°	0.13	0.40	1.00	2.70	
		0°	140°	0.12	0.33	0.89	2.30	
		+30°	140°	0.10	0.27	0.85	1.70	
		+60°	140°	0.12	0.32	0.76	2.31	
		+90°	140°	0.15	0.40	1.25	2.71	
		+110°	140°	0.13	0.44	1.50	3.95	
	Extension	-30°	140°	0.04	0.18	1.00	4.01	
		0°	140°	0.06	0.22	0.86	2.80	
		+30°	140°	0.12	0.20	0.33	0.75	
		+60°	140°	0.13	0.26	0.65	1.10	
		+90	140°	0.08	0.30	1.02	2.11	
		+110°	140°	0.06	0.35	1.20	2.95	
		Elbow Angles (γ)	Adjacent Shoulder Angles	One Elbow Torques (EFT1) in Kgm. - cm. 75	125	200	250	325
Elbow	Flexion	+55°	0°	0.12	0.25	0.60	1.20	-
		+80°	0°	0.10	-	0.30	0.52	0.85
		+110°	0°	0.09	0.19	0.35	0.70	-
		+140°	0°	0.09	0.15	0.42	0.90	-
		+170°	0°	0.10	0.24	0.47	0.92	-
		Wrist Angle	Adjacent Elbow Angles	One Wrist Torques (WFT1) in Kgm. - cm. 20	40	55	70	
Wrist	Flexion	+180°	80°	0.05	0.25	0.42	0.98	

Table 4 (continued on next page)

Experiment Design and E_{inc} Values for Major Factors

E_{inc} Response in Experiments of Major Factors Both Arms:				E_{inc} Values(Kcal/min) for:				
Sights of Activity (Articulations)	Direction of Actions:	Shoulder Angles(*)	Adjacent Elbow Angles	Two Shoulder Torques(S-T2) in Kgm. - cm.				
				280	420	560	700	
Shoulder	Flexion	0°	140°	0.39	0.62	1.32	1.91	
		+30°	140°	0.30	0.61	0.95	1.75	
		+60°	140°	0.56	0.95	1.51	2.22	
		+90°	140°	0.55	1.02	1.41	2.72	
		+110°	140°	0.59	1.15	1.75	2.91	
	Extension	-30°	140°	0.55	0.85	1.85	3.16	
		0°	140°	0.38	0.85	1.35	2.65	
		+30°	140°	0.28	0.60	1.01	1.98	
		+60°	140°	0.34	0.70	1.17	2.19	
		+90°	140°	0.51	0.85	1.30	2.56	
		+110°	140°	0.49	0.98	1.51	2.98	
		Elbow Angles(*)	Adjacent Shoulder Angles	Two Elbow Torques(EFT2) in Kgm. - cm.				
				100	175	250	325	400
Elbow	Flexion	+55°	0°	0.17	0.32	0.50	0.61	-
		+80°	0°	0.12	0.27	0.31	0.39	0.47
		+110°	0°	0.15	0.26	0.40	0.44	-
		+140°	0°	0.18	0.33	0.43	0.54	-
		+170°	0°	0.17	0.31	0.53	0.56	-
		Wrist Angle	Adjacent Elbow Angles	Two Wrist Torques (WFT2) in Kgm. - cm.				
				40	55	70	85	
Wrist	Flexion	+180°	80°	0.08	0.25	0.38	0.56	

Table 4 (continued from preceding page)

Experiment Design and E_{inc} Values for Major Factors of the squared error between the actual and predicted E_{inc} values.[1]

One general requirement to obtain unbiased and consistent least squared error estimates of the unknown parameters in any regression equation is that the E_{inc} observations be normally distributed about their expected value. Because of the large number of underlying processes which could contribute to a particular value of E_{inc}, it would have been logical to assume that their cumulative effects resulted in E_{inc} being normally distributed. A statistical test of the data presented in Table B-2, Appendix B, was performed to verify this belief, and is tabulated in Table B-4. The conclusion from this test is that the distribution in E_{inc} values for known resultant torque conditions, does not differ significantly ($\alpha=0.10$) from a normal distribution.

A second condition to insure unbiased and consistent estimates of the unknown parameters in each of the proposed regression models is that the standard error of the estimates, designated σ_e must remain constant for various expected values of E_{inc}. As was discussed in Chapter III (page 74), this was not the situation, and

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[1] The analysis technique chosen is often referred to as the "General Linear Model-Full Rank", sometimes referred to as a statistical "Prediction Model" (39:106-145).

in fact, the value of σ_e was found to be approximately proportional to the expected value of E_{inc}. Because of this condition, some form of transformation of the E_{inc} data was necessary in order that greater importance in estimating the regression equation parameters be assigned to the E_{inc} values which were expected to have the smallest variances.

The data transformation procedure used in this endeavor was suggested by Davies (28:44). After transforming the data by this procedure, the transformed E_{inc} values (these will be referred to as E_W values) were found to be distributed normally about their mean (Table B-5), have homogeneous variances over the range of E_{inc} values studied (Table B-6), and converge to zero when E_{inc} equals zero (which is by definition when there is no resultant torque at an articulation (page 59)).

Davies transformation is based on $\sigma_e = f(\mu)$. The transformed variable E_W is defined as:

$$E_W = \int \frac{1}{f(\mu)} \, d(\mu).$$

By assuming $\mu = E\{E_{inc}\}$, this becomes:

$$E_W = \int \frac{1}{f[E\{E_{inc}\}]} \, dE\{E_{inc}\}$$

Then substitution of the following equation for σ_e as a function of $E\{E_{inc}\}$ (page 74):

$$\sigma_e = 0.02147 + 0.07963E\{E_{inc}\}$$

allows:

$$E_W = \int \frac{1}{0.02147 + 0.07963E\{E_{inc}\}} \, dE\{E_{inc}\}$$

or, to assist in later computations

$$E_W = \int \frac{1}{0.01[2.147 + 7.963E\{E_{inc}\}]} \, dE\{E_{inc}\}$$

$$= 100 \int \frac{1}{2.147 + 7.963E\{E_{inc}\}} \, dE\{E_{inc}\} \; .$$

When integrated this becomes:

$$E_W = \frac{100 \left\{\log[2.147 + 7.963E\{E_{inc}\}]\right\}}{7.963} + C$$

or

$$E_W = \frac{\log[2.147 + 7.963E\{E_{inc}\}]}{0.07963} + C.$$

Applying the restriction that when $E\{E_{inc}\}$equals zero, E_W also equals zero, allows the integration constant C to be determined as follows:

$$E_W = \frac{\log[2.147 + 7.963(0)]}{0.07963} + C = 0$$

$$C = -\frac{0.33183}{0.07963} = -4.1673$$

Therefore, the transformation of each E_{inc} value observed is:

$$E_W = \frac{\log[2.147 + 7.963(E_{inc})]}{0.07963} - 4.1673 \ .$$

A graph of this relationship is displayed in Figure 15. As may be noted in Figure 15, as E_{inc} increases, the proportional amount of change in E_W decreases. The result of this concept is that the occurrence of a high E_{inc} value will have a smaller effect on the determination of the parameter estimates than lower E_{inc} values. A test of the homogeneity of the E_W values for the repeatability data (Table 3, page 73) disclosed that the variances of the weighted E_{inc} values were constant for the range of expected values of E_{inc} to be investigated in this research project. (Table B-6 in Appendix B presents the homogeneity test results.)

It was therefore concluded that the least squared error regression analysis procedure would produce unbiased and minimum variance estimates of parameters in a linear regression equation of the weighted E_{inc} values on resultant torques. In essence then, the regression procedure used to quantify the relationship between the E_{inc} values and the preset resultant torques was:

1. Each E_{inc} observation was transformed to a weighted E_W value by the equation:

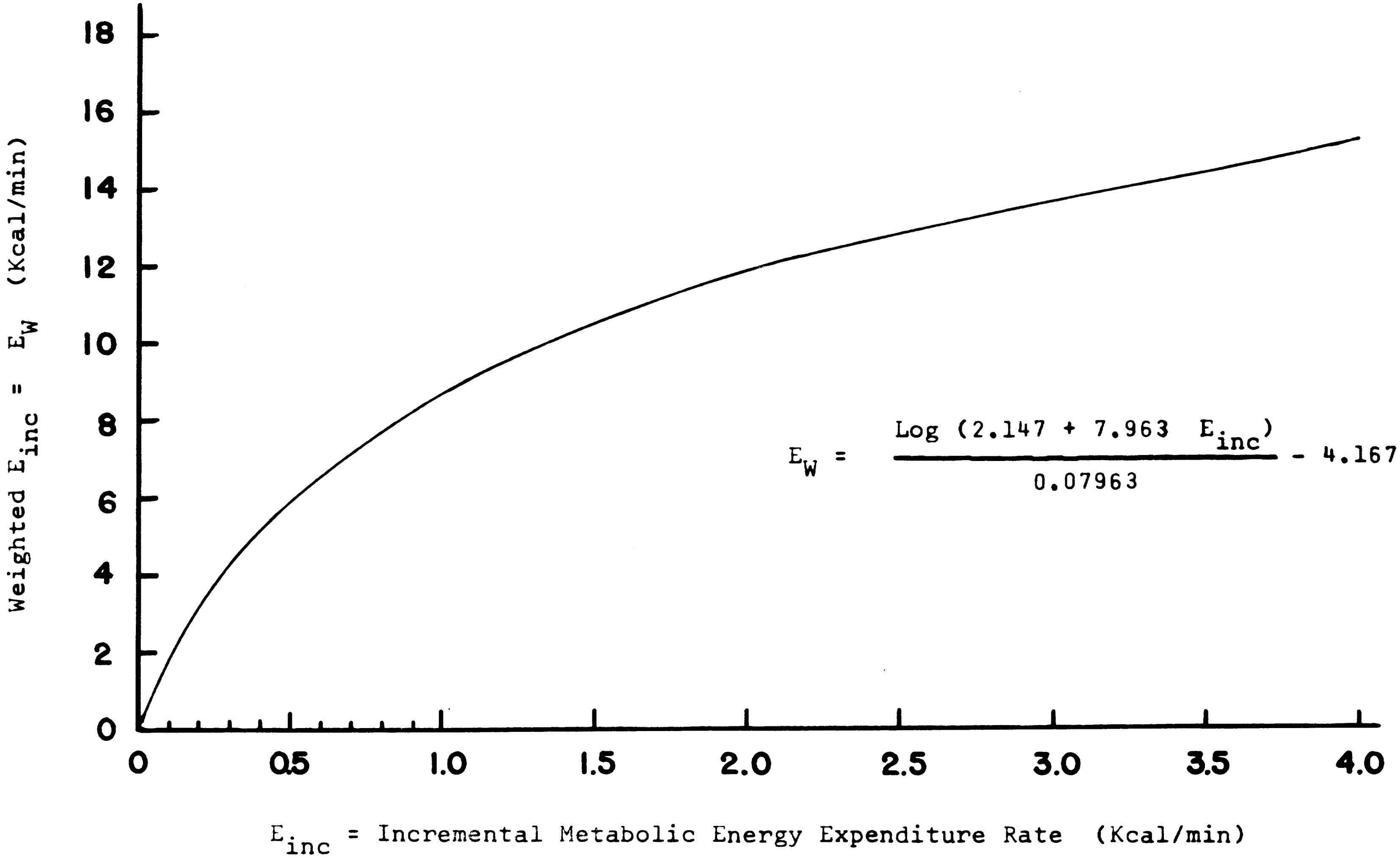

Figure 15

E_W versus E_{inc}

$$E_W = \frac{\log[2.147 + 7.963E_{inc}]}{0.07963} - 4.1673$$

2. A regression analysis was performed on the pairs of E_W and resultant torque data using the procedure of minimizing the squared deviations of the E_W observations and the predicted $\hat{E}_W$ values.

3. The predicted $\hat{E}_W$ values were then transformed to predicted $\hat{E}_{inc}$ values by the inverse of the preceding equation, which assumes $\hat{E}_{inc} = f(\hat{E}_W)$, and is:

$$\hat{E}_{inc} = \frac{\text{antilog}[0.07963(\hat{E}_W + 4.1673)] - 2.147}{7.963}$$

The majority of the analysis described in this section was in respect to step 2, above. Essentially it was concerned with deriving a regression model which accounted for the greatest amount of E_W variation for the different resultant torques and other experiment conditions.

The Selection of a Torque-E_W Regression Model. The selection of the particular form of the regression equation to be used to explain the variance in E_W with a change in the resultant torque, was based on the following conditions:

1. The expected E_{inc} values for zero torque conditions should be zero due to the method of defining E_{inc} (pages 64 and 67). This was a desirable quality due to it maintaining additivity of the torque effects for each muscle group's E_{inc}.

2. The regression equations should contain only one or two parameters due to the limited degrees of freedom available for each estimate. This restriction was also substantiated by the desire to be able to maintain an intuitive relationship between the parameters and the functional aspects as presented in the Questions of Chapter II.

3. The value of E_{inc} (and thus E_W) should continually increase with the resultant torque (page 37).

Based on the first and second conditions above, it was realized that the regression equations would need to be of a configuration which would have the estimated parameters as multipliers of the resultant torque T. The following proportionality model is an example of this:

$$E_W = aT + \sigma_{e/W} .$$

In this equation $\sigma_{e/W}$ is the standard deviation of the error between the weighted E_{inc} values E_W and the predicted weighted values based upon the estimated value of the parameter a at different torque levels T.

However, from the discussion that resulted in Question 5 (page 39) the proposition arose that E_W does not necessarily increase at a proportional rate to T, as is depicted in the preceding model. It could increase as the square of the torque, or for that matter as any power of the torque. It therefore became necessary to evaluate transformations which enabled the torque scale to increase at a rate that would be proportional to the E_W scale. In the proportionality model depicted on the preceding page, the E_W and T scales are already proportional. If however, E_W increased at some higher rate than T, a transformation of the T scale would be necessary to make the two scales proportional. A typical example of this would be the square of the torque, thus giving the following regression model:

$$E_W = a\,T^2 + \sigma_{e/W} .$$

Since the appropriate torque scale transformation was unknown, it was decided to formulate a torque-E_W regression model which contained a second parameter to indicate the magnitude of an appropriate T scale transformation. The regression model chosen for this objective was a logarithmic model of the form:

$$E_W = a\,T^b + \sigma_{e/W}$$

or

$$\log E_W = \log a + b \log T + \log \sigma_{e/W} .$$

This model was believed to have the necessary flexibility to represent the various possible types of torque-E_W relationships which could occur within the restrictions set forth by the three conditions on page 96. Figure 16

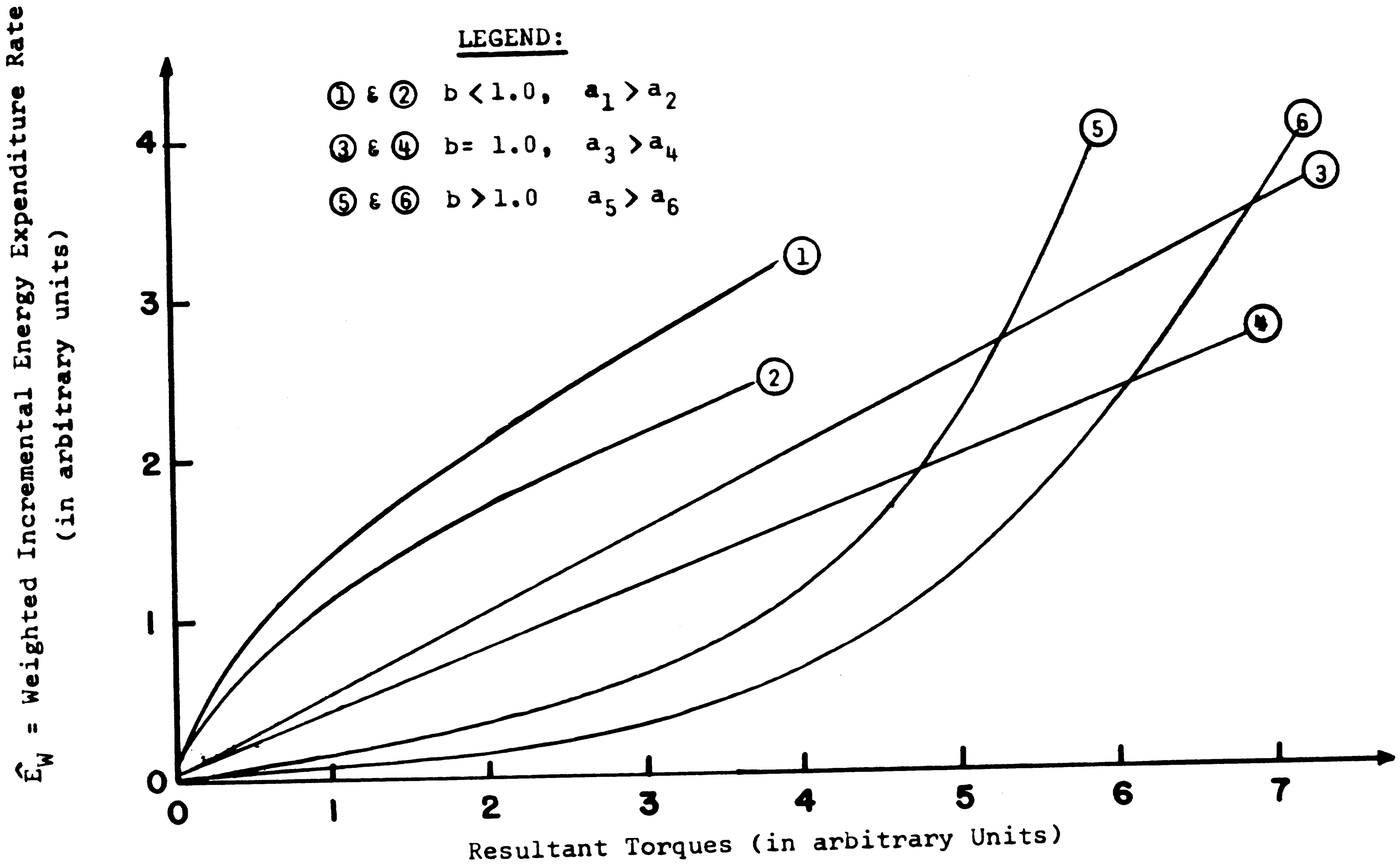

Figure 16

Graphs of $E_W = a(T)^b$

graphically represents the various types of relationships that could be modeled.

The results of Fitting the Logarithmic Model to Weighted E_{inc} Values. Table 4 on page 89 is a summary of both the experiment conditions established to determine the effects of the major factors on E_{inc}, as well as the E_{inc} values obtained from performing the designated metabolic experiments with one subject. As was discussed on pages 85 and 86, four different resultant torque levels were employed to determine the torque-E_{inc} relationship for each of the major factor experiment conditions. Therefore, for each condition four pairs of torque-E_{inc} data were available. Before performing a regression analysis on each of these sets of data, the E_{inc} values were weighted by the procedure developed on pages 92-93. The resulting weighted E_{inc} values (designeated E_W) and their corresponding resultant torques T were then used as inputs into the regression model

$$E_W = a\,T^b + \sigma_{e/W} .$$

The model was made linear by using logarithms of both E_W and T. After performing this transformation, the values of the two parameters a and b were estimated by minimizing the total squared error between the logarithmic values of the E_W data and predicted $\log(E_W)$

values from the model. The resulting a and b estimates are summarized in Table 5 on the next page.

In using this procedure, it was realized that the minimized squared error of the logarithms of E_W could result in less than minimum variance estimates of the a and b parameters, since the logarithmic transformation could destroy the normality and homogeneity of the E_W data. This however, was not considered as an important constraint. The use of the logarithmic model was intended to permit only a first approximation to the form of the final metabolic prediction model.

Two general observations were made from the results of the regression analysis using the logarithmic model. These were:

1. The logarithmic model accounted for a large amount of the change in the E_W values at the different levels of T due to the cumulative effects of: a) using a two parameter model to account for the variance in only four values of E_W, b) having the E_{inc} data weighted in such a way as to decrease the importance of the values which would tend to have a high variance, and c) employing a type of model which takes advantage of the functional definition of the dependent variable (i.e. $E_W \rightarrow 0$ when $T \rightarrow 0$).
2. The value of the b parameter did not vary greatly when the angle of each articulation was varied, but appeared to be sensitive to which muscle actions were involved.

The first observation led to the hope that a more rational model than the logarithmic model could be

Muscle Group	Action	Number Arms	Articulation Angle γ	Least Squared Error Parameter Estimates		Std. Dev. of Error $\log \sigma_{e/W}$	Percent of E_W Variance Predicted $r^2 = \left[1 - \frac{\log \sigma^2_{e/W}}{\log \sigma^2_{E/W}{}^*}\right]$
				$a \times 10^{-2}$	b		
Shoulder	Flex	One	-30°	0.01311	1.966	0.038	99.8%
"	"	"	0°	0.01060	1.991	0.082	99.6%
"	"	"	$+30^\circ$	0.00646	2.061	0.105	99.2%
"	"	"	$+60^\circ$	0.01247	1.956	0.066	99.6%
"	"	"	$+90^\circ$	0.02160	1.885	0.080	99.4%
"	"	"	$+110^\circ$	0.00527	2.152	0.070	99.6%
Shoulder	Flex	Two	0°	2.1034	0.961	0.092	97.0%
"	"	"	$+30^\circ$	1.0576	1.058	0.047	99.4%
"	"	"	$+60^\circ$	9.1036	0.747	0.007	99.8%
"	"	"	$+90^\circ$	6.3759	0.808	0.071	97.4%
"	"	"	$+110^\circ$	6.5999	0.811	0.031	99.6%
Shoulder	Extend	One	-30°	0.0000053	3.032	0.129	97.6%
"	"	"	0°	0.0001145	2.787	0.130	99.4%
"	"	"	$+30^\circ$	0.2315651	1.356	0.177	94.7%
"	"	"	$+60^\circ$	0.0798254	1.592	0.103	98.6%
"	"	"	$+90^\circ$	0.0012470	2.367	0.151	98.6%
"	"	"	$+110^\circ$	0.0001392	2.772	0.275	96.8%
Shoulder	Extend	Two	-30°	3.1744	0.925	0.099	96.4%
"	"	"	0°	1.2207	1.062	0.056	99.2%
"	"	"	$+30^\circ$	0.5316	1.171	0.043	99.6%
"	"	"	$+60^\circ$	1.0604	1.072	0.032	99.6%
"	"	"	$+90^\circ$	4.9305	0.841	0.079	97.2%
"	"	"	$+110^\circ$	2.9817	0.930	0.053	99.0%
Elbow	Flex	One	$+55^\circ$	1.1195	1.185	0.024	99.8%
"	"	"	$+80^\circ$	1.6162	1.057	0.258	95.4%
"	"	"	$+110^\circ$	0.9282	1.187	0.120	98.2%
"	"	"	$+140^\circ$	0.0617	1.710	0.048	99.4%
"	"	"	$+170^\circ$	0.8217	1.243	0.102	99.0%
Elbow	Flex	Two	$+65^\circ$	7.9385	0.767	0.064	98.6%
"	"	"	$+80^\circ$	9.3867	0.685	0.220	91.8%
"	"	"	$+110^\circ$	10.0934	0.694	0.089	96.8%
"	"	"	$+140^\circ$	14.5594	0.647	0.068	97.8%
"	"	"	$+170^\circ$	8.6916	0.748	0.119	95.2%
Wrist	Flex	One	$+180^\circ$	0.6094	1.697	0.290	96.2%
"	"	Two	$+180^\circ$	0.1344	1.920	0.252	92.3%
							avg r^2 = 97.9%

* $\log \sigma^2_{E/W}$ = log var. of E_W data about their mean.

Table 5

Estimated Parameters for Logarithmic Model of E_W Values employed as the final metabolic prediction model. The second observation resulted in the first concept employed in producing a rational prediction model. Essentially this was that the magnitude of the b parameter (which represents the degree of transformation required to make the torque scale proportional to the E_W scale) could be considered as the quantified representation of the different muscle group responses (as depicted by their E_{inc}), to relative changes in the resultant torques.[1] In other words, as the torque at any articulation increases, different muscles are recruited to assist in managing the increased load. This increased muscle involvement may not, however, result in a corresponding proportional increase in the incremental metabolic energy expenditure rate, since each additional muscle has a different mechanical advantage in creating the required reactive torque. Therefore for each different muscle group, such as the shoulder flexion group or the elbow flexion group, the value of the b parameter could be different because of anatomical differences in the muscle groups (Figures 5,6, and 7 display these differences), as well as the various ways in which the individual muscles in the group would be recruited.

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[1] The discussion of the torque effect on page 37, presents the background for this rationale.

With this rationale in mind, it was decided to consider the value of the b parameter as a constant for the different shoulder and elbow angles studied. In other words, the value of b was only dependent on which muscle group was active. The magnitudes of b were chosen as the average values (rounded to one tenth) of the b values estimated from the logarithmic model (Table 5), without regard to the articulation angles.[1] Thus by identifying the value of the b parameter with each muscle group, the a parameter (which now must be estimated with b considered as a constant) becomes indicative of the articulation angle effect on E_W. To estimate the value of a for the various articulation angles, the following model was employed:

$$E_{W_{i\gamma}} = a_{i\gamma} \; T_{i\gamma}^{\;b_i} + \sigma_{e/W_{i\gamma}}$$

where:

$E_{W_{i\gamma}}$ - weighted incremental energy expenditure per minute of resultant torque T_i (E_W transformations from page 96 with E_{inc} data from Table 4).

γ - denotes articulation angle, from smallest to largest at shoulders and elbows.

i - denotes which muscle group's action is considered:

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[1] The b parameter for the wrist flexion action is discussed later (page 123).

1 - one shoulder flexion
2 - two shoulder flexion
3 - one shoulder extension
4 - two shoulder extension
5 - one elbow flexion
6 - two elbow flexion
7 - one wrist flexion
8 - two wrist flexion

b_i - constants equal to average (rounded to one tenth) of b parameter estimates for i muscle group action (Table 5), which are:

$b_1 = 2.0$
$b_2 = 0.9$
$b_3 = 2.4$
$b_4 = 1.0$
$b_5 = 1.3$
$b_6 = 0.7$
$b_7 = 1.9$
$b_8 = 1.7$

$T_{i\gamma}$ - resultant torque at γ articulation angle of i muscle group activity, which is equivalent to (examples):

$T_{1,30}$ = One shoulder flexion torque (abrev. SFT1) designated in Kgm-cm., with the shoulder held at a 30° angle to trunk (c.c.w. = positive).

$T_{6,80}$ = Two elbow flexion torque (abrev. EFT2) with 80° angle between upper and lower arm.

$a_{i\gamma}$ - parameter to be estimated for each i muscle group and at each γ articulation angle.

$\sigma_{e/W_{i\gamma}}$ - residual error between $E_{W_{i\gamma}}$ data and predicted values at given torques for each i muscle group's action and γ articulation angle, using $a_{i\gamma}$ estimated by least squared error technique.

The least squared error estimates of $a_{i\gamma}$ and the predicted percent of E_W variance were computed for comparison to the results when both a and b were estimated in the logarithmic model (Table 5). The $a_{i\gamma}$ estimates and the variances are displayed in Table 6 on the next page.[1] Because the initial a and b estimates in Table 5 were obtained by a logarithmic transformation of the already homogeneous E_W values (page 94), a direct statistical test of whether a significant loss in precision had been made by assuming the b to remain constant for the different articulation angles was not possible. However, inspection of the percent variance accounted for by the regression indicated that the simplifying assumption of a constant b_i for different articulation angles did not substantially increase the residual error, as depicted by the average r^2 value decreasing from 97.9% to 97.0%. It was concluded that the ability to relate the parameters to the physical

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[1] Figures D-1 through D-6 display the predicted and observed E_{inc} values for these parameter estimates.

(i)	Muscle Group Actions	Articulation Angles γ (degrees)	Constant b_i	Est. of $a_{i,\gamma}$	Percent of E_W Var. Predicted by model $r^2 = \left[1 - \frac{\sigma^2_{e/W_i}}{\sigma^2_{E/W_i}}\right]$ *
1	One Shoulder Flexion	-30°	2.0	0.000108	99.8%
	" " "	0°		0.000101	99.2%
	" " "	$+30^\circ$		0.000091	98.8%
	" " "	$+60^\circ$		0.000098	99.6%
	" " "	$+90^\circ$		0.000111	98.8%
	" " "	$+110^\circ$		0.000124	99.4%
2	Two Shoulder Flexion	0°	0.9	0.0311	97.6%
	" " "	$+30^\circ$		0.0287	97.4%
	" " "	$+60^\circ$		0.0346	96.6%
	" " "	$+90^\circ$		0.0357	97.2%
	" " "	$+110^\circ$		0.0376	98.6%
3	One Shoulder Extension	-30°	2.4	0.0000114	97.2%
	" " "	0°		0.0000104	98.8%
	" " "	$+30^\circ$		0.0000059	86.3%
	" " "	$+60^\circ$		0.0000077	86.8%
	" " "	$+90^\circ$		0.0000099	97.4%
	" " "	$+110^\circ$		0.0000111	99.0%
4	Two Shoulder Extension	-30°	1.0	0.01981	98.2%
	" " "	0°		0.01812	99.0%
	" " "	$+30^\circ$		0.01571	97.6%
	" " "	$+60^\circ$		0.01675	99.2%
	" " "	$+90^\circ$		0.01818	96.8%
	" " "	$+110^\circ$		0.01924	98.8%
5	One Elbow Flexion	$+55^\circ$	1.3	0.00664	99.4%
	" " "	$+80^\circ$		0.00427	96.2%
	" " "	$+110^\circ$		0.00513	97.6%
	" " "	$+140^\circ$		0.00567	94.2%
	" " "	$+170^\circ$		0.00607	98.6%
6	Two Elbow Flexion	$+55^\circ$	0.7	0.11462	98.4%
	" " "	$+80^\circ$		0.08590	91.2%
	" " "	$+110^\circ$		0.09726	96.2%
	" " "	$+140^\circ$		0.10878	97.0%
	" " "	$+170^\circ$		0.11306	94.6%
					avg. r^2 = 97.0%

Table 6

Estimates of $a_{i\gamma}$ with b_i Constant for Angles

* σ^2_{E/W_i} = Est. var. of E_{W_i} data about their mean value.

system out weighed the loss in prediction accuracy.

The Analysis of $a_{i\gamma}$ for the Different Articulation Angles. The transformation of the torque scale T to a scale that was proportional to the E_W scale for each muscle group's action, resulted in the $a_{i\gamma}$ parameter becoming a proportionality constant between the two scales. The value of an $a_{i\gamma}$ parameter is a quantified representation of the amount of E_{inc} required of an individual to sustain a given level of torque at an articulation for a one minute period. Its dimensions would be in Kilogram-calories per Kilogram-centimeters to the b_i power per minute.[1] As long as the b_i parameter doesn't change for each i muscle group (as defined in the preceding discussion), the value of $a_{i\gamma}$ for each γ articulation angle could be compared to determine if the various angles that were studied resulted in statistically different amounts of E_W for given resultant torques.

The analysis of the possible angle effect on E_W was performed in the following manner: For each i muscle

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[1] If a broad definition of system efficiency is accepted, i.e. the output rate divided by the input rate, then the inverse of the $a_{i\gamma}$ parameter is the efficiency of the muscle systems, since it reflects the level of static torque (or a transform of it) that is maintained per minute for a specific amount of metabolic energy expended per minute.

group action the torque and E_{inc} data presented in Table 4 were pooled (i.e. no γ articulation angle stratification) and a single a_i parameter estimate was obtained by minimizing the squared deviations between the E_W data and the predicted values from the model:

$$\hat{E}_{W_i} = a_i \; T_i^{\,b_i} \; .$$

The a_i estimates from this model were then used to form the following all angle prediction equations:

For One Shoulder Flexion (i=1):

$$\hat{E}_{W_1} = 0.0001052(SFT1)^{2.0} \qquad r^2 = 95.4\%$$

For Two Shoulder Flexion (i=2):

$$\hat{E}_{W_2} = 0.03355(SFT2)^{0.9} \qquad r^2 = 86.8\%$$

For One Shoulder Extension (i=3):

$$\hat{E}_{W_3} = 0.00000946(SFT1)^{2.4} \qquad r^2 = 84.2\%$$

For Two Shoulder Extension (i=4):

$$\hat{E}_{W_4} = 0.01797(SET2)^{1.0} \qquad r^2 = 92.5\%$$

For One Elbow Flexion (i=5):

$$\hat{E}_{W_5} = 0.00507(EFT1)^{1.3} \qquad r^2 = 81.7\%$$

For Two Elbow Flexion (i=6):

$$\hat{E}_{W_6} = 0.09988(EFT2)^{0.7} \qquad r^2 = 75.8\%$$

The a_i parameter estimates were then assumed to be constant in a parameter significance test presented by Graybill (39:128-133). The null hypothesis of the test being:

Ho: The value of the $a_{i\gamma}$ parameter in each of the regression equations (for each γ articulation angle) does not vary significantly ($\alpha=0.05$) from the parameter values a_i estimated with the angle effect excluded.

An example of this parameter test follows for the two elbow flexion activity (i=6) with the elbow angle γ_e equal to 55° (data from Table 4). The null hypothesis for this example is:

Ho: $a_{6,55} = a_6 = 0.09988$ (value from above)

An analysis of variance table for the data is:

Source	D.F.	Sum of Squares	Mean Square	F_{ratio}
$a_6 = 0.09988$	4	1.771	0.443	
$a_{6,55}$	1	1.647	1.647	39.9*
error	3	0.124	0.041	

* critical $F_{\alpha=0.05} = 10.13$

Table 7

Sample A.O.V. Table for Angle Effect

As can be seen in the example, if the elbow angle is 55° it results in a significant change in the value of the a_6 parameter estimated from the regression equation fit to the all angle data. The next question is, "What about 80° or 110° elbow angle effects on a_6?" To answer this question, the data from each of the angle conditions described in Table 4 were analyzed in respect to the all angle models summarized on page 109. The results of these analyses are contained in Table 8. The conclusion drawn from these analyses was that the angle of the shoulder and elbow articulations were significant factors in the prediction of $\hat{E}_W$, and therefore the value of the a parameter should remain as a function of the articulation angle in the prediction model.

Since the preceding angle effects were established from data obtained at discrete angle conditions, a method was needed to interpolate the effects for other angle conditions. This requirement became of particular importance during the analysis of dynamic tasks (reported in Chapter VI) which required the shoulder and elbow angles to be continually changing during the experiments.

The interpolation procedure employed is based on the concept that n pairs of x, y data can be uniquely related by an n^{th} order polymonial. Thus, by pairing each of the $a_{i\gamma}$ parameter estimates with the magnitude of the γ angle at which each was obtained, a

(i)	Muscle Group Actions	Articulation Angles (γ) (degrees)	Constant b_i	Est. of a_i	Est. of a_i (page109)	F_{ratio} (Table 7)
1	One Shoulder Flexion	-30^o	2.0	0.000108	0.0001052	6.99
	" " "	0^o		0.000101		6.80
	" " "	$+30^o$		0.000091		25.76*
	" " "	$+60^o$		0.000098		14.42*
	" " "	$+90^o$		0.000111		2.89
	" " "	$+110^o$		0.000124		57.69*
2	Two Shoulder Flexion	0^o	0.9	0.0311	0.03355	8.99
	" " "	$+30^o$		0.0287		32.15*
	" " "	$+60^o$		0.0346		1.47
	" " "	$+90^o$		0.0357		6.02
	" " "	$+110^o$		0.0376		39.91*
3	One Shoulder Extension	-30^o	2.4	0.0000114	0.0000095	8.06
	" " "	0^o		0.0000104		14.06*
	" " "	$+30^o$		0.0000059		41.25*
	" " "	$+60^o$		0.0000077		6.35
	" " "	$+90^o$		0.0000099		0.65
	" " "	$+110^o$		0.0000111		11.05
4	Two Shoulder Extension	-30^o	1.0	0.01981	0.01797	17.99*
	" " "	0^o		0.01812		0.21
	" " "	$+30^o$		0.01571		22.17*
	" " "	$+60^o$		0.01675		20.21*
	" " "	$+90^o$		0.01818		0.16
	" " "	$+110^o$		0.01924		13.05*
5	One Elbow Flexion	$+55^o$	1.3	0.00664	0.00507	253.80*
	" " "	$+80^o$		0.00427		51.92*
	" " "	$+110^o$		0.00427		0.10
	" " "	$+140^o$		0.00567		2.45
	" " "	$+170^o$		0.00607		45.38*
6	Two Elbow Flexion	$+55^o$	0.7	0.11462	0.09988	39.90*
	" " "	$+80^o$		0.08590		30.28*
	" " "	$+110^o$		0.09726		0.79
	" " "	$+140^o$		0.10878		11.23
	" " "	$+170^o$		0.11306		8.96

*indicates F_{ratio} exceeds critical $F_{\alpha=0.05}(1,3)=10.13$

Table 8

ANOV of Articulation Angle Effect on $a_{i\gamma}$ Parameter polynomial was determined which would relate the value of the parameter to any given angle. An example of this procedure for the two elbow flexion activity follows. From the regression equations (Table 6), the following parameters were obtained for each of the five angles studied:

Elbow Angle (γ)	55°	80°	110°	140°	170°
parameter $a_{6,\gamma}$	0.11462	0.08590	0.09726	0.10878	0.11306

Table 9

Two Elbow Flexion Parameter a_{6,γ_e}

The fifth order polynomial that was found to describe the value of the parameter as a function of the angle is tabulated (Table 10) and is depicted in Figure 17. Table 10 presents a compilation of the polynomials for each of the regression models selected to represent the muscle actions at the shoulder and elbow articulations.[1] These polynomial equations provided the method for including the angle effect on $\hat{E}_{inc}$ into the total single subject metabolic prediction model.

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[1] These polynomials are also plotted in Figures D-8 through D-13.

i	Muscle Group Action	Polynomial Coefficients					
		Intercept C_1	C_2	C_3	C_4	C_5	C_6
1	One Shoulder Flexion	$+1.010 \cdot 10^{-4}$	$-5.653 \cdot 10^{-7}$	$+1.958 \cdot 10^{-9}$	$+3.049 \cdot 10^{-10}$	$-4.274 \cdot 10^{-12}$	$1.749 \cdot 10^{-14}$
2	Two Shoulder Flexion	$+3.111 \cdot 10^{-2}$	$-5.561 \cdot 10^{-4}$	$+2.358 \cdot 10^{-5}$	$-2.931 \cdot 10^{-7}$	$+1.179 \cdot 10^{-9}$	0
3	One Shoulder Extension	$+1.038 \cdot 10^{-5}$	$-2.230 \cdot 10^{-7}$	$-1.901 \cdot 10^{-10}$	$+1.403 \cdot 10^{-10}$	$-1.912 \cdot 10^{-12}$	$7.498 \cdot 10^{-15}$
4	Two Shoulder Extension	$+1.812 \cdot 10^{-2}$	$-1.300 \cdot 10^{-4}$	$+4.469 \cdot 10^{-7}$	$+6.513 \cdot 10^{-8}$	$-9.410 \cdot 10^{-10}$	$3.794 \cdot 10^{-12}$
5	One Elbow Flexion	$+5.344 \cdot 10^{-2}$	$-1.786 \cdot 10^{-3}$	$+2.337 \cdot 10^{-5}$	$-1.301 \cdot 10^{-7}$	$+2.636 \cdot 10^{-10}$	0
6	Two Elbow Flexion	$+6.226 \cdot 10^{-1}$	$-1.891 \cdot 10^{-2}$	$+2.379 \cdot 10^{-4}$	$-1.263 \cdot 10^{-6}$	$+2.435 \cdot 10^{-9}$	0

Above coefficients are for the polynomial equation:

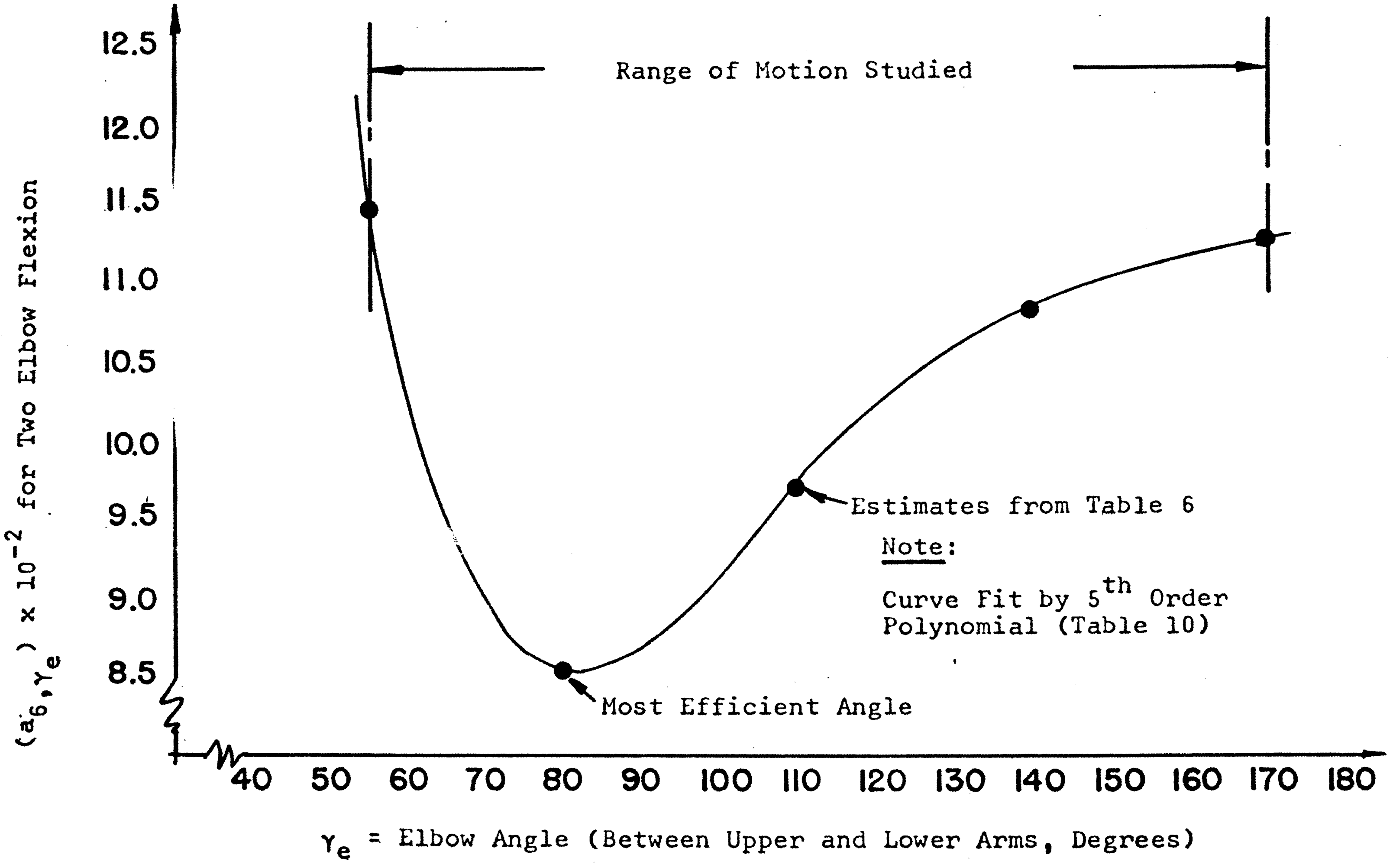
$$a_{i,\gamma} = C_1 + C_2(\gamma) + C_3(\gamma)^2 + C_4(\gamma)^3 + C_5(\gamma)^4 + C_6(\gamma)^5$$

Note:

The six polynomial equations are presented in graph form in Figures D-8 through D-13 in Appendix D.

Table 10

Angle Effects on $a_{i,\gamma}$ Parameter



Estimates from Table 6

Note:

Curve Fit by 5^{th} Order Polynomial (Table 10)

Figure 17

Angle Effect on A_{6,γ_e} Parameter in Two Elbow Flexion Model

The Analysis of One Arm versus Two Arm Actions at Each Articulation Muscle Group. The analysis of the two arm symmetric activities was based on the following hypothesis. If the muscle actions are independent in each arm, the $\hat{E}_{inc}$ predicted from the regression equation for two separate one arm actions should be equal to the $\hat{E}_{inc}$ predicted from the regression equations for two arm symmetric actions, throughout the torques studied. This infers that the forms of the regressions are also similar and thus the b parameters are equal. In other words, if a proportionality model (i.e. b=1.0) describes a two arm activity best, then it should also describe the corresponding one arm activity. Since the b parameter estimates for one and two arm activities were not similar (as displayed in the all angle regression equations on page 109), the question of whether $\hat{E}_{inc}$ for two separate one arm activities was the same as for one symmetric two arm activity, required a comparison of the predicted $\hat{E}_{inc}$ values at different resultant torques.

The first analysis performed was of the one and two shoulder flexion activities. The hypothesis tested was:

$$\hat{E}_{inc_2} = 2\left[\hat{E}_{inc_1}\right] ,$$

where the total resultant torque for the two shoulder action is assumed equally divided between each shoulder, i.e. SFT2 = 2(SFT1). With reference to the all angle regression equations presented on page 109, the above hypothesized relationship becomes:[1]

$$\hat{E}_{inc_2} = f(\hat{E}_{W_2}) = f[0.03355(SFT2)^{0.9}] = 2\left[\hat{E}_{inc_1}\right] =$$

$$2\left[f(\hat{E}_{W_1})\right] = 2\left\{f[0.000105(SFT1)^{2.0}]\right\} .$$

A graphical representation of this relationship is presented in Figure 18 (page 119). The result of this graphical analysis is that for up to 255 Kilogram-centimeters of torque on each shoulder, the one arm flexion model predicts a slightly lower $\hat{E}_{inc}$ for two separate shoulder activities. When the resultant torque is increasing above 255 Kgm-cm. for each shoulder, the two arm flexion model predicts increasingly less energy for the simultaneous shoulder actions. This latter result was expected since high torques require scapula stabilization by muscles in the upper trunk and neck. These stabilizing muscles were proposed in Question 4 (page 37) as possibly being more efficiently used if the load was balanced on both shoulders. When measuring error intervals were projected about the predicted values

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[1] From page 96, $\hat{E}_{inc} = f(\hat{E}_W) = \dfrac{\text{antilog}[0.7963(\hat{E}_W + 4.1673)] - 2.147}{7.963}$

which is graphically presented in Figure 15, page 95

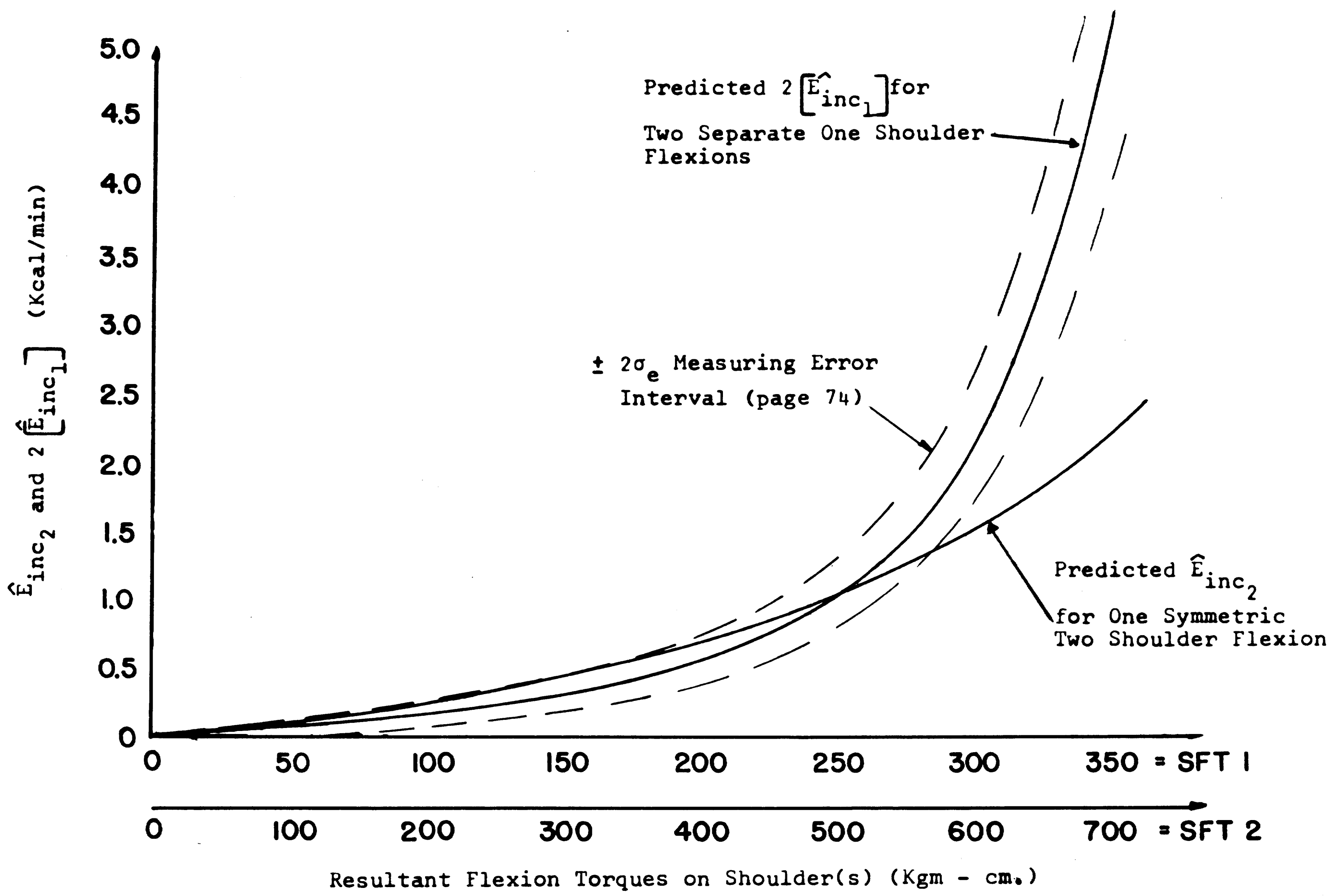

Figure 18

$\hat{E}_{inc_2}$ versus $2\left[\hat{E}_{inc_1}\right]$

for the one shoulder flexion, it was seen that at the higher torques the difference between the $\hat{E}_{inc}$ values for two separate shoulder flexions and one simultaneous flexion becomes significant.[1] From this graphical analysis it was concluded that separate functions should be retained to predict $\hat{E}_{inc}$ for each type of activity.

A similar analysis of the one and two shoulder extension activities was performed. The all angle regression equations from page 109 produce the following hypothesized equality:

$$\hat{E}_{inc_4} = f\left[\hat{E}_{W_4}\right] = f[0.01797(SET2)^{1.0}] = 2\left[\hat{E}_{inc_3}\right] =$$

$$2\left\{f\left[\hat{E}_{W_3}\right]\right\} = 2\{f[0.00000946(SET1)^{2.4}]$$

where again it is assumed that SET2 = 2(SET1). The results of these relationships are graphically displayed in Figure 19. This analysis disclosed that at higher torques the simultaneous two shoulder extension activity predicted less E_{inc} than if the same torque was divided in half and performed by two separate one shoulder

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[1] Using the measuring error interval for the comparison assumes that the average value of E_{inc} is $\hat{E}_{inc}$. Because of the high correlations, Table 6, this did not appear to be a serious assumption.

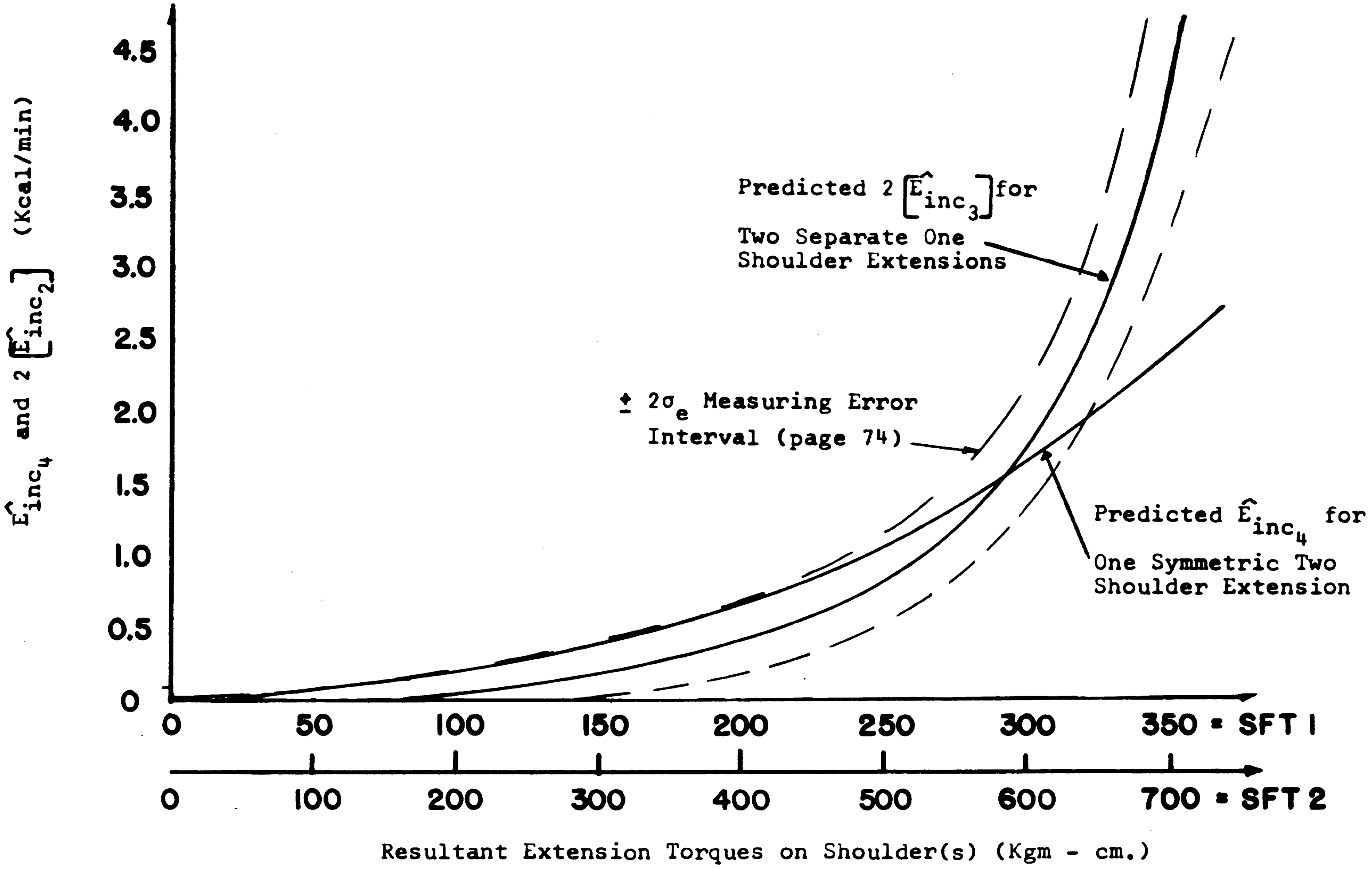

Figure 19

$\hat{E}_{inc_4}$ versus $2\left[\hat{E}_{inc_3}\right]$

activities. From this it was concluded that two separate expressions should be retained to predict $\hat{E}_{inc_3}$ and $\hat{E}_{inc_4}$.

The $\hat{E}_{inc}$ values for one elbow and two elbow flexion activities were compared in a manner similar to the preceding shoulder analysis. The hypothesized equality for this analysis is:

$$\hat{E}_{inc_6} = 2\left[\hat{E}_{inc_5}\right]$$

$$\hat{E}_{inc_6} = f\left[\hat{E}_{W_6}\right] = f[0.09988(EFT2)^{0.7}] = 2\left[\hat{E}_{inc_5}\right] =$$

$$2f\left[\hat{E}_{W_5}\right] = 2\left\{f[0.00507(EFT1)^{1.3}]\right\}$$

The results of the comparison of the predicted $\hat{E}_{inc}$ values for both types of activities are presented in Figure 20. As is depicted, the $\hat{E}_{inc}$ required to perform two separate one elbow flexions is greater than the $\hat{E}_{inc}$ to perform a simultaneous two elbow flexion at higher resultant torques. A rationale for this result which is based on the discussion of <u>muscle</u> recruitment and <u>mechanics</u> in Chapter II, follows: Basmajian reports that at higher flexion loads the biceps became assistors in elbow flexion, thus also applying a flexion torque on the shoulder (page 39). Since two separate one shoulder flexions have already been shown to require a greater E_{inc} than a symmetric

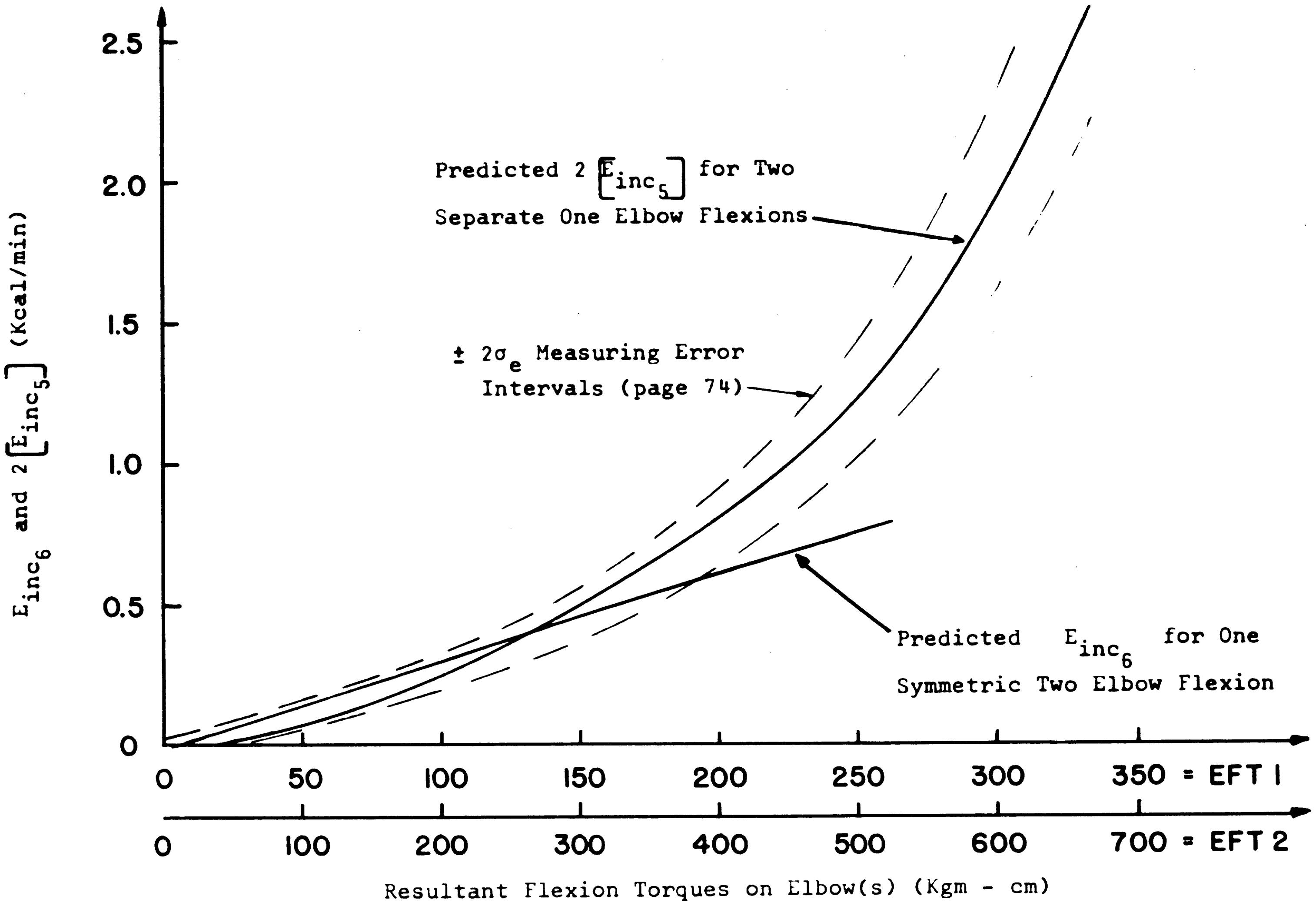

Figure 20

$\hat{E}_{inc_6}$ versus $2\left[\hat{E}_{inc_5}\right]$

two shoulder flexion (page 117), it was conjectured that the resulting imbalance in the shoulder loading during the one elbow flexions could account for the higher E_{inc} values in these types of activities. Because of these results the two different types of expressions (Table 6) were maintained to predict E_{inc} for the one elbow and two elbow flexion activities.

The wrist flexion activities were next analyzed. The parameters presented in Table 5, page 102, were used to predict the two $\hat{E}_{inc}$ values to be compared. These equations form the basis for the following hypothetical equality which was analyzed:

$$\hat{E}_{inc_8} = 2\left[\hat{E}_{inc_7}\right]$$

which became:

$$\hat{E}_{inc_8} = f\left[\hat{E}_{W_8}\right] = f[0.1344(WFT2)^{1.9}] = 2\left[\hat{E}_{inc_7}\right] =$$

$$2\left\{f\left[\hat{E}_{W_7}\right]\right\} = 2\left\{f[0.6094(WFT1)^{1.7}]\right\} .$$

These left and right hand expressions were graphically compared in Figure 21. It was concluded from the results of this comparison that the $\hat{E}_{inc}$ for two separate one wrist flexions was not significantly different from the $\hat{E}_{inc}$ for a symmetric two wrist flexion. This result was expected, since the muscles that flex one wrist are mechanically remote from the same muscles in the opposite

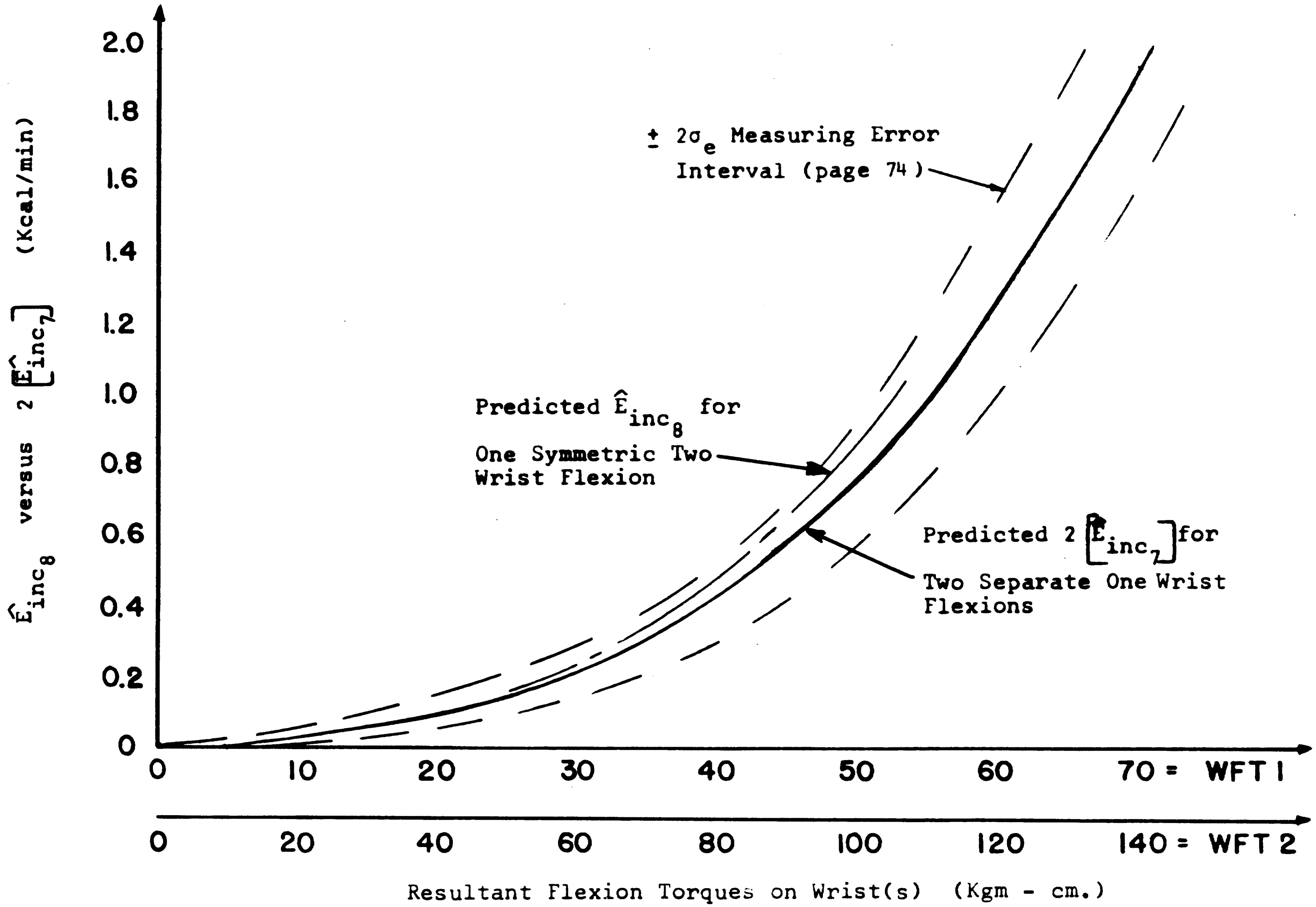

Figure 21

$\hat{E}_{inc_8}$ versus $2\left[\hat{E}_{inc_7}\right]$

arm.

It was therefore decided that a single prediction equation could be employed for both one wrist and two symmetric wrist flexions. The a parameter in this wrist flexion equation was developed by pooling the E_{inc} values for the two types of wrist flexion activities presented in Table 4, pages 89 thru 90 . The equation resulting from the pooled data (which is expressed in terms of the $\hat{E}_{inc}$ predicted for one wrist) is:

$$\hat{E}_{inc_7} = f\left[\hat{E}_{W_7}\right] = f[0.00417(WFT1)^{1.8}]$$

This equation becomes a prediction equation for a symmetric two wrist flexion by simply doubling the predicted value of $\hat{E}_{inc}$ for each wrist's action. In other words, the two wrist flexion prediction is:

$$\hat{E}_{inc_8} = 2\left[E_{inc_7}\right] = 2\left\{f\left[0.00417\left(\frac{WFT2}{2}\right)^{1.8}\right]\right\} ,$$

and the coefficient 0.00417 is constant for both types of actions. This will be designated as a_7 or a_8, depending on which type of action is being considered.

Summary of Results of the Effects of the Major Factors

This section has reported the effects of the following major factors on a torque-E_{inc} relationship:

1. Which particular muscle group was active
2. Which angle was maintained at the shoulder or elbow during the activity.

The analysis of the results disclosed the following:

1. The weighted E_{inc} values E_W could be predicted by the formulation

   $$\hat{E}_W = a\,T^b \quad .$$

   The parameters a and b can be functionally related to the skeletal muscle system as follows:[1]

   b - defines the manner in which a muscle group metabolically responds to a change in torque (page 103).

   a - defines the effect on the metabolism of a muscle group when the angle at the elbow or shoulder changes for a given resultant torque (page 108). It is the proportionality coefficient between E_W and the resultant torque at an articulation.

2. The effect of changing the angle of the shoulder or elbow on the value of the a parameter is statistically significant (page 111).

3. The use of both shoulders performing a flexion or extension, or both elbows performing a flexion, requires less E_{inc} for high torques than if the resultant torque was divided into half and sustained by two separate one arm actions (pages 116-123).

4. The $\hat{E}_{inc}$ predicted for a single wrist flexion is equal to half of the $\hat{E}_{inc}$ predicted when both wrists were flexed with the same torque at each wrist (page 125).

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[1] The b parameter values are presented in Table 6, and a parameters are predicted by the polynomial equations in Table 10, or by the graphs, Figures D-8 through D-13.

The Effects of Adjacent Articulation Conditions

Since there are very few actions of the arms which involve just the muscles of one articulation, it becomes of practical importance to define the interaction effects on $\hat{E}_{inc}$ due to simultaneous actions at adjacent articulations. Already the analysis of one and two symmetric shoulder actions has disclosed that the effects of the muscles involved at these two laterally adjacent articulations can not be considered to be additive. Also, the problem of additivity of the effects due to elbow muscle actions appears to be related to whether shoulder and elbow flexion muscle actions interact, as proposed in Question 7 (page 41).

Specifically, two types of interaction effects were foreseen as possibly being able to alter the additivity of the major factor effects defined in the preceding section. Both of the types of interaction effects foreseen were based on the concept that describes the action of muscles that span two articulations, as discussed on pages 40 and 41. The possible effects on $\hat{E}_{inc}$ due to these types of muscles were:

1. The two articulation spanning muscles's ability to create tension, for a given level of E_{inc}, is altered by its length (discussed on page 48) which in turn is dependent on the angle of both articulations.

2. The two articulation spanning muscles can produce compatible or incompatible reactive torques at both articulations bridged by the muscle, thus possibly reducing or increasing the $\hat{E}_{inc}$ predicted for each articulation when considered as acting separately.

The Adjacent Articulation Interaction Experiments

The concepts presented in the preceding discussion were the basis for two types of experiments. The objectives of these experiments were to determine the effects on $\hat{E}_{inc}$ of: 1) the angle of an articulation that is adjacent to one that is sustaining a resultant torque, and 2) the combination of different resultant torques at two adjacent articulations.

The Adjacent Articulation Angle Effect. Each of the preceding reported experiments of the effects of the major factors on E_{inc} were performed on one articulation muscle group with the adjacent articulation angle held constant. For example, during all of the shoulder studies, the elbow angle was maintained at 140 degrees. For the elbow experiments, the shoulder angle was fixed at zero degrees (i.e. the upper arm longitudinal axis was in line with the trunk axis). The wrist studies were performed with the elbow at an 80° angle. The effect of this type of constraint on the generality of the preceding results was determined by performing 28 additional experiments. In these studies the primary articulation angle (i.e. the articulation that was incurring a resultant torque) was held constant while the adjacent articulation angle was altered. The conditions and results of the experiments are presented in Table 11.

An analysis of variance was performed to determine if changing the adjacent articulation angle would significantly raise or lower the value of E_{inc} for the four resultant torques employed at the primary articulation. The statistical two way analysis of variance model that was used is(43:46-49):

$$E_{W_{ij}} = \mu + T_i + A_j + \sigma_{ij}$$

The variables are:

$E_{W_{ij}}$ - Observed weighted incremental metabolic energy expenditure rate at i resultant torque and j adjacent articulation in Table 11.

μ - Average E_W for all i and j conditions studied

T_i - Resultant torque exerted at primary articulation (four levels employed)

A_j - Angle of adjacent articulation (two levels employed)

σ_{ij} - Residual error of E_W after variations which were consistent with resultant torques and adjacent angles were

Study No.	Action at Primary Articulation	Primary Art. Angle(γ)	Adjacent Art. Angle(A_j)	(T_i)=Torque at Primary Articulation(Kgm-cm.)				($E_{inc_{ij}}$)-Response to Torque(Kcal/min.)			
1	shoulder flexion	0°	80°	140	210	280	350	0.06	0.21	0.91	2.55
			140°	140	210	280	350	0.12	0.33	0.89	2.30
2	shoulder flexion	60°	80°	140	210	280	350	0.05	0.25	0.75	2.52
			140°	140	210	280	350	0.12	0.32	0.76	2.31
3	shoulder extension	0°	80°	140	210	280	350	0.12	0.17	0.99	2.51
			140°	140	210	280	350	0.06	0.22	0.86	2.80
4	shoulder extension	60°	80°	140	210	280	350	0.07	0.21	0.68	1.02
			140°	140	210	280	350	0.13	0.26	0.65	1.10
5	elbow flexion	80°	0°	75	200	250	325	0.10	0.30	0.52	0.85
			60°	75	200	250	325	0.10	0.24	0.60	1.25
6	elbow flexion	140°	0°	75	125	200	250	0.09	0.15	0.42	0.90
			60°	75	125	200	250	0.05	0.12	0.51	1.11
7	wrist flexion	180°	80°	20	40	55	70	0.05	0.25	0.42	0.98
			140°	20	40	55	70	0.11	0.30	0.38	0.92

Table 11

Adjacent Articulation Angle Experiment Conditions and Results removed.[1]

The hypothesis of main concern was:

Ho: The E_W (and thus E_{inc}) values are not different ($\alpha=0.05$) for each of the two different adjacent articulation angles j, within the conditions of the experiments described in Table 11.

The analysis of variance results are summarized in Table 12. From these results, it was concluded that changes in the adjacent articulation angles do not exert a large enough effect on E_{inc} to be statistically significant. Therefore, this effect was not included in the final metabolic prediction model for static tasks.

The adjacent Articulation Torque Interaction Effect. This section presents the experiments (and results) that were performed to estimate the extent of variation in E_{inc} values when a task involves the use of muscle groups that heretofore have been considered in only independent actions. The experiments were performed due to Question 7 in Chapter II, which presents

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[1] The residual error contains both measurement error and a possible torque-adjacent angle interaction effect on E_W. Replication was not attempted to separate these two sources of error since it was disclosed earlier (page 106 that the major part of the E_W variation was predicted by a model that did not contain an interaction between the torque level and primary articulation angle. Thus the torque-adjacent angle interaction effect was assumed to be small.

Study No. (Table 11)	Source of Variance	Variance Estimate	F_{ratio} of Angle Effect
1	Torque (T_i) Angle (A_j) Residual Error	4.25 0.13 0.073	1.78
2	Torque (T_i) Angle (A_j) Residual Error	4.26 0.140 0.093	1.51
3	Torque (T_i) Angle (A_j) Residual Error	4.77 0.030 0.087	0.34
4	Torque (T_i) Angle (A_j) Residual Error	2.09 0.010 0.013	0.77
5	Torque (T_i) Angle (A_j) Residual Error	2.30 0.010 0.047	0.213
6	Torque (T_i) Angle (A_j) Residual Error	2.40 0.180 0.197	0.915
7	Torque (T_i) Angle (A_j) Residual Error	2.25 0.080 0.083	0.964

Critical $F_{\alpha=0.05}$ (1,3) = 7.81

Conclusion: Null hypothesis that Adjacent Articulation Angle Effect is Insignificant is not rejected.

Table 12

Analysis of Variance Table of Adjacent Articulation Angle Effects the possible effects of two articulation spanning muscles (page 40).

The empirically developed $\hat{E}_{inc}$ prediction equations for muscle actions at each articulation (i.e. values obtained from predicted $\hat{E}_W$ values by using Table 6 parameters) were used as a basis for comparison in the experiments.[1] As an example, using the combined one arm shoulder and elbow flexions, the comparison is:

$$E_{inc_{1,5}} = \hat{E}_{inc_1} + \hat{E}_{inc_5} + E_{inc_{15}}$$

The variables are:

$E_{inc_{1,5}}$ - the E_{inc} value observed when both the shoulder and elbow of one arm are flexed simultaneously at given shoulder and elbow angles (i.e. γ_s and γ_e and resultant torques (SET1 and EFT1).

$\hat{E}_{inc_1}$ - the predicted $\hat{E}_{inc}$ value from the transformation (page 96) of $\left[\hat{E}_{W_1} = a_{1,\gamma_s} (\mathrm{SFT1})^{2.0}\right]$, for given shoulder angle γ_s and resultant torque SFT1 , with a_{1,γ_s} value from Table 10.

---

[1] A multiple analysis of variance was not possible due to the proposed additivity of E_{inc} values at each articulation not having a constant variance. When transformed to E_W values the homogeneity was achieved, but his transformation was non-linear. Thus, the E_W values at each articulation were not expected to be additive.

E_{inc_5} - the predicted $\hat{E}_{inc}$ value from the transformation of

$$\left[\hat{E}_{W_5} = a_{5,\gamma_e} \, (EFT1)^{1.3}\right], \text{ for given}$$

elbow angle γ_e, and resultant torque EFT1, with a_{5,γ_e} value from Table 10.

$E_{inc_{15}}$ - the E_{inc} difference to be estimated between the sum of the predicted $\hat{E}_{inc}$ values for the shoulder and elbow flexion when considered as acting independently, and the observed E_{inc} when the shoulder and elbow are flexed simultaneously.

By rearranging the preceding equality, the interaction energy term $E_{inc_{15}}$ could be estimated when various levels of $E_{inc_{1,5}}$ were determined by experiments. In other words:

$$E_{inc_{15}} = E_{inc_{1,5}} - \left[\hat{E}_{inc_1} + \hat{E}_{inc_5}\right]$$

With reference to the scope of this project, the possible interaction of three types of muscle actions were defined for study. These were:

1. Both the shoulder and elbow were flexing.
2. The shoulder was extending while the elbow was flexing.
3. The elbow and the wrist were flexing.

Because the angle effect on E_{inc} was found to be significant at both the shoulder and elbow (Table 8), all of the above types of muscle actions involving one arm were performed with each articulation set at two different angles. By including this condition, the angle effect on the E_{inc} due to the hypothesized muscle interaction was balanced.

The resultant torques at the two articulations were established in a $(2)^2$ factorial experiment design. Graphically, the design is depicted in Figure 22 (43:96):

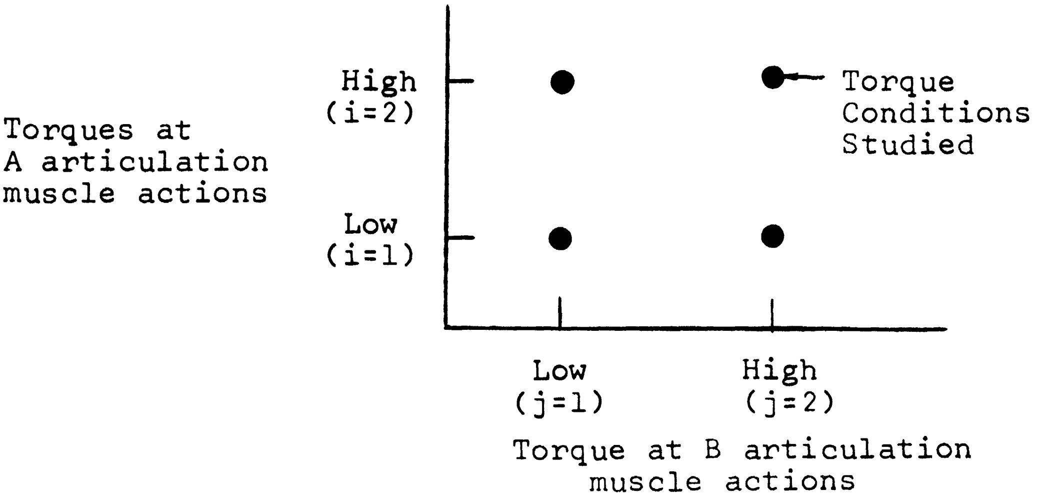


Figure 22 $(2)^2$ Torque Interaction Experiment Design

The experiment conditions, and the E_{inc} response of one subject to the conditions, are displayed in Table 13 on the next page.

The analysis of the torque interaction effect was accomplished by first computing the difference in the E_{inc} values presented in Table 13, and the sum of the $\hat{E}_{inc}$ values predicted for the two active articulation muscle

Studies to Determine the Change in E_{inc} for Various Angles and Torque Levels at Two Adjacent Articulation									$E_{inc_{A,B}}$ Response for T_A and T_B Torques Displayed in Adjacent Columns			
Number Arms	k	Shoulder Angle(γ_s)	Elbow Angle(γ_e)	Sight and Direction of Activity	T_A and T_B Torques in (Kgm-cm.)				(Kcal/min.)			
One	1	0°	140°	Shoulder - Flexion(A) Elbow - Flexion(B)	140 50	350 162.5	350 50	140 162.5	0.22	2.76	2.39	0.44
	2	0°	80°		140 87.5	350 162.5	350 87.5	140 162.5	0.19	2.62	2.36	0.44
	3	60°	140°		140 50	350 162.5	350 50	140 162.5	0.12	2.45	2.12	0.36
	4	60°	80°		140 87.5	350 162.5	350 87.5	140 162.5	0.10	2.24	2.16	0.33
	1	0°	140°	Shoulder - Extension(A) Elbow - Flexion(B)	140 50	350 162.5	350 50	140 162.5	0.17	2.76	2.50	0.34
	2	0°	80°		140 87.5	350 162.5	350 87.5	140 162.5	0.15	2.76	2.36	0.30
	3	60°	140°		140 50	280 162.5	280 50	140 162.5	0.13	0.85	0.78	0.43
	4	60°	80°		140 87.5	350 162.5	350 87.5	140 162.5	0.24	1.55	1.21	0.42
		Elbow Angle(γ_e)	Wrist Angle									
	1	80°	180°	Elbow - Flexion(A) Wrist - Flexion(B)	175 40	250 70	250 40	175 70	0.58	1.22	0.65	0.92
	2	140°	180°		50 20	162.5 42.5	162.5 20	50 42.5	0.07	0.77	0.26	0.44
		Shoulder Angle(γ_s)	**Elbow Angle(γ_e)**		Combined Torques for Both Arms (Kgm-cm.)							
Two	1	0°	80°	Shoulder - Flexion(A) Elbow - Flexion(B)	280 175	700 325	700 175	280 325	0.48	1.97	1.82	0.61
	2	0°	80°	Shoulder - Extension(A) Elbow - Flexion(B)	280 175	700 325	700 175	280 325	0.65	2.81	2.62	0.84
		Elbow Angle(γ_s)	Wrist Angle									
	1	80°	180°	Elbow - Flexion(A) Wrist - Flexion(B)	175 40	325 85	325 40	175 85	0.24	0.74	0.32	0.64

Table 13

Torque Interaction Experiment Design and E Values groups. This is represented as:

$$E_{inc_{AB}} = E_{inc_{A,B}} - \left[\hat{E}_{inc_A} + \hat{E}_{inc_B}\right]$$

where the A and B subscripts indicate which two articulation muscle actions are being considered (A and B values are the same as i explained on page 104). Since there was no prior knowledge of how the interaction of two different adjacent articulation torques could effect $E_{inc_{AB}}$, a cross product of the two torques was used. Thus, for the various torques T_A and T_B designated in Table 13, the interaction effect $E_{inc_{AB}}$ was estimated by minimizing the squared differences in the following:

$$Q = \sum_{\ell=1}^{n} \sum_{i=1}^{2} \sum_{j=1}^{2} \left[E_{inc_{AB_{ij\ell}}} - e_{AB}(T_{A_{i\ell}} T_{B_{j\ell}})\right]^2$$

where ℓ represents the particular articulation angle configuration studied (Table 13), and i and j designate the specific torques for which $E_{inc_{AB}}$ values were computed. The e_{AB} parameter is estimated by differentiating the above equation in respect to e_{AB}, which gives:

$$e_{AB} = \frac{\sum_{\ell=1}^{n} \sum_{i=1}^{2} \sum_{j=1}^{2} \left[(T_{A_{i\ell}} T_{B_{j\ell}})(E_{inc_{AB_{ij\ell}}})\right]}{\sum_{\ell=1}^{n} \sum_{i=1}^{2} \sum_{j=1}^{2} \left[(T_{A_{i\ell}} T_{B_{j\ell}})^2\right]}$$

The resulting estimates of e_{AB} are summarized in Table 14 on the next page. Since the e_{AB} parameter was estimated for various torque and angle combinations, its value represents the average effect for the three types of torque interactions studied in this research project.

From inspection of the values of the e_{AB} parameter, the following conclusions were made:

1. When two adjacent articulations are sustaining simultaneous resultant torques, the total E_{inc} is less than if the resultant torques are sustained in two separate actions,(as displayed by consistent negative values of e_{AB} in Table 14). For the compatible torque conditions this could be explained by the existence of the two articulation spanning muscles. But since incompatible torques (i.e. shoulder extension-elbow flexion) also resulted in a decrease in the total E_{inc}, some other mechanism appears to be acting to result in the E_{inc} conservation. Perhaps the two articulation actions are closer to "normal" everyday actions, which results in the recruitment of more efficient muscle groups.

2. The elbow-wrist simultaneous flexion actions result in the greatest conservation of energy, (approximately 10 times greater than the shoulder-elbow flexion). The simultaneous shoulder extension-elbow flexion actions result in the least energy conservation (approximately five times less savings than in the more compatible torque situation where the shoulder and elbow are both flexing simultaneously).

Since the torque interaction effect was related to the cross product of two resultant torques, its effect on the total E_{inc} for a given activity has to be analyzed in terms of the magnitudes of both torques. This is

Number Arms	Muscle Actions Studied	Torque Interaction Parameter Estimate e_{AB}
one	Shoulder Flexion(A) Elbow Flexion(B)	-1.162×10^{-6}
one	Shoulder Extension(A) Elbow Flexion(B)	-2.254×10^{-7}
one	Elbow Flexion(A) Wrist Flexion(B)	-1.6556×10^{-5}
two	Shoulder Flexion(A) Elbow Flexion(B)	-1.606×10^{-6}
two	Shoulder Extension(A) Elbow Flexion(B)	-3.040×10^{-7}
two	Elbow Flexion(A) Wrist Flexion(B)	-1.089×10^{-5}

Torque interaction parameter estimates from experiments and data in Table 13.

Table 14

<u>Torque Interaction Estimates for e_{AB}</u>

done graphically in Figure 23 on the next page.

Because there appeared to be a consistent conservation of energy in all of the muscle actions studied (this is depicted by the negative e_{AB} parameter estimates in Table 14), exclusion of the effect from the final prediction model was not justified. In other words, the torque interaction effect could not be contributed to a random error. Therefore, exclusion of the torque interaction effect from the final prediction model would introduce a constant bias of the $\hat{E}_{inc}$ predictions towards higher values of E_{inc} than actually exist.

The Single Subject Metabolic Energy Prediction Model for Static Activities

This section combines the effects on $\hat{E}_{inc}$ (due to the major factors and torque interactions) into a single subject metablic energy prediction model. The model is used to predict the $\hat{E}_{inc}$ of the subject performing weight holding tasks which involved the whole arm or arms.

The Single Subject Prediction of $\hat{E}_{inc}$ for Static Tasks

The results of the experiments pertaining to the major factors disclosed that three types of information were required to predict the $\hat{E}_{inc}$ for a particular muscle

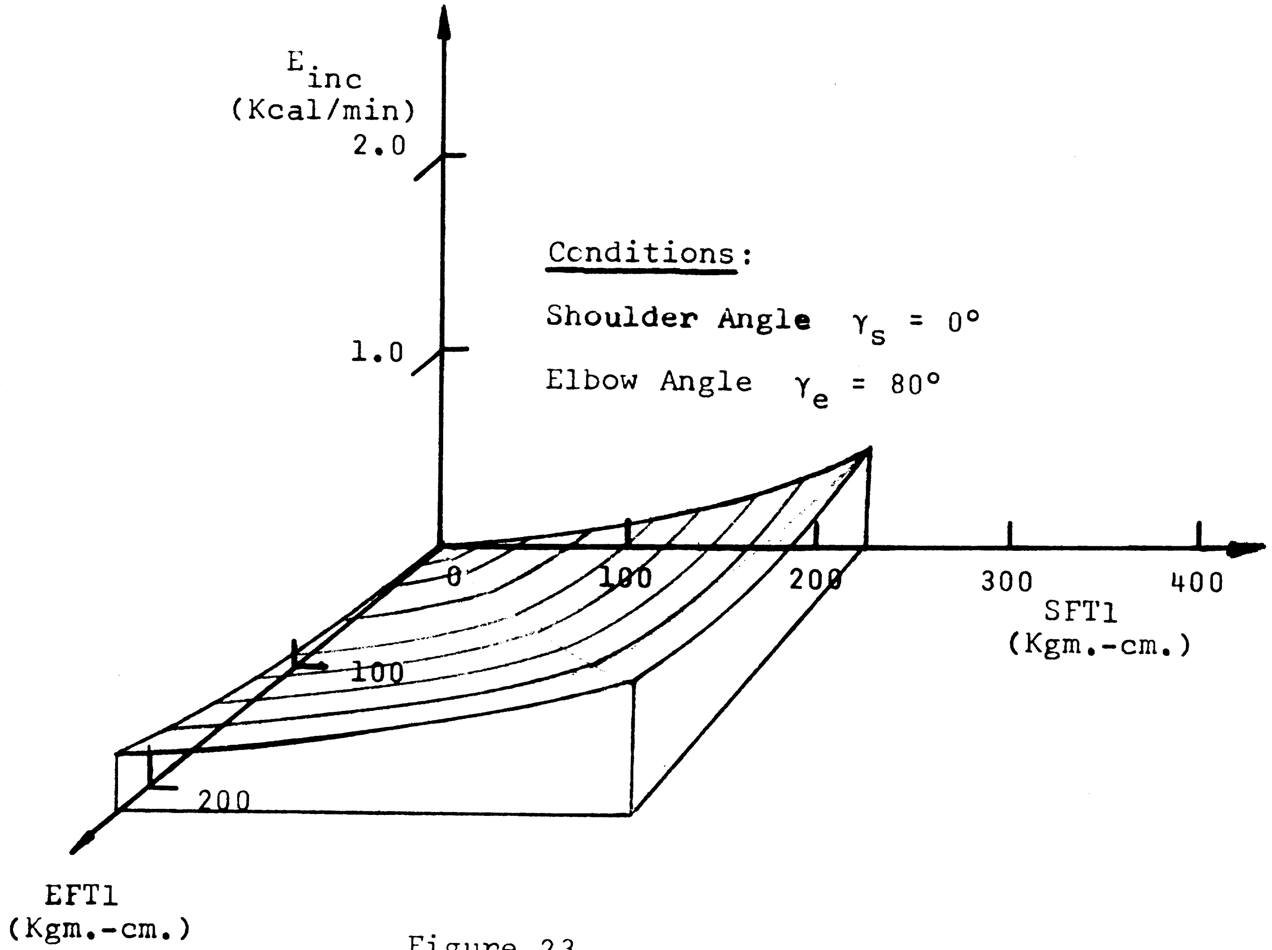


Figure 23

Shoulder - Elbow Flexion Interaction Effect group's action. These were:

1. whether one or both arms were involved in the task.
2. the magnitude and direction of the resultant torque at each articulation
3. the angle of the shoulder and elbow articulations.

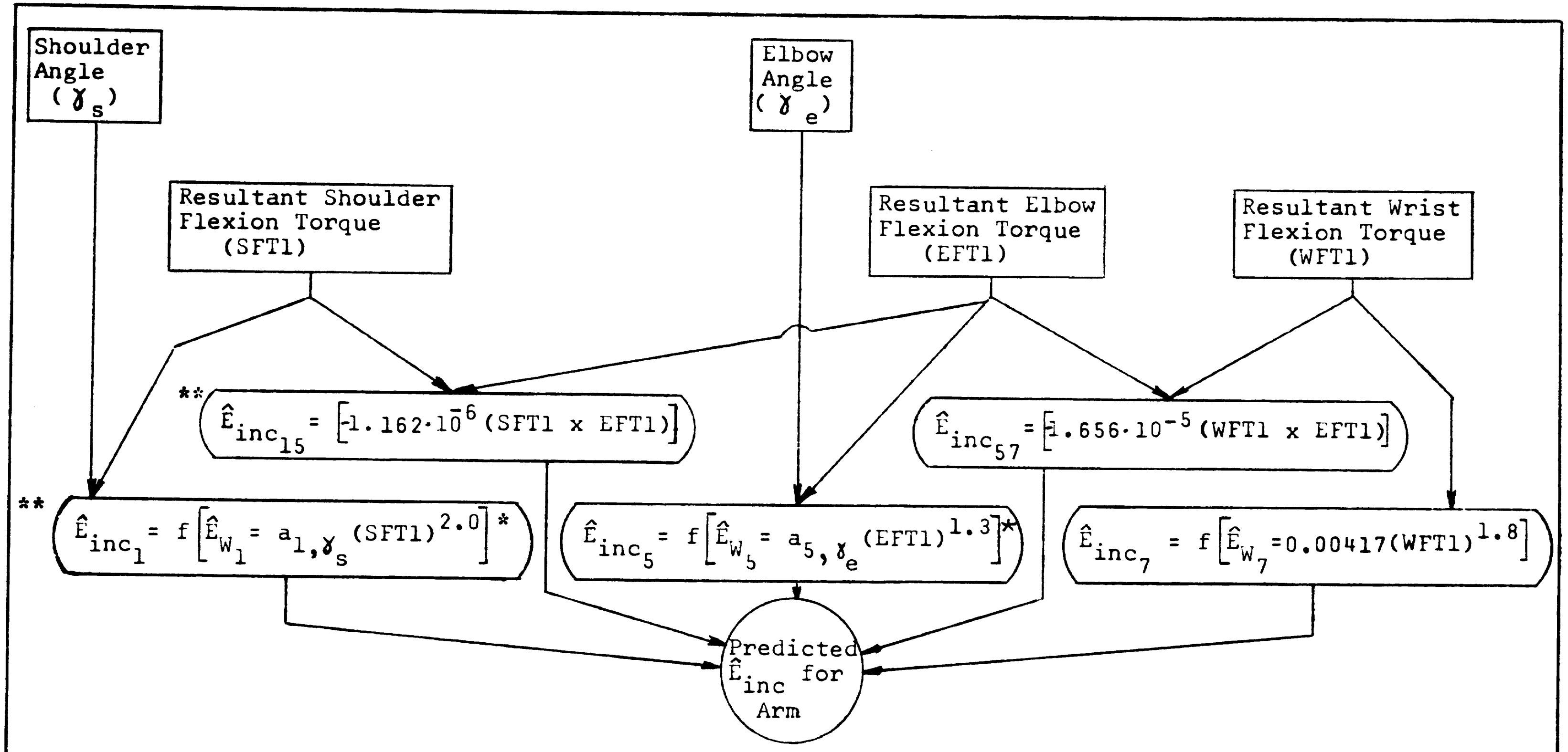
The result of the torque interaction analysis was that the torques at adjacent articulations had to be combined to predict an interaction effect on $\hat{E}_{inc}$.

The consolidation of these effects on $\hat{E}_{inc}$ resulted in the metabolic energy expenditure rate prediction model depicted in Figure 24. The input resultant torques and articulation angles in this model were obtained by the algorithm outlined in Appendix A, and schematically represented in Figure 3, page 27.

The Validation of the Single Subject E_{inc} Prediction Model for Static Tasks

To estimate the prediction accuracy of the Single Subject Model, a series of weight holding activities were performed by the same subject used in the preceding experiments. The three variables manipulated in the experiments were:

1. the involvement of one or both arms in the task



* Parameter (a) values given by computations in Table 10, or in Graphs (Figures D-8 to D-13).

** During shoulder extension these equations change as indicated in Tables 6 and 14.

Legend:

▭ - represents input value

▢ - represents prediction equation

○ - represents output prediction

Note: The two arm E_{inc} prediction model changes, as indicated in Tables 6 and 14, and Page 125.

Figure 24

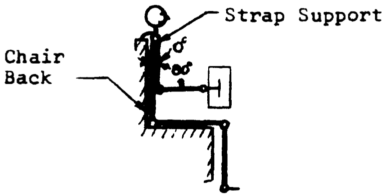
The Single Subject E_{inc} Prediction Model for One Arm Static Activities

2. the position of the arm(s)
3. the weight of an object held in the hand(s).

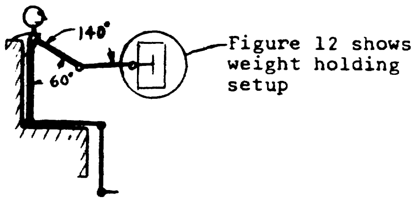
All of the studies were replicated to obtain an estimate of the variation in E_{inc} for each test condition. The specific test conditions employed were selected to study the prediction model under what was judged to be relatively "typical" weight holding conditions, but ones which also had significant differences in the articulation angles and resultant torques. The experiment conditions and resulting E_{inc} observations are depicted in Table 15, with the resultant torques computed by the algorithm presented in Appendix A.

The $\hat{E}_{inc}$ for each of the validation studies in Table 15 was predicted with reference to the prediction model presented in Figure 24. The predicted values are displayed in Table 16. Because the observed E_{inc} values were found to not have the homogeneity required to make a direct comparison of the accuracy of the prediction model, both the actual and predicted values were transformed to E_W values in order to create the required homogeneity for the analysis. A linear regression analysis was then performed on the transformed variables by seeking the least squared error between the observed E_{inc} and the predictions from the following model:

$$E_{W_i} = d(\hat{E}_{W_i}) + \sigma_{e/a}$$



Position A



Position B

Position of arms	Number of arms	Weight held (pounds)	Shoulder Flexion Total Torque (Kgm-cm)	Elbow Flexion Total Torque (Kgm-cm)	Wrist Flexion Total Torque (Kgm-cm)	E_{inc} Values for Conditions in Adjacent Columns			Task No.
						(Kcal/min) First Study	(Kcal/min) Second Study	(Kcal/min) Average	
A ↓	one ↓	5	110	110	21	0.21	0.27	0.240	1
		10	189	189	38	0.75	0.45	0.600	2
		15	268	268	55	1.41	1.78	1.595	3
		20	347	347	72	3.38	2.73	3.055	4
B ↓		5	238	110	21	0.64	0.48	0.560	5
		10	378	189	38	3.09	3.51	3.300	6
A ↓	two ↓	10	219	219	41	0.40	0.52	0.460	7
		20	378	378	75	1.15	0.92	1.035	8
		30	536	536	109	1.96	1.66	1.810	9
		40	694	694	143	3.47	2.89	3.180	10
B ↓		5	337	140	24	0.80	0.96	0.880	11
		10	476	219	41	1.60	1.23	1.415	12
		15	617	298	58	1.72	2.25	1.885	13
		20	756	378	75	3.71	3.02	3.365	14

Table 15

Whole Arm Torques and E_{inc} Observations

Task Number (Table 15)	$\hat{E}_{inc}$ for Shoulder Action (Kcal/min)	$\hat{E}_{inc}$ for Shoulder-Elbow (Kcal/min)	$\hat{E}_{inc}$ for Elbow Action (Kcal/min)	$\hat{E}_{inc}$ for Elbow-Wrist (Kcal/min)	$\hat{E}_{inc}$ for Wrist Action (Kcal/min)	$\hat{E}_{inc}$ for Whole Arm (Kcal/min)
1	0.07	-0.01	0.11	-0.04	0.05	0.18
2	0.25	-0.04	0.28	-0.12	0.19	0.56
3	0.75	-0.08	0.56	-0.24	0.48	1.47
4	2.25	-0.14	1.02	-0.41	1.17	3.89
5	0.48	-0.03	0.16	-0.04	0.05	0.62
6	3.25	-0.08	0.43	-0.12	0.19	3.69
7	0.29	-0.08	0.27	-0.10	0.10	0.48
8	0.62	-0.23	0.47	-0.31	0.37	0.92
9	1.11	-0.46	0.70	-0.64	0.97	1.67
10	1.84	-0.77	0.99	-1.08	2.34	3.31
11	0.62	-0.08	0.24	-0.04	0.03	0.78
12	1.11	-0.17	0.38	-0.10	0.10	1.33
13	1.84	-0.30	0.53	-0.19	0.19	2.08
14	2.93	-0.46	0.70	-0.31	0.37	3.23

Table 16

E_{inc} Predicted for Whole Arm Activity described in Table 15 where the variables are:

E_{W_i} - transformed E_{inc} observations in Table 15, (transformed by E_{inc} weighting procedure, page 96)

d - proportionality parameter to be estimated

$\hat{E}_{W_i}$ - transformed predicted $\hat{E}_{inc}$ values from prediction model, Figure 24.

$\sigma_{e/a}$ - estimated standard deviation of E_{W_i} observations about the predicted $\hat{E}_{W_i}$ values.

The results of this regression showed that the predicted $\hat{E}_{W_i}$ values were relatively unbiased, since d was found to equal 0.983, (if d=1.000 the predicted $\hat{E}_{inc}$ would be completely unbiased). A statistical test of whether the change in the slope from d=0.983 to d=1.000 (performed by the procedure outlined on page 110), disclosed that at $\alpha=0.01$ the difference was not significant.

Confidence intervals about the regression line were then computed (based on the estimated $\sigma_{e/a}$ which was found to equal 1.57). The procedure used was proposed by Graybill (39:120-122). The intervals were computed for the 95 percent confidence level, and were then transformed to E_{inc} values by the inverse transformation $\left[E_{inc} = f(E_W)\right]$, depicted on page 96 . Figure 25 displays the results graphically.

If the weight holding studies employed for the

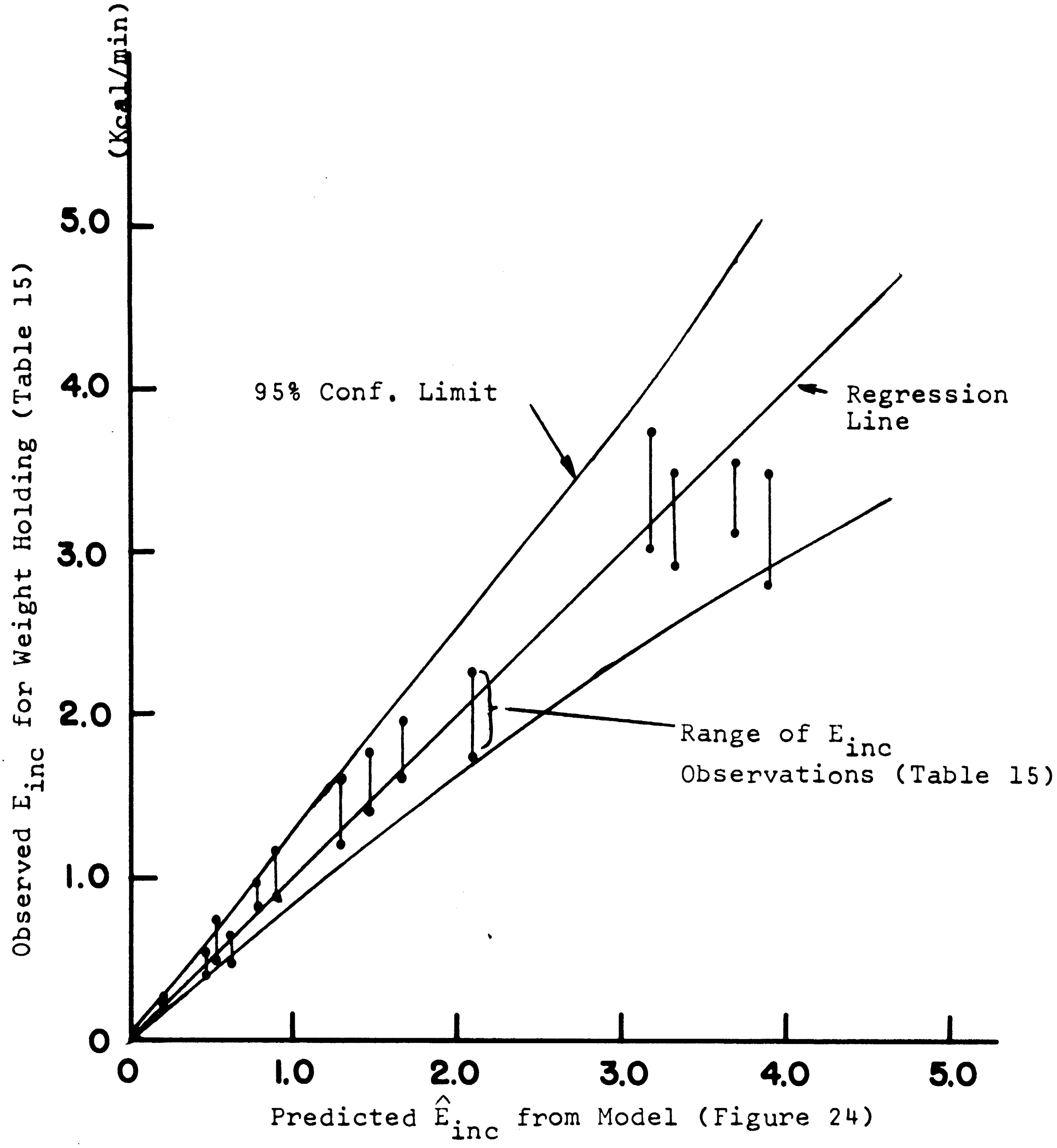


Figure 25

Actual vs. Predicted E_{inc} for Single Subject

Static Arm Activities

validation are considered to be typical in position and weight range, then the fact that 94 percent of the total E_{inc} variation was predicted indicates that the model can be used to gain some insight into the effects of various static activities on one subject's metabolic rate.

Chapter Summary

The results of the preceding metabolic experiments have disclosed that an unbiased estimate of the average incremental metabolic energy expenditure rate for the subject can be achieved by knowing:

1. the resultant torques at his shoulder, elbow, and wrist articulations,
2. the angle of his shoulder and elbow articulations,
3. whether he is using one or both arms in the activity.

The relationship of these "external" factors to the value of his $\hat{E}_{inc}$ resulted in the following observations:

1. The amount of change in E_{inc} for a given change in the resultant torque varies with:
    a. which muscle group is involved in the task (discussed on pages 103-104 and depicted by b parameters in Table 6).
    b. whether one or both arms are employed in the task (pages 116-123).

2. The magnitude of E_{inc} for a specific torque created by a given muscle group's action at the shoulder and elbow is a function of the angle of these articulations (Figures D-8 through D-13, and pages 108-115).

3. Less E_{inc} occurs in activities involving two adjacent articulations than is predicted by considering the articulation actions to be independently performed (pages 131-141).

Chapter V

THE DEVELOPMENT OF A GENERAL SUBJECT METABOLIC PREDICTION MODEL FOR STATIC ARM ACTIVITIES

It was postulated in Chapter II that the following two processes were the major causes of variation in the E_{inc} values of different individuals performing the same task:

1. Anatomical differences which would change the mechanical advantage of the muscle groups (page 32).
2. Muscle recruitment differences which could result in "less mechanically efficient" muscles being used in a task (page 37).

Because of these postulated effects on E_{inc}, three additional subjects were employed in experiments to estimate the value of the speculated individual differences, and how any resultant effects could be included in the single-subject metabolic prediction model developed in the preceding chapter. The experiments [that were] performed with each of the subjects had slightly different specific objectives. Therefore the order of reporting will be to present the experiment designs, results, analyses, and conclusions pertaining to each subject.

The Second Subject's Effect on the Model

The specific objective of the experiments performed with the second subject (designated J.J. in the subject data summary, Table B-1, Appendix B), was to determine if the value of the a and b parameters estimated for the first subject (preceding chapter) would remain the same. To determine this the following concepts served as a basis for subsequent experiments:

1. If the value of the b parameter (exponent) is the same for both subjects, it would indicate that both subjects' muscles respond to changes in torque in a similar manner.
2. If the value of the a parameter (as well as the b parameter) remains the same, then for a given torque at an articulation the values of $\hat{E}_{inc}$ will be equal.
3. If the value of b remains the same but the value of a is different for the two subjects, then the difference could be due to a change in muscle efficiency at various angles, or due to a different "total efficiency" in the muscle groups of each subject. Either type of change in muscle efficiency could be caused by differences in muscle anatomy or muscle recruitment, both of which are unmeasured quantities in this research project.

The Second Subject Experiments to Estimate the b Parameter

The objective of the first set of experiments performed with the second subject was to determine the effect of different articulation torque levels on E_{inc}. In other words, the experiments were to estimate the value of the b exponent. To accomplish this, E_{inc} values were obtained for four torque levels in each of the eight muscle group actions performed by the first subject (Table 6). These are described in Table 17 on the next page. Replication studies for five different experimental conditions provided enough information to substantiate that the standard deviation of the E_{inc} values (for given levels of the experimental conditions) was related to the expected value of E_{inc} in the same manner as was found for the first subject (page 74). Because of this condition, the E_{inc} values were transformed to E_W values for the following analyses.

First, the logarithmic model $E_W = aT^b$ was fit to the E_W-torque values for each muscle group action (the regression procedure is described on pages 96-100). The results of the regression are summarized in the upper half of Table 18.

From inspection of the values of the b parameter, it was observed that the values varied for each muscle group action in a similar manner as the first subject's (page 102). To confirm this observation the first subject's b parameter values were substituted for the exponent in the preceding logarithmic model, and the resulting model was fit to the E_W-torque data by the procedure outlined on pages 103 through 106. The results of this regression are presented in the lower section of Table 18.

From a comparison of the percent of E_W variance accounted for by both regression models, it was concluded that the value of the b parameter was the same for each

Study No.	Muscle Group	Action	Number Arms	Articulation Angle	Torques (Kgm.-cm.)				E_{inc} Response (Kcal/min.) to Adjacent Conditions			
1	Shoulder	Flexion	One	0°	140	210	280	350	0.04	0.35	1.05	2.44
2	"	"	Two	0°	280	420	560	700	0.35	0.74	1.91	2.80
3	"	Extension	One	0°	140	210	280	350	0.08	0.65	1.60	2.60
4	"	"	Two	0°	140	210	280	560	0.08	0.65	1.65	2.80
5	Elbow	Flexion	One	80°	125	165	200	250	0.12	0.32	0.45	0.72
6	"	"	Two	80°	100	250	325	400	0.13	0.41	0.57	0.65
7	Wrist	"	One	180°	20	40	55	-	0.10	0.99	2.17	-
8	"	"	Two	180°	40	55	70	85	0.16	0.70	1.10	1.80

Subject: J.J.

Table 17

Second Subject Experiment Conditions and E_{inc} Results

Study No.	Muscle Group	Action	Number Arms	Articulation Angle (γ)	Least Squared Error Parameter Estimates		Percent of E_W Variance Predicted r^2
					a*	b*	
1	Shoulder	Flexion	One	0^o	0.00000017	2.1433	96.2%
2	"	"	Two	0^o	0.0060821	1.1801	97.2%
3	"	Extension	One	0^o	0.00000808	2.4769	91.7%
4	"	"	Two	0^o	0.0004894	1.6428	91.2%
5	Elbow	Flexion	One	80^o	0.0005497	1.72271	93.2%
6	"	"	Two	80^o	0.04111719	0.8639	97.8%
7	Wrist	Flexion	One	180^o	0.1101417	1.4725	99.2%
8	"	"	Two	180^o	0.0989107	1.56114	99.1%
					a**	b**	avg. = 95.7%
1	Shoulder	Flexion	One	0^o	0.0001073	2.0	94.5%
2	"	"	Two	0^o	0.0352165	0.9	93.9%
3	"	Extension	One	0^o	0.00001149	2.4	94.6%
4	"	"	Two	0^o	0.0216205	1.0	86.0%
5	Elbow	Flexion	One	80^o	0.0053443	1.3	93.9%
6	"	"	Two	80^o	0.1055293	0.7	95.6%
7	Wrist	Flexion	One	180^o	0.0086905	1.8	85.6%
8	"	"	Two	180^o	0.0082056	1.8	82.8%
							avg. = 90.9%

*Estimates from Logarithmic Model (page 100)
**Estimates from assuming b exponent is the same as for first subject (pages103and 107)

Table 18

The a and b Parameter Estimates for the Second Subject

subject. In other words, both subjects' E_{inc} responded in a similar manner to changes in torque for the particular muscle actions studied.

The Second Subject Experiments to Determine the Effect on the a Parameter

Since the value of the b parameter was found to be similar for each subject, the a parameter was evaluated in a manner similar to its analysis with the first subject (pages 108-116). The first question considered was in regards to how a could change in respect to each articulation angle. In other words, was the value of the a parameter (which reflects the efficiency of a muscle group) dependent upon the angle of each articulation for the second subject as was found to be the case with the first subject?

To determine this, eight additional experiments were performed with the second subject. The muscle action involved was a two-elbow flexion, in which torques of 100 and 250 Kilogram-centimeters were sustained with the elbow angles set at 55°, 110°, 140°, and 170 degrees. The E_{inc} results of these experiments are presented in Table 19.

By fitting the elbow prediction model used for the first subject (page 107) to the data in Table 19, the $a_{6\gamma_e}$ values were estimated for each angle. The

Elbow Angle (γ_e)	E_{inc} Response (Kcal/min) to Torques of:	
	100 Kgm-cm.	250 Kgm-cm.
55°	0.21	0.66
110°	0.18	0.54
140°	0.19	0.58
170°	0.20	0.63

Table 19

E_{inc} Values for Different Elbow Angles

results are summarized in graphical form in Figure 26 on the next page. The $a_{6\gamma_e}$ parameter values for the first subject are plotted for comparison. As is depicted by this comparison, the $a_{6\gamma_e 2}$ parameter value for the second subject was also dependent on the articulation angle, and in fact, varied in a manner which corresponded to that of the first subject's.

The conclusion drawn from this result was that differences in the E_{inc} for the two subjects apparently did not depend on the angle of the articulation. Instead, it was attributed to a more general effect, possibly due to anatomical differences in bone size and muscle structure, or possibly a consistent use of "less efficient" muscles regardless of the articulation

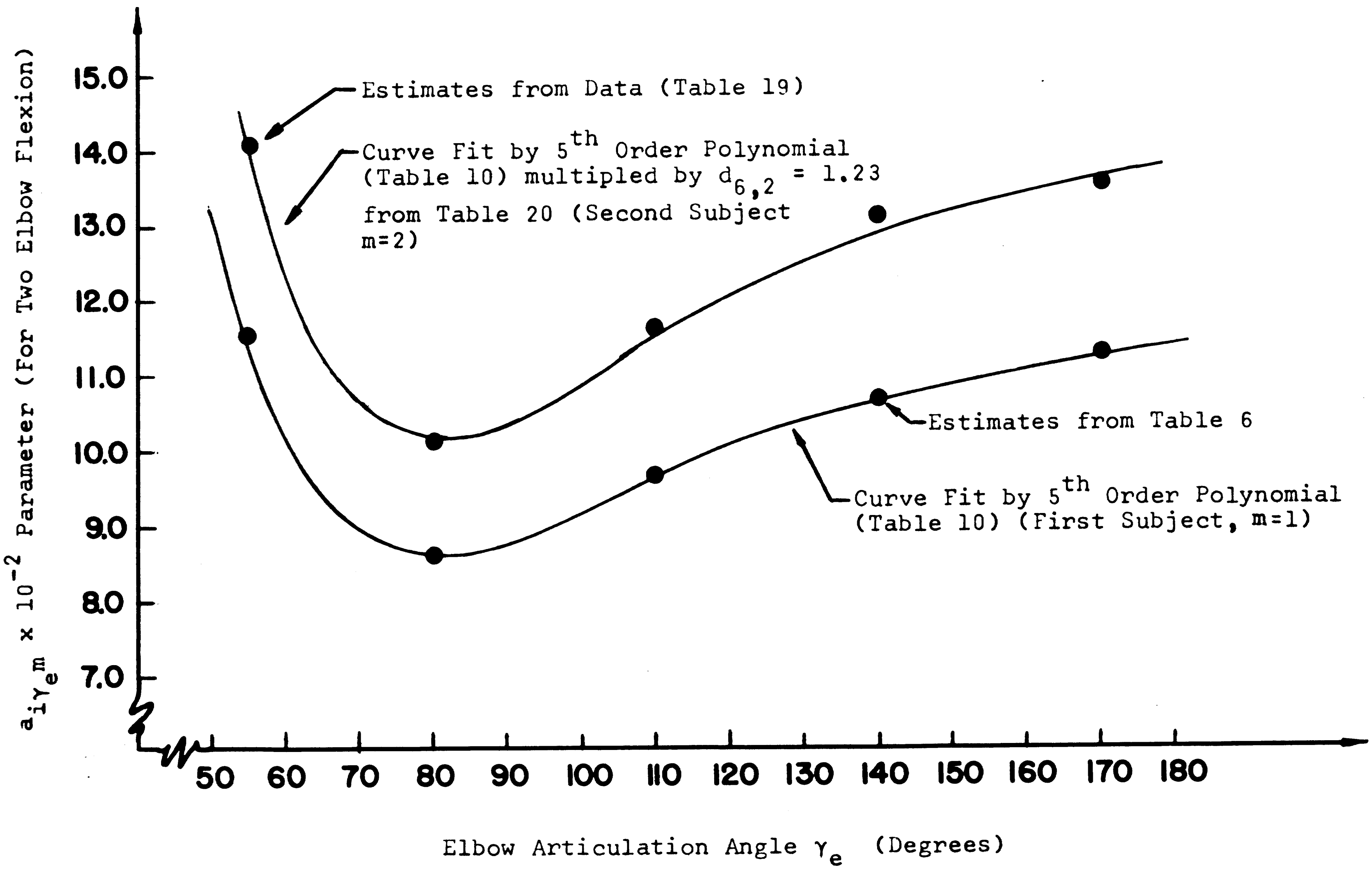


Figure 26

Model Comparison with Second Subject's Elbow $a_{i\gamma_e m}$ Parameter

during Two Elbow Flexion

angle. Because of the apparent independence between the subject difference effect and articulation angle, it was decided to derive a <u>subject parameter</u> which would be based on the differences in the a parameter values for each subject, as determined from E_{inc} studies at only one articulation angle.

The Second Subject Difference Parameter

As was discussed in the preceding chapter, the a parameter relates the value of E_{inc} (via the value of E_W) to a given amount of torque (page 108). Therefore, when the a parameter value for one subject was higher than that of another subject, the first subject was operating less efficiently than the second, i.e. he expended more energy to sustain the same amount of torque at an articulation.[1] This concept allowed the

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[1] It may be noted that because the same functional relationships between E_{inc} and E_W, as well as between E_W and changes in the torque for a particular muscle action have been empirically substantiated for both subjects (page 153), any change in the value of the a parameter between subjects indicates that the difference in efficiencies increases as E_{inc} increases. In other words, a person who requires a higher amount of E_{inc} than another on a low E_{inc} requiring task will require substantially more E_{inc} than the second person if the E_{inc} requirement of the task is increased. A comparison of E_{inc} values for wrist flexions (Figure 27) substantiates this observation for the first and second subject.

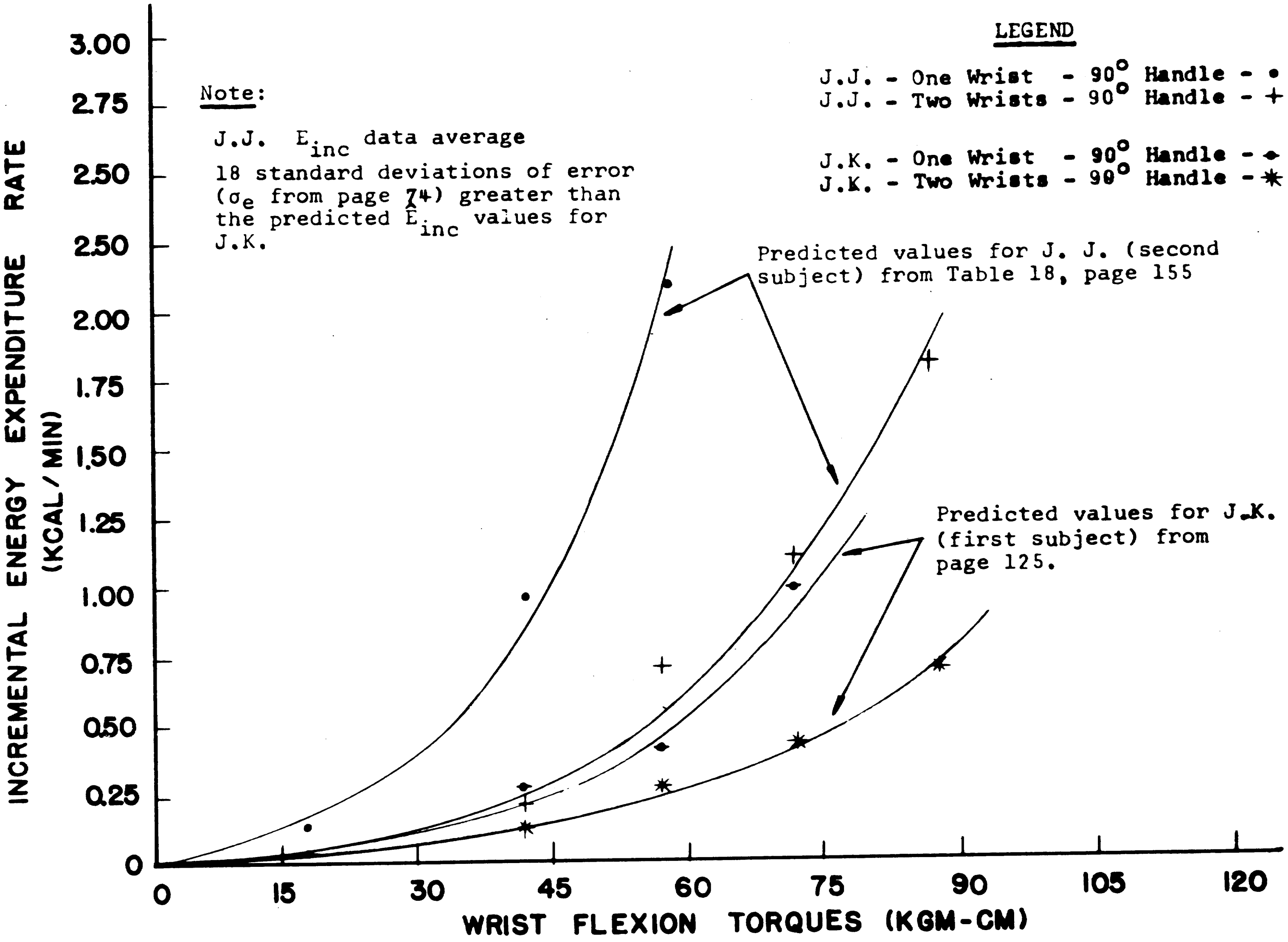

Figure 27

E_{inc} for First and Second Subjects Performing Wrist Flexions formulation of a third parameter for the metabolic prediction model, which was designated by the letter d for subject difference. In algebraic form, it was defined as follows:

$$d_{im} = \frac{a_{i\gamma m}}{a_{i\gamma}} .$$

The m subscript was used to designate the particular subject whose a parameter value was being compared to the subject discussed in Chapter IV. The i and γ notation are the same as defined on page 105 for the single subject model.

This subject difference concept was employed in order to compare the second subject's a parameter values (Table 18) with the values derived for the single subject model of Chapter IV. The results are displayed in Table 20. Inspection of the resulting d values disclosed that a large variation in the muscle efficiency existed between the subjects, depending upon the type of muscle action considered.[2] For the shoulder flexion activities the subjects were closest with an average difference of approximately 10 percent.

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[2] The d values were not expected to be similar for one and two arm shoulder and elbow activities because the absolute magnitudes of the a parameter values depend on b which is different for one and two arm activities (pages 116-123).

One Shoulder Flexion (i=1)

$$d_{1,2} = \frac{a_{1,0,2}^{*}}{a_{1,0}^{**}} = \frac{0.000107}{0.000101} = 1.06$$

Two Shoulder Flexion (i=2)

$$d_{2,2} = \frac{a_{2,0,2}}{a_{2,0}} = \frac{0.03522}{0.03110} = 1.13$$

One Shoulder Extension (i=3)

$$d_{3,2} = \frac{a_{3,0,2}}{a_{3,0}} = \frac{0.0000115}{0.0000104} = 1.11$$

Two Shoulder Extensions (i=4)

$$d_{4,2} = \frac{a_{4,0,2}}{a_{4,0}} = \frac{0.02162}{0.01812} = 1.19$$

One Elbow Flexion (i=5)

$$d_{5,2} = \frac{a_{5,80,2}}{a_{5,80}} = \frac{0.00534}{0.00427} = 1.25$$

Two Elbow Flexion (i=6)

$$d_{6,2} = \frac{a_{6,80,2}}{a_{6,80}} = \frac{0.10553}{0.08590} = 1.23$$

One Wrist Flexion (i=7)

$$d_{7,2} = \frac{a_{7,2}}{a_{7}} = \frac{0.00869}{0.00417} = 2.08$$

Two Wrist Flexions (i=8)

$$d_{8,2} = \frac{a_{8,2}}{a_{8}} = \frac{0.00821}{0.00417} = 1.98$$

*These a parameter values are from Table 18.
**These a parameter values are from Table 6 and page 125.

Table 20

Second Subject Difference Parameters $d_{i,2}$

The largest difference occured at the wrists, with the second subject's a parameter being greater than twice the value of the first subject's.

The General Subject Metabolic Prediction Model for Static Arm Activities and the Second Subject Validation

A general subject metabolic prediction model was formulated for validation based on the following, empirically substantiated and assumed conditions:

1. The amount of change in E_{inc} for a given change in torque is dependent upon which muscle action is being considered, but can be considered to be constant between subjects (page 156).
2. The amount of E_{inc} required to sustain a given resultant torque at the elbows and shoulders varies with the angle of these articulations, but in a similar manner for different subjects (page 157).
3. The difference in the value of the $a_{i\gamma m}$ parameter for different m subjects, is indicative of each subject's efficiency in his i^{th} muscle action. This difference can be formulated as a subject difference constant d_{im}, for each subject's muscle action (Table 20).
4. The adjacent articulation torque interaction terms (Table 14), can be assumed to be constant between subjects due to their relatively small contribution to the metabolic energy prediction for a given whole arm task.

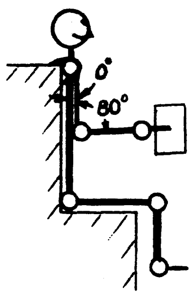
The effect of the above conditions on the single subject metabolic prediction model displayed in Figure 24, page 143, was to require that a subject difference parameter d_{im} be added to each of the major muscle action prediction equations, thus giving:

$$\hat{E}_{inc_{i\gamma m}} = f\left\{\hat{E}_{w_{i\gamma}} = d_{im}\left[a_{i\gamma}T_i^{\,b_i}\right]\right\} \quad .$$

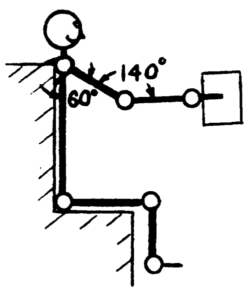
To test the validity of this formulation, the d_i values developed for the second subject (Table 20) were interjected into the single subject prediction model (as indicated above) and $\hat{E}_{inc}$ predictions were made by assuming the subject to be holding different amounts of weight in different positions, and with one and two arms. The second subject then performed the designated tasks twice which allowed the actual E_{inc} values to be estimated for comparison. Table 21 presents the test conditions, $\hat{E}_{inc}$ predictions, and observed E_{inc} values. By the regression analysis explained on pages 144-147, it was found that the predicted $\hat{E}_{inc}$ values accounted for 94percent of the observed E_{inc} values, and were statictically unbiased estimates of the mean values of E_{inc}.

Conclusion from Second Subject Experiments

It was concluded from the preceding validation study that the subject effect could be successfully included in the single subject prediction model by forming a ratio of the a_i parameters for each subject. This formulation was then employed in



Position A



Position B

Position of Arms	Number Arms	Weight Held (pounds)	Torques in Kilogram-Centimeters			E_{inc} Observed(Kcal/min)		$\hat{E}_{inc}$ Predicted (Kcal/min.)
			Shoulder (SFT)	Elbow (EFT)	Wrist (WFT)	First Study	Second Study	
A	1	6.5	138	138	25	0.40	0.54	0.45
		16.5	305	305	60	5.20	4.13	5.14
	2	6.5	169	169	29	0.41	0.59	0.54
		16.5	335	335	63	1.75	1.43	1.44
		26.5	502	502	97	3.81	3.02	3.75
B		6.5	387	169	29	1.01	1.40	1.32
		16.5	681	335	63	3.58	4.25	4.09

Subject: J.J.

Table 21

Second Subject E_{inc} versus $\hat{E}_{inc}$

experiments with the two additional subjects.

The Third Subject's Effect on the Model

The objective of the experiments performed with a third subject was to provide further validation of the general subject metabolic prediction model developed in the preceding section. This was accomplished by first obtaining estimates of the $a_{i\gamma 3}$ parameter for the third subject, by employing the same procedure as was used with the second subject (page 156). The resulting $a_{i\gamma 3}$ values were divided by the $a_{i\gamma 1}$ values estimated for the first subject, resulting in d_{i3} values for each i muscle action. The d_{i3} values were then incorporated into the single subject prediction model (Figure 24) by the formulation on page 143. For validation, the $\hat{E}_{inc}$ predictions from this model were compared to E_{inc} values observed while the subject held different magnitude weights in different positions.

The Third Subject d_i Parameter Estimates

The third subject $a_{i\gamma 3}$ parameter estimates were obtained by observing the subject's E_{inc} while he performed (at three different levels of resultant torques) two shoulder flexions ($i=2$, $\gamma=0^\circ$), two elbow flexions ($i=6$, $\gamma=80^\circ$), and two wrist flexions ($i=8$). The estimates of his $a_{i\gamma 3}$ parameters were obtained by assuming that his b_i exponents were the same as the first subject, and employing a least squared error regression of the resulting E_{inc}-torque values as described on page 104. The values obtained were:

1. For the two shoulder flexion at 0°:

   $a_{2,0^{\circ},3} = 0.03702$

2. For the two elbow flexion at 80°:

   $a_{6,80^{\circ},3} = 0.08830$

3. For the two wrist flexion:

   $a_{8,3} = 0.00450$

When these $a_{i\gamma 3}$ values were divided by the corresponding $a_{i\gamma 1}$ values for the first subject (Table 6, and page 125), the following d_{i3} values were obtained:

1. For the two shoulder flexion:

   $d_{2,3} = 1.19$

2. For the two elbow flexion:

   $d_{6,3} = 1.03$

3. For the two wrist flexion:

   $d_{8,3} = 1.08$

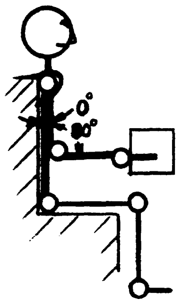
The Third Subject Validation

The d_{i3} parameter values developed in the preceding section were incorporated into the single subject prediction model (Figure 24) by the formulation on page 164. The resulting model was then used to predict the $\hat{E}_{inc}$ for the various two arm weight holding activities depicted in Table 22 on the next page. Actual E_{inc} values were obtained for comparison by having the subject perform the designated tasks twice.

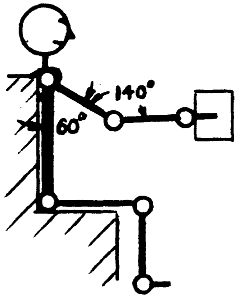
A regression analysis of the actual and predicted E_{inc} values disclosed that the predictions accounted for 96 percent of the total variation in E_{inc}. This result was considered to be confirmation of the technique employed in quantifying the subject difference effect on E_{inc}, since the d_{i3} values of this third subject were of different magnitudes than the d_{i2} values (Table 20) of the second subject, from which the technique was developed.

The Fourth Subject's Effect on the Model

As with the third subject, the objective of the experiments performed with a fourth subject was to provide further validation of the general subject prediction model. The $a_{i\gamma 4}$ parameter values were estimated in only three E_{inc} studies. In these studies, the subject held weights of three different magnitudes in both hands, while his E_{inc} was measured. The position of the arms remained constant for each study.



Position A



Position B

Position of Arms	Weight Held (pounds)	Torques in Kilogram Centimeters			E_{inc} Observed (Kcal/min)		$\hat{E}_{inc}$ Predicted (Kcal/min.)
		Shoulder (SFT2)	Elbow (EFT2)	Wrist (WFT2)	First Study	Second Study	
A ↓	6.5	168	168	26	0.38	0.45	0.44
	16.5	329	329	57	0.87	1.04	0.93
	26.5	489	489	87	1.50	1.87	1.75
B ↓	6.5	396	168	26	1.62	1.22	1.32
	16.5	682	329	57	3.56	4.15	3.95

Table 22

Subject: J.S.

Third Subject E_{inc} versus $\hat{E}_{inc}$

The resulting data obtained was:

Articulation Angle		Weight Held (pounds)	Resultant Torques(Kgm-cm.)			Observed (Kcal/min)
γ_s	γ_e		SFT2	EFT2	WFT2	
0°	80°	6.5	169	169	28	0.40
0°	80°	16.5	336	336	60	0.98
0°	80°	26.5	502	502	93	1.79

Table 23

Fourth Subject Data for $a_{i\gamma 4}$ Parameter Estimates

The $a_{i\gamma 4}$ values were approximated by a sequencial substitution of various values into the single subject prediction model (Figure 24), until the error between the observed and predicted $\hat{E}_{inc}$ values was less than 2-and-1/2 percent. This procedure produced the following estimates:

1. For two shoulder flexions ($i=2, \gamma_s=0^\circ$):

   $a_{2,0^\circ,4} = 0.0343$

2. For two elbow flexions ($i=6, \gamma_e=80^\circ$):

   $a_{6,80^\circ,4} = 0.0903$

3. For two wrist flexions (i=8):

$a_{8,4} = 0.00729$

These values were then used to estimate the fourth subject difference parameter $d_{i,4}$ for two arm activities. The values are:

1. For two shoulder flexions (i=2):

   $d_{2,4} = 1.10$

2. For two elbow flexions (i=6):

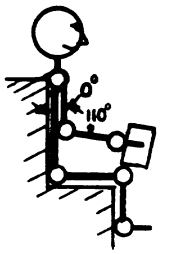
   $d_{6,4} = 1.05$

3. For two wrist flexions (i=8) :

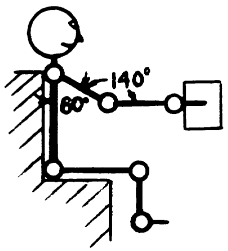
   $d_{8,4} = 1.76$

These subject difference parameter estimates were incorporated into the single subject prediction model (Figure 24) by the procedure on page 164. This resulted in a fourth subject prediction model for two arm weight holding activities. The $\hat{E}_{inc}$ predictions from this model were then compared to observed E_{inc} values while the subject held various magnitude weights in different positions. The experimental conditions and resulting E_{inc} values are presented in Table 24 on the next page.

When the actual and predicted E_{inc} values were compared by the procedure outlined on page 144, it was



Position A



Position B

Position of Arms	Number Arms	Weight Held (pounds)	Shoulder Flexion Torque (Kgm-cm.)	Elbow Flexion Torque (Kgm-cm.)	Wrist Flexion Torque (Kgm-cm.)	E_{inc} Values (Kcal/min)	
						Observed	Predicted
A	2	6.5	161	161	26	0.55	0.47
		16.5	320	320	58	1.24	1.12
		26.5	479	479	89	1.98	2.43
B		6.5	389	169	28	1.33	1.16
		16.5	685	336	60	2.81	3.51

Subject: E.H.

Table 24

Fourth Subject E_{inc} versus $\hat{E}_{inc}$

found that 85 percent of the variance in E_{inc} had been accounted for by the predictions. Since the torques and positions of the arms during the validation studies were different than those used to determine the subject's $a_{i\gamma}$ estimates, further validation was given to the technique to quantify the subject differences.

Summary and Discussion of Chapter

The research that contributed to this chapter has disclosed the following:

1. The values of the b_i exponents estimated for the first subject represent for three others, the way in which their skeletal muscle groups metabolically respond to a <u>change</u> in the torque at the shoulder, elbow and wrist.
2. Individual differences in E_{inc} values for given muscle groups, torques, and articulation angles have disclosed that as $\hat{E}_{inc}$ increases for the task, the amount of E_{inc} variation increases due to having different subjects (page 161). In addition, the subject difference effect on E_{inc} can be predicted by estimating the value of the $a_{i\gamma m}$ parameter for the muscle groups which are involved in a given task.

The apparent success of using the parameter d_{im} as a quantification of the subject difference effect indicates that: 1) individual efficiencies vary considerably for different muscle group actions, and 2) individual efficiencies change in a similar manner with the angle of the articulation being studied.

Some indication is given that the individual difference effect is related to the anatomical structure. This is due to the fact that in the muscle action that resulted in the highest difference between two individuals, i.e. the wrist flexions between the first and second subjects (Figure 27), the width of the first subject's wrist (defined by the distance between the radial and ulna styloid processes) was found to be 25 percent greater than the second subject's. This difference could conceivably result in the moment arms of those muscles used by the first subject being greater than the second subject's, thus reducing the amount of tension, and therefore E_{inc} required in the flexion. Figure 7 on page 35 depicts the possible muscles that could be utilized. Whatever the nature of the processes that generate individual differences in E_{inc}, the large differences disclosed by this research project are substantiation for future research efforts.

Chapter VI

THE DEVELOPMENT OF A SINGLE SUBJECT METABOLIC PREDICTION MODEL FOR DYNAMIC TASKS

The preceding chapters have discussed static flexions at the shoulder and elbow, which were defined as the muscle actions required to maintain a stationary position of the arm against resultant torques which would tend to rotate the arm in a clockwise direction, i.e. downwards and backwards (page 23). The discussion in this chapter is concerned with estimating E_{inc} during dynamic arm flexions, which occur when the reactive torques created by the arm and shoulder muscles overcome the resultant torques produced by the gravitational and inertial forces. (The computational procedure for estimating the magnitude of these torques is presented in Appendix A.)

Past experiments, performed by others who studied various isolated animal muscles, have suggested three processes to account for the total energy expended by muscle tissue when producing tension and shortening. These are: 1) the kinetic energy expended in moving the body mass (or any external mass), 2) the heat energy liberated by the shortening muscle tissue, and 3) the heat energy liberated by the chemical reactions that maintain the contraction state (45:897-903). (An hypothesized equation of these energies is presented on page 180). The research reported in this chapter, though performed with only one subject, discloses that when a group of muscles are producing tension and shortening, the total amount of energy liberated can not be explained as simply the addition of the three energies suggested from isolated-muscle models.

The E_{inc} Response to Dynamic Flexions at the Shoulder and Elbow

A discussion of the difficulty of relating an isolated-muscle energy model to a functional muscle group has been presented by Nubar (59). One of the major conclusions of his development is that the isolated-muscle energy models can only be relevant to the functioning system by knowing the relative tensions of each muscle during an action, which he displays to be a function of each muscle's moment arm.

A further difficulty is presented by the fact that some muscles span two articulations, and apparently are useful in reducing the energy expenditure when adjacent articulations are active (as disclosed by the research reported on pages 131-141). An additional factor to be considered in utilizing an analytical approach is that a single muscle is used in varying degrees during a dynamic movement, depending upon the speed of the movement (pages 45-50 discuss this concept).

Because of the apparent complexities of the problem (caused by the lack of quantified descriptions of the basic processes), a need was foreseen to perform the following experiments to estimate the metabolic energy expended during dynamic arm activities. The objective of these experiments was to determine how the first subject's E_{inc} varied with the radial velocity of the upper and lower arm segments when rotated about the shoulder and elbow during dynamic arm activities. It was believed that inferences could then be made pertaining to the processes that cause the resulting E_{inc}.

Experiments to Estimate E_{inc} Values for Dynamic Shoulder and Elbow Flexions

The contemporary literature indicates that in addition to work being done during a dynamic flexion (i.e. an increase in the gravitational potential energy of the arm or a weight moved by the arm's action), a heat loss occurs (74:897-903). During the static arm actions discussed in the preceding chapters, no work is done. Therefore, all of the metabolic energy is liberated as heat. Dr. A. V. Hill has designated this energy as the "heat of maintenance". This heat is from the chemical reactions required to maintain the muscle contraction (74). From this concept it was hypothesized that the $\hat{E}_{inc}$ values predicted from the preceding models were quantified values of Hill's "heat of maintenance", expressed as a rate, i.e. Kiolgram-calories per minute of static contraction.

Since the static heat loss appeared to be predictable the question to be answered by the research was: "What is the magnitude of the additional energy expenditure during dynamic tasks?" Hill has formulated this second expenditure as a function of the amount of shortening in isolated muscles. It is now necessary to attempt a characterization of this heat loss in the functioning muscle system.

Because it was not possible to determine the specific muscle anatomy and usage during a dynamic task, an empirical approach was utilized. The first subject (designated J.K. in the Subject Data Table, B-1) was employed in experiments to estimate his incremental metabolic energy expenditure rate during dynamic shoulder and elbow flexions. This rate of metabolic energy expenditure will be designated as E_D (still measured in Kilogram-calories per minute), to distinguish it from its counterpart during static tasks, E_{inc}.

The Dynamic Activity Experiment Procedure. The major experimental variable manipulated during the dynamic test activities was the radial velocity produced by the arm segments when rotated about the shoulder and elbow. During each of the flexion studies, the torque was maintained within plus-or-minus eight percent of a constant value by the procedure described on pages 79 through 82. The specific procedure to estimate the subject's E_D for each experimental condition was:

1. The subject was prepared for the experiment as outlined on pages 64-70.
2. During the initial 10 minute <u>resting</u> segment the subject "jerked" lightly against the test load at intervals that coincided with the intervals during which he would be flexing in the 10 minute <u>active</u> segment that followed.
3. During the 10 minute active segment the subject flexed his elbow or shoulder so as to rotate the distal arm segment at a predetermined constant rotational velocity.[1] This action was repeated once every 10 seconds. At the end of each motion the test weight was supported by the experimenter while the subject dropped his arm to the resting position. (Figure 14 on page 81 depicts the test setup.)

The maximum velocity of the elbow flexion studied was that which still allowed the subject to maintain a constant velocity throughout the required range of motion. This was found to be approximately 2.48 radians per second for the 40 degree flexion of the elbow.[2]

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[1] The velocity of each flexion was determined by an accelerometer attached to the weight being moved, as well as by an electric timer, which was actuated by switches attached to the weight holding fixture.

[2] A preliminary analysis disclosed that a whole-arm motion performed at a normal speed (as determined from MTM Standard Motion Time Data) seldom required the elbow or shoulder radial velocities to exceed two radians per second.

The lowest velocities employed were 0.44 radians per second. One or two intermediate velocities were also used.

The Initial Dynamic Energy Prediction Model. The first group of dynamic task experiments had the objective of determining if Dr. Hill's energy model for a single muscle could be used as a basis for the prediction of the energy expended by a group of functioning muscles in the human body. The following is Hill's single muscle energy model (45:897-903):

$$E_T = A + ax + W$$

where:

E_T - total muscle energy expended for a single contraction

A - heat energy expended by reactions required to maintain a contraction

a - coefficient which represents heat loss due to shortening in muscle tissue during the isotonic contraction

x - distance that muscle shortens

W - mechanical work done by muscle displacing mass.

This model served as the basis for an hypothesized metabolic prediction model. The energy terms in this hypothesized model were expressed as heat energies per minute of activity. This was done to remain consistent with the aforementioned static energy rates. The model was:

$$E_D = \hat{E}_{inc} + g\omega + P$$

where:

E_D - the average metabolic energy expenditure per minute of an isotonic contraction

$\hat{E}_{inc}$ - the metabolic energy expenditure predicted per minute of an equivalent static flexion, as determined by averaging the E_{inc} values for small discrete segments of a given motion. This represents the same type of energy loss as A in Hill's formulation

g - coefficient which relates the muscle group's heat loss due to the radial distance traveled per unit of time (this was considered to be equivalent to a in Hill's formulation for a single muscle)

ω - angular displacement of the distal arm segment per unit of time (equivalent to angular velocity, which was expressed in radians per second)

P - mechanical power output as computed by the work (i.e. the increase in gravitational potential energy of the mass moved) per minute of flexion

This model relied on a basic concept which was proposed for empirical evaluation. This was that the value of g was independent of the amount of torque at the articulation, i.e. the speed effect on E_D does not interact with the torque effect. Hill's model was also based on this concept. For evaluation, the following experiments were performed, with the assistance of the first subject (designated J.K. in Subject Data Table, B-1).

The muscle group action used was a one elbow flexion, referred to as i=5 (page 104). The range of motion was from $\gamma_e = 100°$ to $\gamma_e = 60°$.[1] By varying the radial velocity and the average torque (as described in Table 25), the effects of these variables on the subject's E_D values were estimated as follows. First, the equivalent average static $\hat{E}_{inc}$ was predicted for each motion by assuming the motion to be composed of a sequence of discrete, static, one elbow flexions, and then averaging the predicted $\hat{E}_{inc_5}$ for each static position. (The $\hat{E}_{inc_5}$ prediction procedure is discussed on page 134). The mechanical power (i.e. rate of work) was also computed from the average torques developed during the flexions. (Both the average $\hat{E}_{inc_5}$ and the power output values are presented in Table 25).

To determine if the g coefficient varied with the torque, the average $\hat{E}_{inc_5}$ and output power estimates were subtracted from each of the observed E_D values obtained by having the first subject perform each of the test activities designated in Table 25. A least squared error regression was then executed to estimate the values of the g coefficient for the two different torques employed. The model used was:

$$E_D - \hat{E}_{inc_5} - P = g\omega + \sigma_{E_D}$$

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[1] The range of motion will be referred to as the <u>region of angulation</u> and will be defined by the notation γ = initial angle → final angle.

Average Torque (Kgm-cm.)	Average Angular Velocity ω (radians/second)	Observed E_D value (Kcal/min)	Predicted Static $\hat{E}_{inc_5}$ (Kcal/min)	Power Output P (Kcal/min)
321	0.44 (slow)	1.29	1.05	0.18
	0.64	1.68		0.26
	0.97	3.25		0.39
	1.40 (fast)	4.43		0.58
208	0.58	0.69	0.38	0.15
	0.87	1.08		0.22
	1.40	1.37		0.36

Region of angulation: $\gamma_e = 100° \rightarrow 60°$

Subject: J.K.

Table 25

Dynamic Experiment Conditions and E_D Results during One Elbow Flexion - I

The standard deviation of the errors between the model predictions and the observed E_D values is designated as σ_{E_D}. The results of this analysis were that $g = 1.69$ for the 321 Kgm-cm torque, and $g = 0.45$ for the 208 Kgm-cm torque. A parameter significance test disclosed that the difference in the g values was significant at $\alpha=0.05$ confidence (39:120-122).

Because of this result it was concluded that the speed and torque effects on the total metabolic energy expended by a group of muscles were probably not additive. Additional substantiation for this conclusion was realized from gross electromyographic data reported by others (10:1108-1109). This data (which is summarized in Table 1, page 38) disclosed that additional muscles are used during fast flexions (a proposed explanation for these shifts is presented on page 46). Because of moment-arm differences between muscles, the speed effect alters the tension of each muscle, and thus changes the heat of maintenance and power contribution of each. The end result of these changes is probably what caused the high rate of increase in E_D with speed, when a high torque was involved.

An Alternative Dynamic Energy Prediction Model. Because of the apparent failure of an additive model of the speed and torque effects on E_D, the following alternative model was developed for testing. The rationale for this model is presented below.

The value of $\hat{E}_{inc}$ has been shown (by the research in Chapters IV and V) to reflect the amount of energy required for a given static torque. In other words, it represents each muscle group's ability to create a desired torque at a given articulation angle.

In the performance of a dynamic task, energy is expended as some function of the speed of motion. If the motion is the rotation of an arm segment about an articulation, the function can be expressed as $f(\omega)$, where ω is the angular velocity of the segment. Part of this energy increase with speed has been explained by Hill as the heat liberated by the shortening muscle tissue. Part of it must also be contributed to a loss of total muscle efficiency (due to additional muscles being required in high speed moves, as discussed on page 46). Finally, the rate of mechanical work increases in proportion to the angular velocity during a dynamic flexion.

By referring to the concept that the average $\hat{E}_{inc}$ predicted over the range of motion represents the ability of the muscle groups involved to create the required torque, the following dynamic energy prediction model was formed:

$$E_D = \hat{E}_{inc} f(\omega) \quad .$$

In this form the function $f(\omega)$ is a modifier of the average $\hat{E}_{inc}$ predicted for the motion when considered as a sequence of static activities. The following two conditions were defined to describe $f(\omega)$:

1. When $\omega=0$, which is a static task, $f(\omega)=1$.
2. When $\omega > 0$, which is a dynamic task where positive work is being performed, $f(\omega)$ increases as a continuous monotonic function of the angular velocity.

One function that has these two qualities is:

$$f(\omega) = P^{\omega}$$

where P is an empirically derived constant that is greater than one. When this function was substituted into the dynamic energy equation, it became:

$$E_D = \hat{E}_{inc}(P)^{\omega}$$

which is often referred to as a semi-logarithmic model.

Evaluation of the Semi-Logarithmic Model of E_D. If the preceding model was to be used as a predictor of E_D for various dynamic tasks, the value of P had to be determined. Specifically, if the model was valid, P had to be a constant for the various conditions that could change E_{inc} and thus E_D. To determine this, additional experiments were performed with the first subject. Since the one elbow flexion action had been used in testing the additivity model (Table 25), this action was again employed so that the prior E_D results could be used.

As was presented in Chapter IV, two major factors that affect the value of E_{inc} for a particular muscle action are:

1. the level of torque
2. the angle of the articulation involved.

The preceding experiments (Table 25) were performed at only one region-of-angulation, i.e. $\gamma_e = 100° \rightarrow 60°$. Because of this, a set of dynamic experiments were performed in a region-of-angulation that had a different predicted, equivalent, static $\hat{E}_{inc}$. The region chosen was $\gamma = 170° \rightarrow 130°$. In addition, the short 40° motion intervals restricted the variation in the angular velocity ω to being no greater than 1.40 radians per second (page 179). Therefore a set of experiments were performed with $\gamma_e = 155° \rightarrow 55°$, i.e. a 100° flexion, which allowed ω to be as large as 3.48 radians per second. The experiment conditions and resulting observed E_D values are displayed in Table 26 on the next page.

A least squared error regression of the E_D data in Tables 25 and 26 was performed to estimate the value of P for the different angle and torque conditions. The results are presented in Table 27.

Region of Angulation (degrees)	Average Torque (Kgm-cm)	Average Angular Velocity ω (Radians/second)	Observed E_D values (Kcal/min)	Predicted Static $\hat{E}_{inc_5}$ (Kcal/min)
170° → 130°	321	0.44	2.90	1.58
		0.88	4.61	
		1.40	6.01	
155° → 55°	195	0.59	0.94	0.39
		1.00	1.51	
		2.51	3.01	
		3.48	8.33	

Subject: J.K.

Table 26

Dynamic Experiment Conditions and E_D Results during One Elbow Flexion - II

Region of Angulation (degrees)	Average Torque (Kgm-cm)	Estimate of P
100° → 60°	321	2.729
100° → 60°	208	2.773
170° → 130°	321	2.877
155° → 55°	195	2.449

Table 27

<u>Estimates of P for One Elbow Flexion</u>

By pooling the data, an estimate of P=2.559 was obtained which had a correlation coefficient of 0.94. A parameter difference test disclosed that none of the estimates of P in Table 27 were significantly different than P=2.559, with the confidence level set at α=0.05 (39:120-122).

The conclusion drawn from this result is that the average $\hat{E}_{inc}$ for a dynamic task must be modified by the following <u>energy-speed function</u>:

$$f(\omega) = (2.559)^{\omega} .$$

This function was then incorporated into the static metabolic prediction model, which resulted in:

$$E_{D_{i,\gamma_1 \rightarrow \gamma_n,\omega}} = \hat{E}_{inc_{i,\gamma_1 \rightarrow \gamma_n}} (2.559)^{\omega_i}$$

where:

$E_{D_{i,\gamma_1 \rightarrow \gamma_n,\omega}}$ - Average incremental metabolic energy expenditure rate during dynamic flexions involving the ith muscle action, in a region-of-angulation from γ_1 to γ_n, at an average angular velocity of ω_i.

$\hat{E}_{inc_{i,\gamma_1 \rightarrow \gamma_n}}$ - Predicted static $\hat{E}_{inc}$ for subjects ith muscle action averaged over angles from γ_1 to γ_n (page 181).

ω_i - Average angular velocity of distal body segment about joint, in radians per second.

Validation of the Preceding Prediction Model for Whole-Arm Dynamic Tasks. The preceding results disclosed that for one particular muscle group's action (i.e. a one elbow flexion) the $\hat{E}_{inc}$ must be modified by a speed function, which was represented as a constant (2.559) raised to the power of the angular velocity (expressed in radians per second). The generalization of this effect (in order to predict $\hat{E}_D$ during a whole arm dynamic task) required the following assumptions:

1. The value 2.559 remains constant for other muscle group actions besides the one elbow flexion.
2. The torque interaction effect during a dynamic task does not change significantly from its predicted value during a similar static task.

3. The changes in torques and speeds during a whole-arm motion do not affect the $\hat{E}_D$ prediction.

The resulting whole arm dynamic task prediction model formulated from these assumptions is depicted in Figure 28, on the next page. The "instantaneous" torques, angles, and velocities, were computed in discrete intervals, as described in Appendix A.[1] These were then used to predict $\hat{E}_D$ during each of the intervals. The average $\hat{E}_D$ for the motion was defined as the sum of the values for each interval averaged over the total motion time. Table 28 presents the predictions for a short vertical lift of a container weighing 16.5 pounds (Figure A-4 on page 226 displays the test setup, with the acceleration similar to that depicted in Figure A-3, page 224).

To test the validity of the $\hat{E}_D$ predictions obtained by this model, the first subject performed a series of whole-arm lifting tasks while his actual E_D was measured for comparison. The specific task conditions and his E_D values are presented in Table 29, as well as the resulting $\hat{E}_D$ predictions. The study procedure was to have the subject vertically lift an object at three different average elapsed times. An accelerometer

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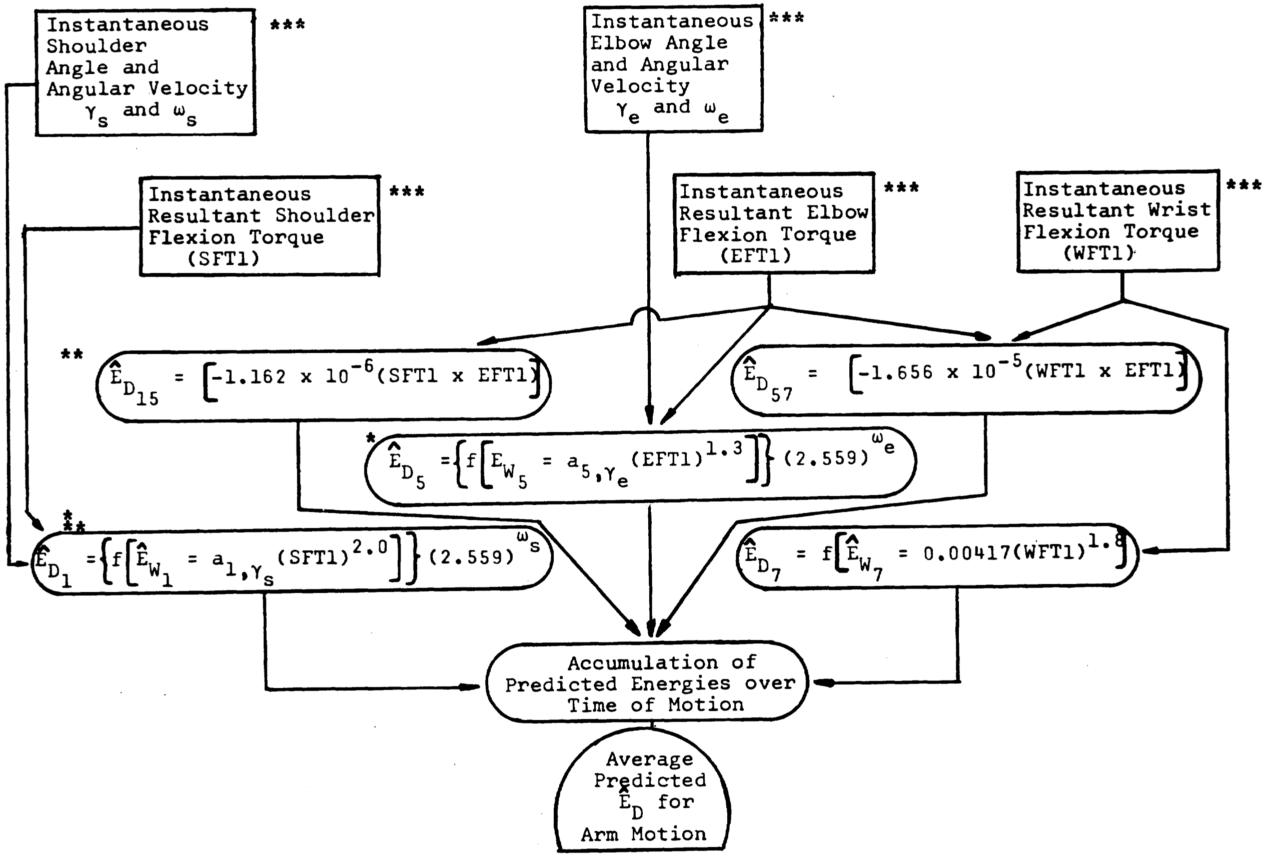
[1] The interval used was set at $\Delta t = 0.02$ seconds to obtain an acceptable displacement accuracy, as discussed on page 226.



***Instantaneous values are discrete approximations (page 220)
**During shoulder extension these equations change as indicated in Tables 6 and 14.
*Parameter a values given by computations in Table 10, or in Graphs (Figures D-8 to D-13)

Note: The two arm $\hat{E}_D$ model changes as indicated in Tables 6 and 14, page 125

Figure 28

The Single Subject $\hat{E}_D$ Prediction Model for One Arm Dynamic Activities

Elapsed Time (seconds)	Total Vertical Displacement (cm.)	Shoulder Angle γ_s	Shoulder Angular Velocity ω_s	Elbow Angle γ_e	Elbow Angular Velocity ω_e	Resultant Torques (Kgm-cm)			Predicted $\hat{E}_D$ (Kcal/min)
						Shoulders	Elbows	Wrists	
0.10	.477	2.39	-0.123	107.52	0.526	403	389	78	1.413
0.20	3.205	1.22	-0.251	101.80	1.462	422	411	83	2.838
0.30	8.898	0.12	-0.49	91.44	2.056	424	411	83	4.232
0.40	17.155	1.56	0.634	79.48	1.989	424	388	79	4.222
0.50	26.825	7.99	1.628	69.71	1.333	412	326	65	4.081
0.60	36.649	19.81	2.389	64.77	0.378	341	212	42	4.392
0.70	45.371	43.92	2.383	64.98	-.371	271	122	22	3.460
0.80	51.961	45.87	1.715	68.01	-.590	270	86	15	2.250
								Average $\hat{E}_D$ =	3.528

Note: The experiment setup is depicted in Figure A-4. The action is a two arm lift of a container weighing 16.5 pounds.

Table 28

Physical Parameters and Resulting E_D Prediction for

Two Arm Lift of 16.5 Pound Container

Number Arms	Weight Lifted (pounds)	Average Elapsed Time (seconds)	Observed E_D (Kcal/min)	Predicted $\hat{E}_D$ (Kcal/min)	Percent Deviation $\left[\frac{E_D - \hat{E}_D}{\hat{E}_D}\right] 100$
1	8¼	0.49 (fast)	7.39	4.82	+53%
		0.47 (fast)	5.27	4.82	+9%
		0.71 (med)	4.32	1.85	+134%
		0.70 (med)	3.28	1.85	+72%
		0.91 (slow)	2.85	1.21	+135%
		0.90 (slow)	2.36	1.21	+95%
2	6½	0.49 (fast)	3.77	3.78	-0-
		0.70 (med)	2.12	1.69	+25%
		0.67 (med)	3.49	2.12	+65%
		0.89 (slow)	2.81	1.17	+140%
	16½	0.51 (fast)	9.08	8.09	+12%
		0.72 (med)	6.89	3.52	+96%
		0.71 (med)	6.53	3.52	+85%
		0.93 (slow)	4.47	2.39	+87%
	26½	0.52 (fast)	13.07	14.77	-11%
		0.75 (med)	10.63	5.87	+81%
		0.72 (med)	8.39	6.22	+35%
		0.95 (slow)	5.70	4.19	+36%

Medium Speed - time values are MTM normal times

Slow and Fast Speeds = ± 30% of MTM normal times

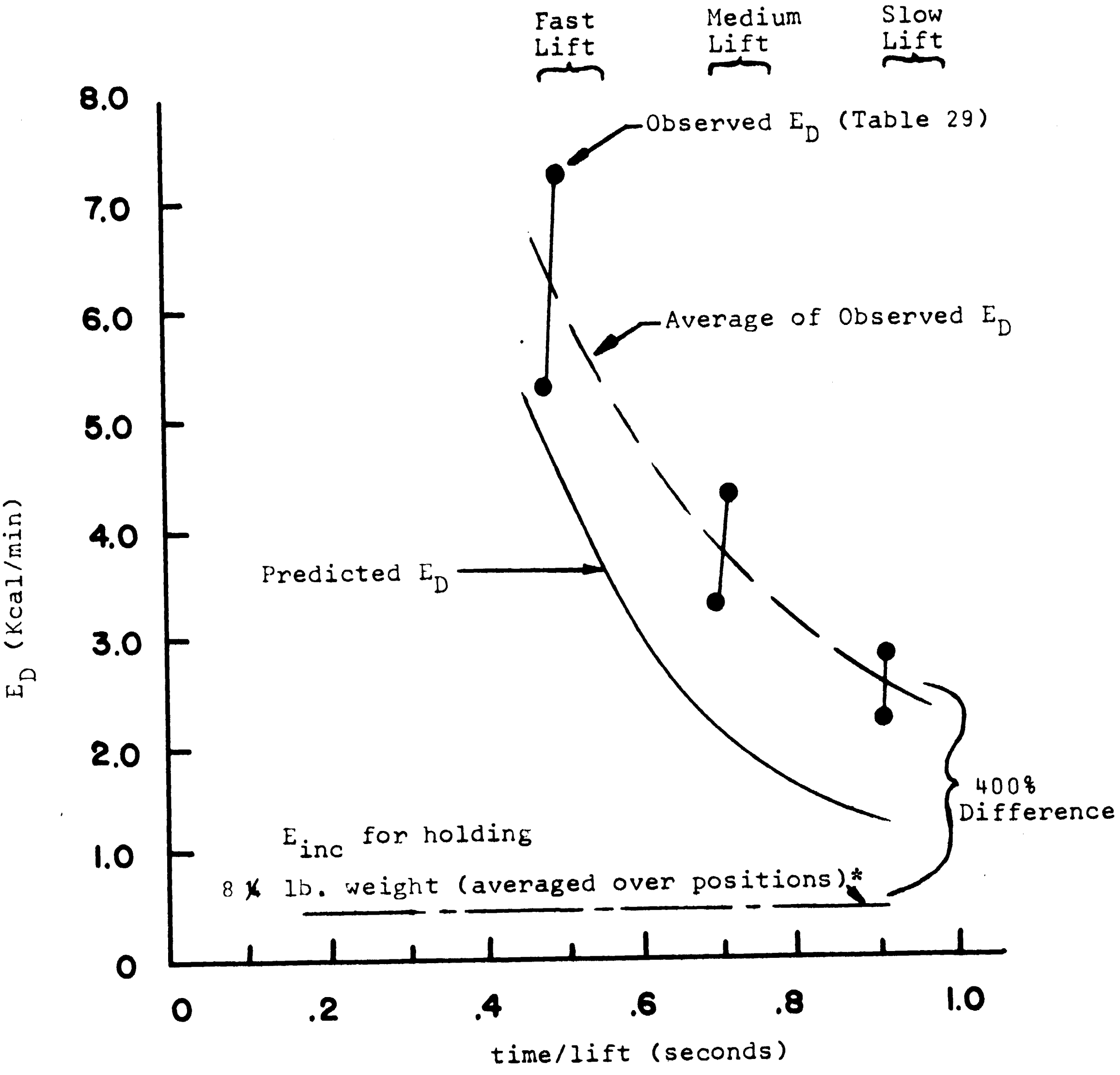
Table 29

Whole Arm Model - Dynamic Task Validation Study Results attached to the object permitted the determination of the instantaneous velocity and displacement of the object during each lift. These values were used to compute the resultant torques, angular displacements, and angular velocities (by the procedure in Appendix A) that are used in the prediction model of Figure 28. To maintain the desired average elapsed time of each lift, the subject viewed an electronic timer which was actuated by switches at the beginning and end of the area that was traversed by the object during each lift.

An analysis of the actual and predicted $\hat{E}_D$ values disclosed that only 46 percent of the variation in the actual values had been accounted for by the model. It was also noted that the predictions were more accurate for the higher speed motions. A summary of the deviations of the actual values from those predicted is as follows: 13 percent high for the fast lifts, 74 percent high for the medium speed lifts, and 99 percent high for the slow lifts. Figure 29 graphically displays the actual and predicted values for the 8 1/4 pound one arm lifts.

It was concluded from the results of the model validation that a significant difference between the predictions and the actual E_D values existed as the speed of the motion decreased. A discussion of this difference follows.

The basic form of the <u>speed effect</u> on E_{inc} was



*This value is equivalent to weight being moved infinitely slowly.

Figure 29

Observed versus Actual E_D for One Arm

8 1/4 Pound Lifts

empirically well substantiated for the one elbow flexion activity under constant angular velocity conditions (page 189). However, three assumptions had to be evoked to extend this effect into a whole-arm dynamic task prediction model (page 190). The first assumption was that the speed effect on E_{inc} was similar for all the muscle group actions. This assumption was not believed to be a major cause of error, based on the results of two additional dynamic task metabolic experiments with the same subject. In these experiments, a one shoulder flexion was performed, with an average torque of 320 Kilogram-centimeters. The two angular velocities used were 1.05 and 2.01 radians per minute. The speed effect constant P, estimated from the resulting data, was 1.981. This value is lower than the 2.559 derived for the one elbow flexions (page 190). Therefore the speed effect predicted at the shoulder would be lower than the effect used in the existing model that was compared in the preceding whole-arm validation study.

The second assumption concerned the consistency of the torque interaction effect between dynamic and static activities. Since the interaction which is in question exists between the shoulder and elbow, and is usually less than 10 percent of the total E_{inc} (Table 16), it did not appear that violation of this assumption could cause the large differences in E_D that were disclosed during the slow speed validation lifts.

The third assumption stated that any torque and speed variation during a motion should not affect the accuracy of the $\hat{E}_D$ predictions. In retrospect, it was found that this assumption (or an extension of it) could be a major contributor to the type of errors detected in the preceding whole-arm validation studies. In evaluating the experimental procedure used in the validation experiments (page 190), it was recognized that some amount of muscle control was required by the subject to move the object a prescribed distance, with the restriction that he obtain maximum accuracy in the elapsed time. For the fast lifts this control effect on E_D could be minimized, since the movement times were so short that the subject could not adjust his motion while performing it. Thus the only muscles used were those contributing directly to the lift. In the medium and slow speed moves, the subject changed acceleration during the lifts, so as to reach the end point of the lift at the prescribed time. It is hypothesized that in exerting this control, he could have been using muscles antagonistically to maintain this type of control. The end result being that additional tension, and therefore heat energy, would be expended, as discussed by Weir (59).

To attempt to confirm the existence of a control effect on E_D, two additional metabolic experiments were performed by another subject (E.H. in Subject Data Table, B-1). In the first experiment he lifted the object in much the same manner as described in the preceding section (i.e. he attempted to obtain a predetermined time). In the second experiment he did not refer to the timer but lifted at what he believed to be a comfortable and consistent speed. (The time was recorded by the experimenter for the E_D computation.) The average lifting times for each experiment were within 0.05 seconds of each other. The result was that the E_D value for the first time controlled task was 152 percent of the latter self-paced task. This was believed to be a reasonable justification for hypothesizing the existence of a control effect on E_D, which hopefully will be substantiated in future research.

Summary of Chapter

The dynamic task research reported in this chapter was performed with the subject whose static task results are reported in Chapter IV. The initial research was an attempt to extend Hill's single muscle energy model to predict the metabolic rate of the subject when performing simple elbow flexions at different angular velocities and torques. The conclusion drawn from this research was that a separate heat loss term, based on the speed of the flexion, can not be added to the mechanical power and heat of maintenance predicted for a muscle group's action (page 184).

The objective of the second phase of the research was to derive an alternative, dynamic task, metabolic prediction model for muscle group actions. The formulation presented and substantiated for a single elbow flexion was:

$$E_D = \hat{E}_{inc} \, (2.559)^{\omega}$$

which stated that the energy expended per minute of a dynamic task E_D is simply the average $\hat{E}_{inc}$ for an equivalent static task multiplied by an empirically substantiated function of the angular velocity. The function derived had the constant 2.559 raised to the power ω. This function was then utilized (with assumptions presented on page 190) to form the single subject metabolic prediction model for whole arm dynamic activities presented in Figure 28, page 192.

Validation studies of the $\hat{E}_D$ prediction model were performed. These disclosed that the predictions accounted for only 46 percent of the variation in E_D for a group of weight lifting studies performed at different loads and speeds (page 195). It was found, in addition, that the prediction error was highly dependent upon the speed of the lifts (page 195). The primary reason proposed for this result was that the experimental procedure used in the validation studies required the subject to exert extra effort (and thus E_D) to control the speed of movement during the slower lifts (page 190).

Chapter VII

SUMMARY AND DISCUSSION

The general concept that has been proposed and substantiated by this research is that the amount of incremental metabolic energy expended by a person (E_{inc} or E_D) is primarily a function of the torque produced at each articulation by the inertial and gravitational forces exerted upon each body segment. The form of this torque-E_{inc} or E_D relationship has been empirically related to the following conditions:

1. The particular muscle group action that is studied (i.e. flexion or extension; shoulder, elbow, or wrist; one or two arms)
2. The articulation angle at which the torque is occuring
3. The magnitude of the torques at adjacent articulations
4. The person who is performing the task
5. The speed at which a dynamic task is performed

The Torque-E_{inc} Relationship during Static Tasks

Eight different muscle group actions were studied in this project. These were:

1. One Shoulder Flexion

2. Two Shoulder Flexion
3. One Shoulder Extension
4. Two Shoulder Extension
5. One Elbow Flexion
6. Two Elbow Flexion
7. One Wrist Flexion
8. Two Wrist Flexion

In general, the energy expended per minute of sustained contraction increases with the magnitude of the torque at each articulation (Figures D-1 through D-7 in Appendix D). By increasing the torque in defined steps during each of the above muscle actions, it was determined that the magnitude of the E_{inc} increases at a rate that is dependent upon which particular muscle action is involved (page 143).

The resulting <u>change</u> in E_{inc}, for given changes in the torque during each of the eight preceding muscle actions, was found to be similar for: 1) the four subjects tested (page 173), 2) one and two wrist flexions (page 125). It was also found that though the angle of the elbow or shoulder could affect the magnitude of E_{inc} by over 200 percent (Figures D-8 through D-13), the variation in the E_{inc} values caused by different angles appears to remain consistent between individuals (page 157).

It was determined, however, that individual differences in E_{inc} for a given torque could be as great as 300 percent, and that the difference was not constant for different levels of E_{inc}, or for all the muscle group actions studied (pages 173 and 174). The consequence of this disclosure was that a metabolic prediction could vary by more than 300 percent between individuals if the metabolic efficiency of each individual's different muscle actions was not first ascertained and used to correct the prediction model parameters (page 174).

The results of the static arm research have resulted in $\hat{E}_{inc}$ being predicted for each i^{th} muscle action by the following formulation:

$$\hat{E}_{inc_{i\gamma m}} = f\left[\hat{E}_{W_{i\gamma m}} = d_{im}\, a_{i\gamma}\, T_i^{\,b_i}\right]$$

where:

$\hat{E}_{inc_{i\gamma m}}$ - predicted average incremental metabolic energy expended per minute of torque T sustained by the i^{th} muscle action, of the m^{th} subject (expressed in Kilogram-calories per minute)

$\hat{E}_{W_{i\gamma m}}$ - weighted $\hat{E}_{inc}$ values (page 164)

$a_{i\gamma}$ - first subject's muscle group efficiency coefficient for i^{th} muscle action and γ articulation angle, as predicted by equations in Table 8 and graphed in Figures D-8 through D-13

d_{im} - individual difference parameter, which is equal to the $a_{i\gamma m}$ value of m^{th} subject divided by the $a_{i\gamma}$ value of the first subject (page 161).

T_i = resultant torque at articulation spanned by muscles that produce the i^{th} muscle action

b_i = the i^{th} muscle action's exponent which transforms the rate of increase in torque to be proportional to the increase in E_W (values in Table 6 and page 125).

It was also found that when torques exist at two adjacent articulations, as is the situation during most whole-arm activity, the sum of the predicted $\hat{E}_{inc}$ values for each articulation action will be greater than the actual E_{inc} (page 140). The amount of difference was correlated with the cross product of the torques at each articulation, and the resulting torque interaction effect (Table 14) was incorporated into the whole-arm metabolic prediction model (Figure 24, page 143). Since the magnitude of the $\hat{E}_{inc}$ contributed by the torque interaction effect was found to be small in many types of whole-arm moves, it was assumed to be the same for different subjects. Subsequent validation studies involving whole-arm activities with three subjects appeared to substantiate this assumption.

The validation of the preceding metabolic prediction model disclosed that the model predictions accounted for between 85 and 97 percent of the variance in the subjects' E_{inc} during various one and two arm weight holding activities.

Discussion and Recommendations for Future Research of E_{inc} during Static Arm Activities

The static arm metabolic energy prediction model developed in this research project is believed to be a contribution to the objective of understanding the complex behavior of the skeletal-muscle system during arm activities. The prediction model gives a structure to all of the factors which have been shown by past research (see literature review, pages 8-11) to affect a person's metabolic energy expenditure rate.

Because of the many variables that were found to have a significant effect on E_{inc}, the metabolic prediction model, in its present form, is numerically difficult to use. This difficulty can not be reduced by simplifying the metabolic equations because the basic torque computations would still be lengthy. It therefore appears that implementation of the model for work-place design and evaluation could possibly be best accomplished by an on-line computer with a cathode-ray tube input-output display. In this way, the job designer could modify the work-place and worker's dimensions and achieve immediate feedback as to the resulting change in the metabolic rate required by the worker. It is hoped that this extension can be developed in the future.

The complexity of the prediction model makes it difficult to develop an intuition as to how E_{inc} varies with different whole-arm static activities. To help in achieving this intuition, two tables of E_{inc} values for the first subject have been computed, with the only two input variables being the position of the arms (as expressed by the shoulder and elbow angles), and the weight of an object held in the subject's hands (see Tables 30 and 31 on the next two pages). The following two observations are made from inspection of these tables:

1. By holding a weight close to the body (i.e. $\gamma_s = -30^\circ$ or 0°) the E_{inc} predicted is lower than the other positions due to the low resultant articulation torques. This is particularly interesting when it is realized that neither $\gamma_s = 0^\circ$ or $\gamma_s = -30^\circ$ is the most efficient angle for the shoulder (Figures D-1 and D-2). Therefore the change in muscle efficiencies with angle is only important when the torque is not altered, as is the situation when the elbow is rotated ($\gamma_e = 55^\circ$, 80°, and 110°) while the shoulder remains at $\gamma_s = 0^\circ$. In general then, for this subject the torque effect on E_{inc} overpowers the angle effect, thus resulting in the most efficient working area being the area closest to the body.

2. In general, when holding any load over 10 pounds, the use of two arms is metabolically justified.

In addition to developing work place design criteria, the prediction model research has for the first time (to

Shoulder Angle γ_s (degrees)	Elbow Angle γ_e (degrees)	Predicted $\hat{E}_{inc}$ Values in Kcal/minute of Holding Weights with One Arm (Weight values in pounds)					
		Empty	5	10	15	20	25
-30°	55°	0.03	0.22	0.66	1.65	3.94	*
	80°	0.02	0.12	0.33	0.76	1.65	3.60
	110°	0.01	0.09	0.19	0.38	0.67	1.16
	140°	0.01	0.03	0.06	**	**	**
0°	55°	0.03	0.19	0.54	1.27	2.82	*
	80°	0.02	0.18	0.56	1.47	3.89	*
	110°	0.02	0.19	0.58	1.45	3.60	*
	140°	0.02	0.11	0.29	0.60	1.14	2.10
	170°	0.00	0.02	0.04	**	**	**
+30°	55°	0.02	0.13	0.34	0.76	0.69	4.00
	80°	0.03	0.21	0.71	2.40	*	*
	110°	0.04	0.34	1.29	5.22	*	*
	140°	0.04	0.33	1.21	4.54	*	*
	170°	0.03	0.20	0.60	1.62	4.72	*
+60°	80°	0.04	0.19	0.64	2.05	*	*
	110°	0.06	0.43	2.00	*	*	*
	140°	0.07	0.63	3.69	*	*	*
	170°	0.07	0.60	3.31	*	*	*
+90°	110°	0.05	0.30	1.18	5.08	*	*
	140°	0.08	0.65	4.08	*	*	*
	170°	0.10	0.94	*	*	*	*
+110°	110°	0.04	0.15	0.44	1.18	3.33	*
	140°	0.06	0.42	1.98	*	*	*
	170°	0.09	0.82	6.35	*	*	*

Note: Predictions in Kcal/min of holding weight.
Input data from first subject (165 lbs, 5'8")

* Values would require extrapolation of prediction data that model is derived from.

**Values excluded due to lack of finger grip E_{inc} prediction.

Table 30

Predicted $\hat{E}_{inc}$ for One Arm Weight Holding Activities

Shoulder Angle γ_s (degrees)	Elbow Angle γ_e (degrees)	Predicted $\hat{E}_{inc}$ Values in Kcal/minute of Holding Weight with Both Arms (Weight values in Pounds)					
		Empty	10	20	30	40	50
-30°	55°	0.14	0.58	1.29	2.51	4.92	*
	80°	0.11	0.39	0.86	1.66	3.22	*
	110°	0.12	0.22	0.43	0.71	1.08	1.66
	140°	0.12	0.24	0.38	**	**	**
0°	55°	0.16	0.51	0.95	1.57	2.61	*
	80°	0.15	0.48	0.92	1.68	3.31	*
	110°	0.16	0.51	0.96	1.70	3.15	*
	140°	0.12	0.39	0.68	1.05	1.55	2.31
	170°	0.04	0.12	0.20	**	**	**
+30°	55°	0.17	0.44	0.75	1.14	1.66	2.37
	80°	0.20	0.55	1.01	1.74	2.99	*
	110°	0.24	0.71	1.41	2.71	*	*
	140°	0.25	0.74	1.46	2.72	*	*
	170°	0.20	0.57	1.03	1.69	3.82	*
+60°	80°	0.26	0.68	1.32	2.37	4.08	*
	110°	0.34	1.05	2.37	*	*	*
	140°	0.39	1.32	3.23	*	*	*
	170°	0.39	1.30	3.11	*	*	*
+90°	110°	0.31	0.85	1.76	3.33	*	*
	140°	0.40	1.31	3.14	*	*	*
	170°	0.45	1.61	4.20	*	*	*
+110°	110°	0.23	0.54	1.01	1.73	2.81	4.43
	140°	0.35	1.05	2.32	4.71	*	*
	170°	0.43	1.52	3.86	*	*	*

Note: Predictions in Kcal/minute of holding weight.
Input data from first subject (165 lbs, 5'8")

* Values would require extrapolation of data that model is derived from.

**Values excluded due to lack of finger grip E_{inc} prediction.

Table 31

Predicted $\hat{E}_{inc}$ for Two Arm Weight Holding Activities this author's knowledge) separated the differences in the metabolic energy expenditure of various persons performing physical tasks into two categories: 1) that which is due to differences in body weight and size, and 2) that which is due to a change in the muscle group efficiencies. With this separation of effects has come the realization that the E_{inc} values between individuals can vary substantially, even though the mechanical output (i.e. torque) is the same.

It is believed that future research of this type of individual difference could produce significant benefits in the area of selecting and placing personnel for various types of physical tasks. As an example of this, it is understood by this author that one large manufacturing organization is placing only the women with large wrist and elbow dimensions into jobs that require the use of heavy hand tools. Their justification for this has been the occurrence of forearm muscle pains in women with small arm bones. This could be attributed to local muscle fatigue in those individuals that have low elbow and wrist muscle efficiencies. One problem in the present placement procedure is that those individuals with large elbow and wrist dimensions may have heavy arms and hands. This would raise the torques, thus possibly requiring as much or more E_{inc} than a smaller boned individual. In conclusion then, the resulting 300 percent variation in E_{inc} found between two subjects in one simple task is justification for further research of the effects of individual difference on E_{inc}.

The Torque - E_D Relationship during Dynamic Tasks

The dynamic task research disclosed the following:

1. The effects of torque and angular velocity on E_D were in some manner confounded, and could not be treated as a summation of the energies hypothesized as being liberated from a single muscle contraction (page 184).

2. The effects of different torques and angular velocities during the subject's one elbow flexion actions were explained by:

   $$\hat{E}_D = \hat{E}_{inc} (2.559)^{\omega}$$

   which was found to have a correlation coefficient of 0.94 (page 189).

3. The use of the speed effect (derived from the elbow data) as a basis for a whole-arm metabolic prediction model for dynamic tasks (Figure 28) appeared to be justified for fast motions (page 195), but considerable error was found when predicting the $\hat{E}_D$ for slower motions (page 196).

4. The study of slow movements with a preset elapsed time produced experimental results which suggest that future metabolic research on dynamic tasks will need to consider the amount of muscle control as a separate variable.

Recommendations for Future Research of E_D during Dynamic Arm Activities

The research of the E_D during dynamic tasks has stimulated the following recommendations for future research:

1. The possibility of a control effect on E_D raises many questions as to the applicability of metabolic rates to tasks other than the task on which the rate was estimated. It is believed that resolving whether or not the control effect is significant should be part of the future research in work physiology.

2. The single muscle energy models proposed by various muscle physiologists should be extended to the functioning skeletal muscle system. Only in this way will a true understanding of the various factors studied in this project be possible. It is proposed that to utilize the single muscle models, there must first be a complete specification of the activity that is being performed. This will require knowledge of the forces exerted on and within the body. Only by combining measures of a person's metabolic rate and multiple action potentials, augmented by a biomechanical analysis, will it be possible to describe a skeletal muscle system.

Appendix A

The Mechanics of Arm Activities

This appendix presents the mechanics equations applicable to two types of arm activities in the sagittal plane. The first occurs where the arm is resisting external forces but is not moving. This activity will be referred to as a static activity, and requires the muscles to create tension by isometric contraction. The second arm activity discussed occurs when the muscle tensions and external forces are not equal at each articulation, thus resulting in planar motion of the arm. This situation will be referred to as a dynamic activity and requires non-isometric contractions of the arm muscles.[1]

Mechanics of Static Arm Activities

Since the arm is considered to be a three bar linkage under the assumptions presented in Chapter 2, a static arm activity only exists if the resultant forces and moments created at each articulation by external forces on the arm are balanced by the reactive forces and moments created by the arm muscles. Figure A-1 displays a free body diagram of the arm as

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[1] The term non-isometric contractions is used to indicate that the angular acceleration at an articulation could be varying during a dynamic activity, thus changing the torque. If the torque remained constant during the motion, then the muscle action will be referred to as isotonic.

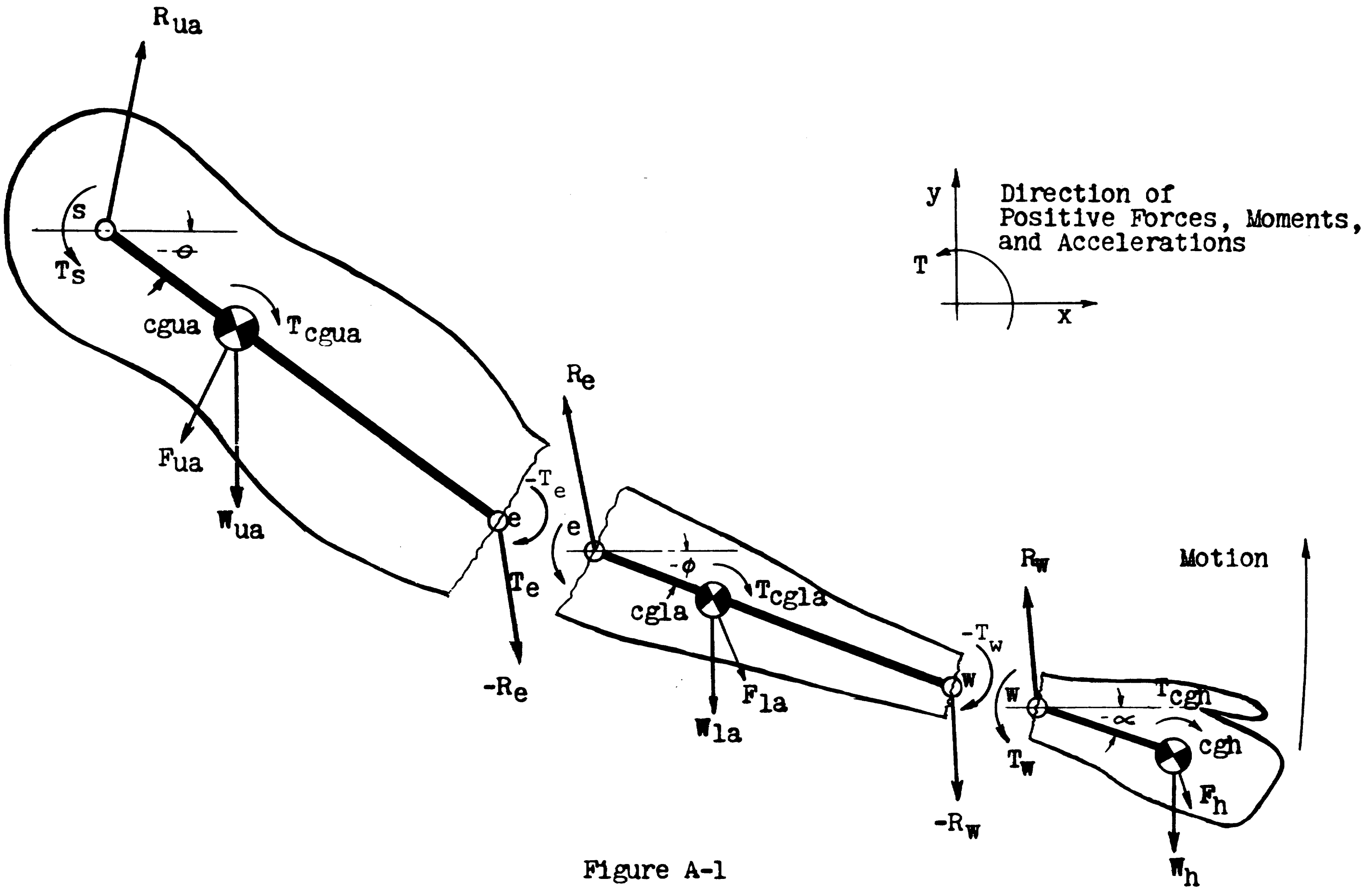

Figure A-1

Articulation Forces and Moments during Arm Motion described in Chapter 2. The anthropometric relationships required to obtain values for the various dimensions described in the following equations are explained in Table A-1.

From both Newton's Third Law and the Principle of Moments, the reactive forces and moments at the wrist can be expressed as:[1]

$$R_w = -W_h \qquad \text{(A-1)}$$

$$T_W = -[(w \cdot cgh)(\cos\alpha)(W_h)] \qquad \text{(A-2)}$$

Where:

R_w - reactive force at wrist

W_h - weight of hand (ref. Table A-1) and weight of object that may be held in hand

T_w - reactive torque at wrist

$w \cdot cgh$ - distance from wrist joint to center of gravity of hand and object (ref. Table A-1)

α - angle between horizontal axis and line connecting hand center of gravity and wrist joint.

Similarily, the reactive forces and moments at the elbow are:

$$R_e = -[W_{1a} - R_w] \qquad \text{(A-3)}$$

$$T_e = [T_w + T_{ew} + T_{ecgla}] \qquad \text{(A-4)}$$

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[1] The (•) designates that the distance between two reference points is being considered.

Arm Weight Distribution: (Kg) (ref. 30:187)	Corr. Coef. (r):
W_h = Hand Weight = 0.0063(Body Weight)	r = 0.96
W_{la} = Lower Arm Weight = 0.0155(Body Weight)	r = 0.95
W_{ua} = Upper Arm Weight = 0.0265(Body Weight)	r = 0.95

Measurement End Points for Radius (31: 247): (with forearm semiprone, elbow nearly extended and relaxed)

Proximal end point: The palpable sulcus between the circumference of the radius and the capitulum of the humerus at the humeroradial articulation in the dimple posterolateral to the elbow = radiale.

Distal end point: The palpable tip of the radial styloid process at the lateral border of the wrist = radial styloid.

Conversions to Upper and Lower Arm Link Lengths (31:253-256): (cm.)

(e·w) = Lower Arm Link = [1.0709 (Radius Length)] coef. var. = 3.53%

(s·e) = Upper Arm Link = [5.80752 + (0.9646 x Radius Length)] r = 0.94

Locations of Arm Centers of Gravity from Proximal Articulation (30: 192):(cm.)

(s·cgua) = Shoulder to Upper Arm Center of Gravity = [0.436(s·e)]

(e·cgla) = Elbow to Lower Arm Center of Gravity = [0.430(e·w)]

Reference Points of Hand Link (30: 125): (with hand relaxed)

(w) = Wrist axis location: On the palmar side of the hand, the distal wrist crease at the palmaris longus tendon, or the midpoint of a line between the radial styloid and the center of the pisiform bone; on the dorsa side of the hand, the palpable groove between the lunate and capitate bones, on a line with metacarpel bone III.

(cgh) = Center of gravity of the hand: A point on the skin surface midway in the angle between the proximal transverse palmar crease and the radial longitudinal crease in line with the third digit; flattening or cupping the hand changes the relative location of this point very little, except to change the position normal to the skin surface.

Conversion to Hand Link Length (30: 192): The length of the slightly oblique line from the wrist center (w) to the center of gravity of the hand(cgh).

(w·cgh) = hand link = 0.506(wrist axis to knuckle III)

Mass Moment of Inertias of Body Segments at Centers of Gravity (62: 106): (expressed in gram - centimeter - sec^2) by application of relationship

$I = \frac{K}{M}$, where K = radius of gyration expressed as a fraction of link length, which gives:

I_{cgh} = $[(W_h/g)(0.587 \times (\text{wrist axis to knuckle III}))]$

I_{cgla} = $[(W_{la}/g)(0.526 \times (e \cdot w))]$

I_{cgua} = $[(W_{ua}/g)(0.542 \times (s \cdot e))]$

The mass moment of inertias of various shaped objects which may be held in the hand can be computed from equations in reference (67) pages 222 thru 231.

Table A-1

Definitions and Computations for Arm Dimensions

Where the new variables are:

R_e - reactive force at elbow

W_{1a} - weight of lower arm link (ref. Table A-1)

T_e - reactive torque at elbow

and the contributing torques T_{ew} and T_{ecgla} are computed by:

$$T_{ew} = [(e\cdot w \quad x \quad \cos \phi)(R_w)] \qquad \text{(A-5)}$$

$$T_{ecgla} = [(e\cdot cgla \quad x \quad \cos \phi)(-W_{1a})] \qquad \text{(A-6)}$$

Where:

T_{ew} - reactive torque due to reactive force at wrist

e w - distance from elbow to wrist (ref. Table A-1)

ϕ - angle between horizontal axis (located to right of origin) and line connecting elbow and wrist centers of rotation

T_{ecgla} - reactive torque due to weight of lower arm link

e·cgla - distance from elbow to center of gravity of lower arm (ref. Table A-1).

The computation of the reactive forces and torques at the shoulder is accomplished in the same manner as for the elbow (equations A-3 and A-4).

It can be seen that the human body is characterized for the computations by the three link lengths and weights as described in Table A-1. The static activity is described by the angles at each articulation and the amount of weight held in the hand.

Mechanics of Dynamic Arm Activities

A planar motion of the arm is more complicated to analyze than the static arm situation. Pearson et al. developed a two link biomechanical model of this case, which assumes the hand and lower arm to be a single link of the two link system (61). The following equations treat the hand and lower arm as separate links, thus requiring a three bar linkage analysis. This is, however, a simple extension of Pearson's analysis (61).

Essentially, two differences occur between the static and dynamic cases. First, in the dynamic case the external forces exerted on the segments of the arm must include, in addition to gravity, the effects of inertia. Therefore, the forces acting on each segment do not necessarily act in the same direction. This now requires vector addition of the forces, which was not required in the static case where all forces acted in a parallel direction to gravity.

The second addition required to transform the static model into a dynamic model is the inclusion of an inertial torque at the center of gravity of each segment. This term characterizes the force created by rotational acceleration of the segments about their gravity centers.

A Method for Quantifying the Arm Motion

The first phase in the development of a dynamic analysis of the arm requires the resolution of the instantaneous angular displacements, velocities, and accelerations for each articulation. This can be accomplished by directly measuring each, or by kinematic analysis. Because the measuring equipment required to measure simultaneously the instantaneous accelerations, velocities, and displacements was not available, a kinematic model was developed.[1] The following discusses the development of this model.

It was noted by Pearson et al. that the semiprone hand and the lower arm remained aligned during motions which involved the whole arm in the sagittal plane (61:4). In addition, McFarland states that the average person's elbow can flex through an angle of only 138 degrees (54:95). The realization of these two concepts allowed the development of the following method for

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[1] Pearson et al. used a film analysis to determine discrete angular displacements at the shoulder and elbow during arm motions and then computed the angular velocities and accelerations using repeated finite differencing of a Taylor series of the discrete displacement data (61:11-13). This method was attempted by the author but due to the photographic technique employed, which limited the minimum time intervals to 0.05 seconds, an unacceptable "round off" error was found with acceleration patterns as depicted in Figure A-3.

resolving the angular accelerations at the various arm articulations.

Initial Conditions.

First, the initial location of the hand center of gravity at the onset of a motion is established in respect to the shoulder joint. This is accomplished by measurements of the horizontal and vertical distances between these two points. Figure A-2 displays these measurements as x_o and y_o distances. The c length of the right triangle (s-0-cgh) is found by:

$$c = \sqrt{x_o^2 + y_o^2} \quad . \tag{A-7}$$

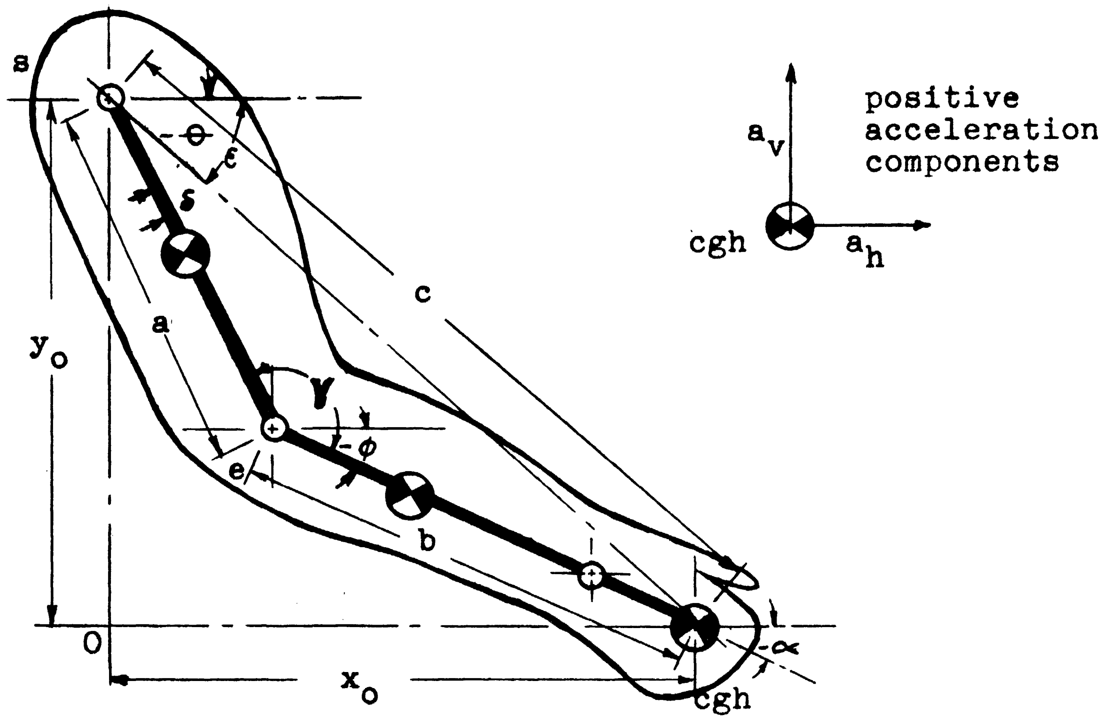
The c dimension is then used to obtain the angle ε by:

$$\varepsilon = \cos^{-1}\left[\frac{x_o}{c}\right] \quad . \tag{A-8}$$

Since the c side is common to both the (s-0-cgh) and (s-e-cgh) triangles, and the a and b dimensions are known for a subject, the perimeter p and the radius of the inscribed circle r of the oblique triangle (s-e-cgh) can be obtained as follows (23:21).

$$p = 1/2\ (a + b + c) \tag{A-9}$$

$$r = \sqrt{\frac{(p-a)(p-b)(p-c)}{p}} \tag{A-10}$$



Where:

a - Upper Arm Link Length (Table A-1)

b - Lower Arm Link and Hand Link Length (Table A-1)

c - Reference Distance between Shoulder and Hand Center of Gravity

x_o & y_o - Horizontal and Vertical Initial Distances from Shoulder to Hand Center of Gravity

ϕ, θ, α - Articulation Angles to Horizontal Axis

δ, γ - Included Angles in Oblique Triangle (s-e-cgh)

ε - Angle between (c) Dimension and Horizontal Axis at Shoulder (s)

Figure A-2

Trigonometric Representation of Arm

These quantities are then used to compute the included angles of the oblique triangle (s-e-cgh) as follows (23:21).

$$\delta = 2(\tan^{-1} \frac{r}{p-b}) \qquad \text{(A-11)}$$

$$\gamma = 2(\tan^{-1} \frac{r}{p-c}) \qquad \text{(A-12)}$$

Thus, the initial angles from the arm segments to the horizontal axis at the shoulder, elbow, and wrist (defined as θ_o, ϕ_o, and α_o respectively) are as follows:

$$\theta_o = [\varepsilon + \delta] \qquad \text{(ref. A-8, A-11)} \qquad \text{(A-13)}$$

$$\phi_o = [\gamma - (180 - \theta_o)] \qquad \text{(ref. A-12, A-13)} \qquad \text{(A-14)}$$

$$\alpha_o = \phi_o \qquad \text{(ref. A-14, assumption)} \qquad \text{(A-15)}$$

The preceding method for determining the magnitude of each articulation angle can easily be utilized to determine the angular velocities and accelerations as the arm moves. To accomplish this, two additional measurements are required. These are the instantaneous horizontal and vertical acceleration components of the center of gravity of the hand. By measuring and integrating these accelerations in respect to the elapsed time of the move, the plane motion of the hand can be described in terms of its dy and dx displacements from the initial position y_o and x_o. This is obtained by numerical integration, since the mathematical descriptions of the acceleration functions are unknown. The numerical integration technique is described in the following subsection.

Angular Change during Arm Motion.

Consider the instantaneous accelerations above gravity depicted in Figure A-3 as representing the vertical acceleration of the hand center of gravity during a vertical motion.

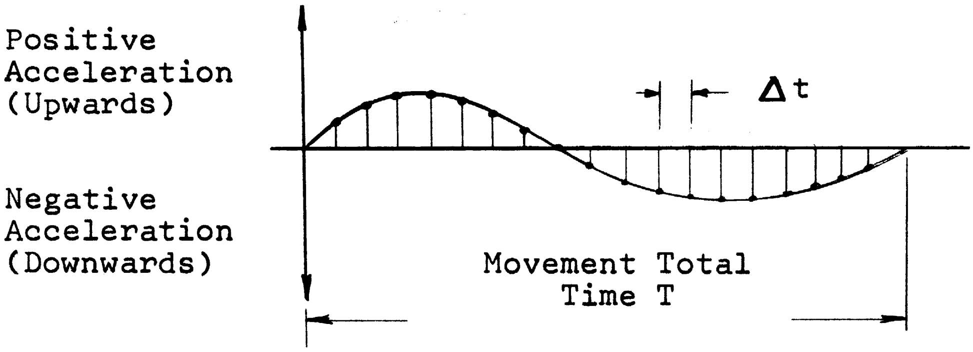


Figure A-3

Instantaneous Vertical Accelerations at Hand Center of Gravity

Let the instantaneous accelerations be represented as $a_o, a_1, a_2 \ldots a_i \ldots a_n$, where $(i=0,1,2\ldots n)$ time intervals of Δt time and $(T = n\Delta t)$. Assuming

Δt intervals are constant and small, the velocities and vertical displacement of the hand during the motion can be approximated by using the trapezoidal area in successive i intervals, which yields:

$$v_i = \begin{bmatrix} \text{velocity} \\ \text{at } i^{th} \text{ interval} \end{bmatrix} = \Delta t(a_{i-1} + a_{i+1}) \qquad \text{(A-16)}$$

$$d_i = \begin{bmatrix} \text{displacement} \\ \text{at } i^{th} \text{ interval} \end{bmatrix} = \Delta t(v_{i-1} + v_{i+1}) \; . \qquad \text{(A-17)}$$

Test of Displacement Approximation Method.

The central question regarding the use of the above procedure is, "How small does Δt need to be to obtain an acceptable accuracy?" Smaller values would give greater accuracy, but require timely data reduction procedures. Therefore, an experiment was designed to evaluate the effects of different time intervals in estimating the displacement for a given acceleration pattern.

Acceleration data from a 20 inch vertical lift were the inputs into the above computations. The experiment procedure is as follows (Figure A-4 describes the setup): The subject performing the lifts was first told the normal time for the move, as determined by the Methods - Time Measurement System (8:420). The subject performed 20 practice lifts, after which three lifts were recorded. After each lift

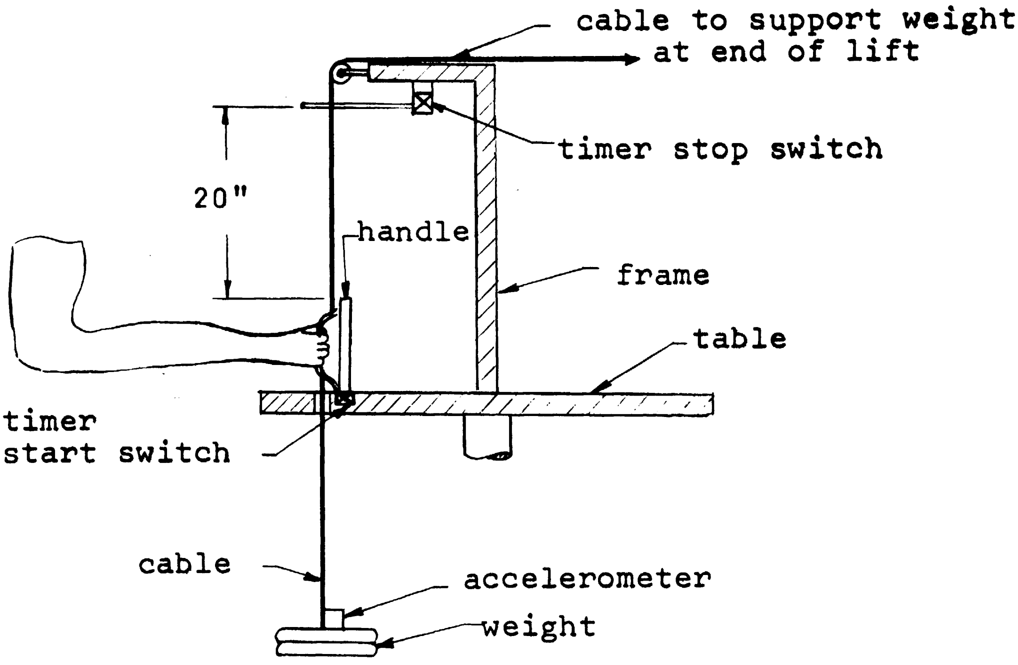


Figure A-4

Dynamic Lifting Setup

he was told what his time was, but was not encouraged to adhere to the MTM normal time, but rather to move at a "comfortable" rate. The total time T of the lifts was obtained to the nearest 0.01 second by micro switches which would start and stop an electric timer. The instantaneous acceleration was recorded on a linear strip chart recorder with a paper speed of 5 i.p.s.. The accelerometer gain was adjusted to one inch per g.

An average acceleration function in respect to time is depicted in Figure A-3. The continuous acceleration function was approximated by choosing and recording points at discrete intervals of 0.01, 0.02, 0.05, and 0.10 seconds. These values were used in computing the distance moved for each of the three total measured times T. The predicted displacements for each of the motions, and for the different time intervals are depicted in Table A-2.

Time Interval Δt Lift	0.01 sec.	0.02 sec.	0.05 sec.	0.10 sec.
1	19.6	19.4	23.6	17.2
2	20.7	20.4	20.5	18.1
3	19.5	19.6	17.7	18.2
Average Error	0.5	0.5	2.1	2.2

Table A-2

<u>Predicted Displacements (inches)</u>
<u>vs. 20 Inch Lift</u>

Numerical integration using the trapezoidal area equations was thus assumed to be an adequate method of determining the displacement if a maximum $\Delta t \leq 0.02$ sec. is utilized, with an acceleration function such as Figure A-3. This method, i.e. equations A-16 and A-17, furnished the displacement values required to compute, by equations A-7 through A-15, the values of the articulation angles at each i^{th} time interval.

The foregoing procedure can now be used to compute the angular velocities and accelerations by a method proposed by Pearson et al. (61:11-13). Again, numerical analysis is used to differentiate the unknown displacement functions.

Define ϕ_i as the included angle at the elbow at the i^{th} interval, Δt time long. By a Taylor series expansion:

$$\phi_{i+1} = \phi_i + \Delta t\dot{\phi}_i + \frac{\Delta t^2}{2}\ddot{\phi}_i + \ldots \qquad \text{(A-18)}$$

and:

$$\phi_{i-1} = \phi_i - \Delta t\dot{\phi}_i + \frac{\Delta t^2}{2}\ddot{\phi}_i + \ldots \qquad \text{(A-19)}$$

where $\dot{\phi}$ and $\ddot{\phi}$ are the first and second derivatives in respect to time, which for this situation are the angular velocities and accelerations respectively. When (A-18) and (A-19) are subtracted and rearranged, the angular velocities and accelerations become:

$$\dot{\phi}_i = \frac{\phi_{i+1} - \phi_{i-1}}{2\Delta t} \qquad \text{(A-20)}$$

and

$$\ddot{\phi}_i = \frac{\phi_{i+1} + \phi_{i-1} - 2\phi_i}{(\Delta t)^2} \qquad \text{(A-21)}$$

These equations can now be used to determine the linear acceleration components of the arm center of gravities by the following computations.

Computation of Linear Acceleration Components and Inertial Forces.

The linear acceleration components for any point on a rotating body can be derived from the kinematic relationship of rectilinear and rotational motion, which state (67:312-314):

$$a_t = r\ddot{\phi} \qquad \text{and } a_n = r\dot{\phi}^2$$

Where:

a_t - tangential acceleration of reference point

a_n - normal acceleration of reference point

r - distance between pivot and reference point on rotating body

$\ddot{\phi}$ - angular acceleration (estimated in A-21)

$\dot{\phi}$ - angular velocity (estimated in A-20).

Therefore, the linear acceleration components at the center of gravity of the upper arm (cgua in Figure A-1) are:

$$A_{cgua/x/i} = [(\ddot{\phi}_i)(s \cdot cgua/y/i) + (\dot{\phi}_i)(\dot{\phi}_i)(s \cdot cgua/x/i)] \qquad \text{(A-22)}$$

$$A_{cgua/y/i} = [(\ddot{\phi}_i)(s \cdot cgua/x/i) + (\dot{\phi}_i)(\phi_i)(s \cdot cgua/y/i)] \qquad \text{(A-23)}$$

Where the variables are:

$A_{cgua/x/i}$ - horizontal acceleration of the upper arm center of gravity at i^{th} interval

$\ddot{\phi}_i$ - angular acceleration of upper arm about shoulder at i^{th} interval (equations A-13 and A-21)

$s \cdot cgua/y/i$ - distance in vertical direction between shoulder and upper arm center of gravity, which equals $(\cos\phi_i)(s \cdot cgua)$; where $s \cdot cgua$ is from Table A-1

$\dot{\phi}_i$ - angular velocity of upper arm about shoulder at i^{th} interval (equations A-13 and A-20)

$s \cdot cgua/x/i$ - same as $s \cdot cgua/y/i$ but in horizontal direction

$A_{cgua/y/i}$ - vertical acceleration of upper arm center of gravity at i^{th} interval.

The inertial forces acting at the upper arm center of gravity at the i^{th} interval can now be computed by Newton's Second Law, which defines inertia as a force equal to mass times acceleration (65:73-76), and by application of D'Alembert's Principle of Motion (67:244-246):

$$F_{ua/x/i} = -[(W_{ua}/g)(A_{cgua/x/i})] \qquad \text{(A-24)}$$

$$F_{ua/y/i} = -[(W_{ua}/g)(A_{cgua/y/i})] \qquad \text{(A-25)}$$

Where the new variables are:

$F_{ua/x/i}$ - horizontal component of inertial force at the upper arm center of gravity at at i^{th} interval

W_{ua} - weight of upper arm (ref. Table A-1)

g - acceleration due to gravity (constant)

$F_{ua/y/i}$ - vertical component of inertial force at the upper arm center of gravity at i^{th} interval.

The vertical and horizontal components of acceleration at the elbow are computed in a similar manner as those at the gravity center of the upper arm. The equations are:

$$A_{e/x/i} = [(\ddot{\phi}_i)(s \cdot e)(\cos\phi_i) + (\dot{\phi})(\dot{\phi})(s \cdot e)(\sin \phi_i)] \qquad \text{(A-26)}$$

$$A_{e/y/i} = [(\ddot{\phi}_i)(s \cdot e)(\sin \phi_i) + (\dot{\phi})(\dot{\phi})(s \cdot e)(\cos \phi_i)] \qquad \text{(A-27)}$$

Where the new variables are:

$A_{e/x/i}$ - horizontal acceleration component of elbow at i^{th} time interval

$A_{e/y/i}$ - vertical acceleration component of elbow at i^{th} time interval

$s \cdot e$ - distance between shoulder and elbow (ref. Table A-1).

The above elbow acceleration components are utilized in the following manner to compute the acceleration at the lower arm gravity center. First the elbow is assumed to be in a fixed position. The acceleration components at the center of gravity of the lower arm can now be expressed as:

$$A_{cgla/x/e/i} = [(\ddot{\phi}_i)(e\cdot cgla)(\cos \phi_i) + (\dot{\phi}_i)(\dot{\phi}_i)(e\cdot cgla)(\sin \phi_i)] \qquad (A-28)$$

$$A_{cgla/y/e/i} = [(\ddot{\phi}_i)(e\cdot cgla)(\sin \phi_i) + (\dot{\phi}_i)(\dot{\phi}_i)(e\cdot cgla)(\cos \phi_i)] \qquad (A-29)$$

Where the new variables are:

$A_{cgla/x/e/i}$ - horizontal acceleration component of lower arm center of gravity with elbow stationary at i^{th} time interval

$A_{cgla/y/e/i}$ - vertical acceleration component of lower arm center of gravity with elbow stationary at i^{th} time interval

$e\cdot cgla$ - distance between elbow and center of gravity of lower arm.

When the elbow is not stationary, the horizontal acceleration ($A_{cgla/x/i}$) and the vertical acceleration ($A_{cgla/y/i}$) of the lower arm center of gravity are the vector sum of (A-26) and (A-27) with (A-28) and (A-29) respectively; which gives:

$$A_{cgla/x/i} = A_{e/x/i} + A_{cgla/x/e/i} \qquad (A-30)$$

$$A_{cgla/y/i} = A_{e/y/i} + A_{cgla/y/e/i} \qquad (A-31)$$

The inertial forces at the gravity center of the lower arm are then:

$$F_{la/x/i} = [(W_{la}/g)(A_{cgla/x/i})] \qquad \text{(A-32)}$$

$$F_{la/y/i} = [(W_{la}/g)(A_{cgla/y/i})] \qquad \text{(A-33)}$$

Where the new variables are:

$F_{la/x/i}$ - horizontal component of inertial force at lower arm center of gravity at ith time interval

W_{la} - lower arm weight (ref. Table A-1)

$F_{la/y/i}$ - vertical component of inertial force at lower arm center of gravity at ith time interval.

The inertial force components at the center of gravity of the hand are derived by the same procedure as was applied to resolving the inertial forces at the lower arm gravity center (equations A-28 to A-33).

Computation of Reactive Forces and Torques.

The equation for the reactive torque at the wrist (T_w in Figure A-1) is:

$$T_{w/i} = [-(w \cdot cgh/y/i)(R_{w/x/i}) + (w \cdot cgh/x/i)(R_{w/y/i}) + (I_{cgh})(\ddot{\alpha}_i)] \qquad \text{(A-34)}$$

Where the new variables are:

$T_{w/i}$ - reactive torque at wrist at ith time interval

$w \cdot cgh/y$ or x/i - distances between wrist and center of gravity of hand in vertical y and horizontal x directions at i^{th} time interval

$R_{w/x \text{ or } y/i}$ - reactive force components at wrist in horizontal x and vertical y directions at i^{th} interval, which are equal to, in the vertical direction, the summation of the weight of the hand, weight of the object in hand, and the vertical component of the inertial force; and in the horizontal direction the horizontal component of the inertial force

I_{cgh} - mass moment of inertia of hand and object in hand about center of gravity of hand (ref. Table A-1)

$\ddot{\alpha}_i$ - angular acceleration of hand about wrist at i^{th} time interval (equations A-7 to A-21)

The reactive force and torque at the elbow is computed in the following manner. First, the reactive force components are computed by:

$$R_{e/x/i} = R_{w/x/i} - F_{la/x/i} \qquad \text{(A-36)}$$

$$R_{e/y/i} = R_{w/y/i} - F_{la/y/i} \qquad \text{(A-37)}$$

Where:

$R_{e/x \text{ or } y/i}$ - reactive force components at elbow in horizontal x and vertical y directions at i^{th} interval

$R_{w/x \text{ or } y/i}$ - reactive force components at wrist (equation A-34)

$F_{la/x \text{ or } y/i}$ - inertial force components at lower arm center of gravity (equations A-32 and A-33)

W_{la} - weight of lower arm (ref. Table A-1).

With reference to the preceding reactive forces, the reactive elbow torque at the i^{th} interval $T_{e/i}$ is the summation of the torques related to the various planar forces, as follows:

$$T_{e/i} = T_{w/i} + T_{cgla/i} + T_{ecgla/i} + T_{ew/i} \qquad \text{(A-38)}$$

Where the constituent torques are:

$T_{w/i}$ - reactive torque at wrist at i^{th} time interval (equation A-34)

$T_{cgla/i}$ - inertial torque due to mass moment of inertia of lower arm about center of gravity at i^{th} interval (equation A-39 following)

$T_{ecgla/i}$ - reactive torque due to planar forces acting at lower arm center of gravity at the i^{th} time interval (equation A-40 following)

$T_{ew/i}$ - reactive torque due to reactive force at wrist at i^{th} interval (equation A-41 following).

The above torques are computed by the following equations:

$$T_{cgla/i} = (I_{cgla})(\ddot{\phi}_i) \qquad \text{(A-39)}$$

Where the new term is:

I_{cgla} - mass moment of inertia of lower arm about center of gravity (ref. Table A-1).

and:

$$T_{ecgla/i} = -[(e\cdot cgla)(\sin \phi_i)(F_{la/y/i} + W_{la}) + (e\cdot cgla)(\cos \phi_i)(F_{la/x/i})] \qquad \text{(A-40)}$$

Where the new terms are:

$e\cdot cgla$ - distance from elbow to lower arm center of gravity (ref. Table A-1)

$F_{la/y \text{ or } x/i}$ - inertial force components at lower arm center of gravity (equations A-32 and A-33)

W_{la} - weight of lower arm

and:

$$T_{ew} = [(e\cdot w)(\sin \phi_i)(R_{w/y/i}) - (e\cdot w)(\cos \phi_i)(R_{w/x/i})] \qquad \text{(A-41)}$$

Where the new variables are:

$e\cdot w$ - distance from elbow to wrist (ref. Table A-1)

$R_{w/y \text{ or } x/i}$ - reactive force components at wrist at i^{th} interval (equation A-34).

The procedure for resolving the reactive forces and torques at the shoulder is the same as the equations (A-38 to A-41) for the elbow.

The preceding computations were programmed for computer analysis, and the results of some specific arm motions are presented in Chapter 4 of this paper.

Appendix B

Miscellaneous Data Summaries

Subject	Age (yrs)	Weight (pounds)	Height (in)	Vital Capacity		Time Rate Expiration % of Vital Cap. after:			Step Test Rating**	General Medical History	Wrist to Knuckle III*** (in.)	Radius Length (in.)
				c.c.	% of Est. Avg.*	1 sec.	2 sec.	3 sec.				
J.K.	19	165	68	4600	96%	65%	90%	100%	Excellent PEI = 96	No Outstanding Maladies	5.9	10.9
J.J.	22	160	69	4700	98%	85%	98%	100%	High Average PEI = 78	No Outstanding Maladies	5.9	10.9
J.S.	21	175	69	4300	90%	82%	97%	100%	Good PEI = 80	No Outstanding Maladies	5.3	10.7
E.H.	23	160	70	4860	102%	70%	96%	100%	High Average PEI - 76	No Outstanding Maladies	5.7	11.0

* Average for this age group is 4780 cc. from (7 : 243-278).
** Step test norms from (40).
*** Length measures as explained in Table A-1 in Appendix A.

Table B-1

Subject Data

Study Number	$\bar{E}_r$ (Kcal/min)	$\bar{E}_a$ (Kcal/min)	$\bar{t}_{aa}$ (sec.)	$\bar{t}_{ar}$ (sec.)	$\bar{t}_{ra}$ (sec.)	E_{inc} (Kcal/min)	Mean E_{inc} (Kcal/min)	Variance E_{inc} (Kcal/min)^2
11	1.31	1.47	5	1	10	0.62	0.72	0.0081
12	1.25	1.46				0.79		
13	1.20	1.40				0.75		
21	1.39	1.68	7.5	1	7.5	0.69	0.76	0.0065
22	1.20	1.57				0.75		
23	1.22	1.64				0.85		
31	1.16	1.49	5	1	5	0.66	0.73	0.0065
32	1.30	1.71				0.82		
33	1.17	1.53				0.72		

Activity: Lift 11.5 pound box - both arms - $\gamma = 60^\circ$, $\theta = 100^\circ$

Using Aspin-Welch test of differences between means with unknown variances which are possibly not equal (32: 467-478), results in not rejecting the hypothesis that the three sample means of E_{inc} are equal to each other, at $\alpha = 0.05$ level.

Table B-2

Data for Test of Time Active versus Time Resting Effect on E_{inc}

$\dfrac{\text{Average Time Active } (\bar{t}_{aa})}{\text{Average Time Resting } (\bar{t}_{ra})}$	
$\dfrac{7.5 \text{ seconds}}{7.5 \text{ seconds}}$	$\dfrac{5 \text{ seconds}}{10 \text{ seconds}}$
WFT $\leq$ 40 Kgm. cm.	WFT $\geq$ 40 Kgm. cm.
EFT $\leq$ 210 " "	EFT $\geq$ 210 " "
SFT $\leq$ 210 " "	SFT $\geq$ 210 " "
SET $\leq$ 210 " "	SET $\geq$ 210 " "

Where:

WFT - one arm wrist flexion resultant torque level
EFT - " " elbow " " " "
SFT - " " shoulder " " " "
SET - " " shoulder extension " " "

Table B-3

Active and Resting Times used for Different Resultant Torque Levels and Sights of Activities

X E_{inc} Data* (Kcal/min)	X' Upper Cell Limits	$\frac{X' - \bar{X}}{\theta_e}$ (Z)	Theor. Cumm. Prob. (%)	Number of Values of: $X \leq X'$	Actual Cumm. Freq. (%)	Difference: |Theor. Prob. _ Act. Freq.| (D)
0.85	0.895	+2.05	98%	9	100%	0.02
0.82	0.845	+1.40	91%	8	89%	0.02
0.79	0.795	+0.74	77%	7	78%	0.01
0.75	↓	↓	↓	↓	↓	↓
0.75						
0.72	0.745	+0.07	52%	4	45%	0.07
0.69	0.695	-0.60	28%	3	31%	0.03
0.66	↓	↓	↓	↓	↓	↓
0.62	0.645	-1.27	10%	1	11%	0.01

*Values from Table B-2

$\bar{X}$ = 0.74Kcal/min.

θ_e = 0.075

Max D = 0.07

For sample size of nine at α = 0.10, critical value of D = 0.388, from Table E of reference (66: 251).

Conclusion: Hypothesis that E_{inc} values are normally distributed about expected value is not rejected.

Table B-4

Kolomogorov - Smirnov Test of Normality of E_{inc}

E_{inc} Data* (Kcal/min)	X E_W (Kcal/min)	X' Upper Cell Limits	$\frac{X' - X}{\sigma_e}$ (Z)	Therotical Cumm. Prob. (%)	Number of Values of X X'	Actual Cumm. Freq. (%)	Difference Ther. Prob. Act. Freq. (D)
.85	7.78	8.00	+1.85	97%	9	100%	0.03
.82	7.66	7.75	+1.29	90%	8	89%	0.01
.79	7.48	7.50	+0.74	77%	7	78%	0.01
.75	7.24	7.25	+0.02	51%	6	67%	0.16
.75	7.24	↓	↓	↓	↓	↓	↓
.72	7.08	↓	↓	↓	↓	↓	↓
.69	6.88	7.00	-0.38	35%	3	33%	0.02
.66	6.74	6.75	-0.94	17%	2	22%	0.05
.62	6.48	6.50	-1.49	7%	1	11%	0.04

* Values from Table B-2

Max D = 0.16

$\bar{X} = \frac{64.55}{9} = 7.17$

For sample size of nine at α = 0.10, critical value of D = 0.388, from Table E of reference (66: 251).

$\sigma_e = 0.449$

<u>Conclusion:</u> Hypothesis that E_W values are normally distributed about expected value is not rejected.

Table B-5

Kolomogorov - Smirnov Test of Normality of E_W

E_{inc}* (Kcal/min)	E_W (Kcal/min)	Expected Value of E_W (Kcal/min)	Est. Var. of E_W $(Kcal/min)^2$
.21	3.14	3.50	0.1355
.24	3.47		
.28	3.88		
.80	7.52	7.82	0.1900
.97	8.32		
.82	7.62		
.20	3.03	3.09	0.2051
.25	3.58		
.17	2.67		
.38	4.80	5.19	0.1482
.48	5.58		
.43	5.20		
.10	1.72	2.09	0.1214
.13	2.15		
.15	2.41		
1.00	8.45	7.97	0.2166
.89	7.95		
.80	7.52		
.06	1.10	1.26	0.1928
.07	1.26		
.08	1.42		
.86	7.81	7.86	0.2275
.98	8.36		
.78	7.41		
2.80	13.27	13.72	0.2885
3.31	14.11		
3.10	13.77		
.34	4.45	4.87	0.1467
.40	4.96		
.43	5.20		

*Data from Table 3, page 73.

Homogeneity Test of Variances (14: 606-607):

$$\frac{\text{Max. Var.}}{\text{Min. Var.}} = \frac{0.2885}{0.1214} = \underline{2.37}$$

Critical Value at ($\alpha = 0.05$), for 10 sets of data with 2 d.f. in each set is 550.

Conclusion: Do not reject hypothesis that variance of weighted energy values are uniformily distributed.

Table B-6

Weighted Energy Values - Homogeneity Test

Appendix C

Technique for Reducing Oxygen Data to Estimates of the Metabolic Energy Expenditure Rates

This Appendix describes the following aspects of the procedure used to estimate the metabolic energy expenditure rate: 1) the measurement equipment, 2) the form of the data, and 3) the computations.

The Measurement Equipment

As developed from the discussion of the Biochemical Factors in Muscle Contraction in Chapter III, the metabolic energy expenditure rate can be closely estimated by measuring a person's oxygen utilization rate. In this research project the following equipment was used to perform this measurement:

1. Nose and mouth face mask number P-344, manufactured by Warren E. Collins Company, Boston, Massachusetts.
2. Plexiglass two-way breathing valve and respirometer with a 60 liter/minute capacity, by Max-Planck Institut für Arbeitsphysiologie, Gottingen, West Germany.
3. Gas manometer with a capacity of 77 cc./minute, by Brooks Instrument Company, Inc., Hatfield, Pennsylvania.
4. Continuous flow oxygen analyzer model C2, manufactured by Beckman Instruments Inc., Fullerton, California.
5. Barometer by Airguide Instrument Company, Chicago, Ill.

A diagram of the equipment layout is depicted in Figure C-1.

The error created by the valve and respirometer

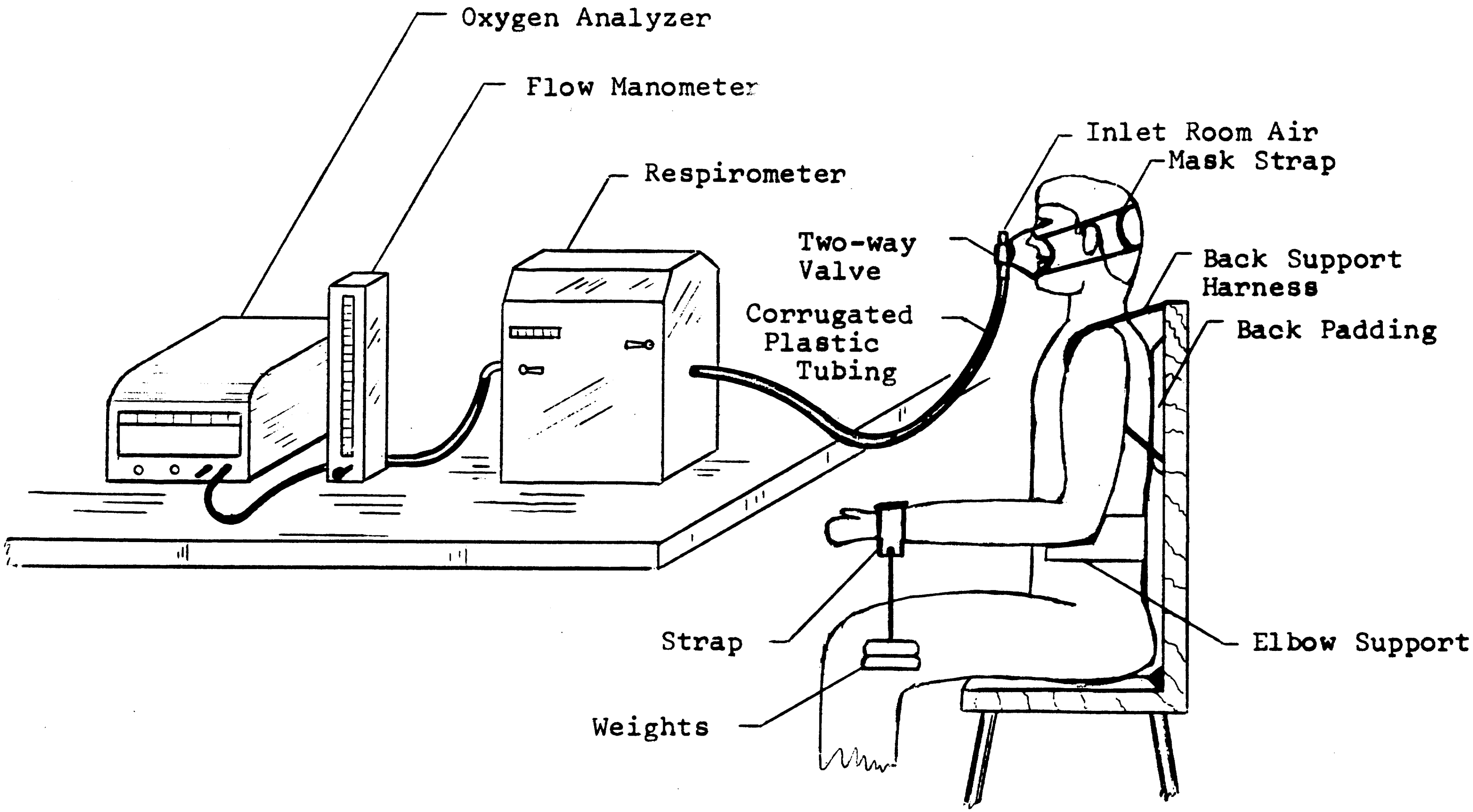


Figure C-1

<u>Typical Test Setup and Equipment</u>

combination was checked near the end of the experiment period. This was accomplished by pumping known volumes of air from a lung vitalometer (accuracy of ± 0.5 percent), through the valve and respirometer while noting the respirometer readings. The test flow rates were varied from 5 to 50 liters per minute. The average ventilation rate of the subjects used in the experiments ranged from 6 to 15 liters of air per minute, but due to the naturally uneven "inhale-exhale" pattern, the major expiration flow rate for each breath was estimated as varying from 30 to 50 liters per minute. In this upper range, the respirometer was found to measure the gas volume to within three percent of the actual volume forced through it. At the lowest flow rate of 5 liters per minute, the respirometer registered only 40 percent of the volume of gas forced through it, as depicted in Figure C-2. This meant that any expirations with a low flow rate would be under estimated. Because of this possibility, a second respirometer, which was checked and found to track the actual gas volumes to within two percent (for flow rates from 5 to 50 liters per minute) was employed in the last series of experiments. Two sets of old respirometer studies were repeated with the new respirometer. These two studies required average ventilation rates of from 7 to 13 liters per minute. No significant difference in the incremental metabolic energy

Figure C-2

<u>Respirometer Calibrations</u>

expenditure rates was detected. Thus, the low flow error in the old respirometer (which had been used for the majority of the studies) did not appear to be affecting the accuracy of the incremental energy estimations.

As can be observed from the Computations section at the end of this Appendix, the Beckman oxygen analyzer did not need to be accurate in determining the absolute oxygen content, since the room oxygen was sampled before each study and this value was used as the "base" for computing the oxygen utilized by the subjects. Thus, if there was any day-to-day "drift" in the absolute estimates by the analyzer, it would not be included in the computations. In addition, by obtaining the "resting" oxygen uptake rate immediately before each "active" oxygen uptake measurement, any "drift" which could influence the accuracy of the incremental metabolic energy estimation would need to occur during the twenty minute duration of each study.

The linearity of the oxygen analyzer was stated to be within ± 1.0 percent of full scale, which would mean ± 0.04 percent error was possible in analyzing the difference in two gases which had an actual four percent difference. (Four percent is about the percent oxygen extracted from each breath when resting.) A check was made using the ambient air and two different bottled gases which had 16 and 20 percent oxygen in a nitrogen background gas. It showed the analyzer to be within its specified linearity. It was concluded that because the "resting" oxygen uptake rate was compared to the "active" uptake rate in <u>each</u> study, and the maximum difference was found to be only 0.7 percent, the linearity error for this small difference would need to be much larger than ± 1.0 percent before it would appreciably influence the estimate of E_{inc}.

The Data Format

The volume of expired air and the oxygen content of the air were recorded at one minute intervals during the twenty minute study periods. Table C-3 depicts a typical data sheet. The barometric pressure was recorded during each study. The temperature of the expired air was obtained from a thermometer in the respirometer. The times were established as explained in Chapter III (page 69).

Estimation of E_{inc}

The following computational technique was used to estimate the incremental metabolic energy expended by a person for each minute that he performs a designated task. The first subsection presents the computations used in estimating the average metabolic energy expenditure

METABOLISM DATA SHEET

Subject: J.K. Date: 8-2-66 Arm: Rr.

Articulation:	Shoulder	Elbow	Wrist
Direction:	FLEXION	~	~
Angle:	0°	140°	180°
Torque:	210	SUPPORTED	SUPPORTED

	Resting Exp.		Active Exp.	
Exp. No.	8020004		8022100	
Bar. Pres. (inches)	28.96		28.96	
Exp. Air (°C)	25		25	
Resting Time (sec.)	14	(t_{rr})	7.5	(t_{ra})
Active Time (sec.)	1	(t_{ar})	7.5	(t_{aa})
Room O_2 (percents)	20.80		20.80	
Exp. Air O_2 (percents)	16.40		16.35	
O_2 Uptake (percents)	4.40		4.45	

Respirometer Readings (Liters Air Exp./min.) and Oxygen Analyzer Readings (Percent Oxygen in Expired Air)

Initial	277.0 (16.68)	(10 min)	344.0 (16.45)
(1 min)	284.5 (16.48)	(11 min)	350.5 (16.45)
(2 min)	291.0 (16.32)	(12 min)	357.0 (16.28)
(3 min)	297.0 (16.32)	(13 min)	363.8 (16.23)
(4 min)	303.8 (16.38)	(14 min)	370.5 (16.23)
(5 min)	310.5 (16.39)	(15 min)	377.0 (16.19)
(6 min)	317.0 (16.37)	(16 min)	384.5 (16.32)
(7 min)	323.0 (16.32)	(17 min)	392.0 (16.33)
(8 min)	330.0 (16.38)	(18 min)	398.9 (16.33)
(9 min)	337.6 (16.39)	(19 min)	405.8 (16.36)
(10 min)	334.0 (16.45)	(20 min)	413.8 (16.40)

Figure C-3

Example of Data Format

rates for the resting and active segments of a study. The second subsection presents a sample calculation of E_{inc} based on the data of Figure C-3, and the equation developed in Figure 11 (page 67).

Average Metabolic Energy Expenditure Rate Estimation

The data inputs for the estimation of the average metabolic energy expenditure rates during the last five minutes of either the "resting" or "active" segments of a study are as follows:

V_{air} - volume of air expired during last five minutes of study segment

O_e - average percent oxygen in expired air during last five minutes of study segment

O_i - percent oxygen in room during study

B - barometric pressure in millimeters of mercury during study

T - temperature of expired air in degrees centegrade

t's - average times of various activities

The first computation is an estimate of the respiratory quotient R.Q.. This is estimated from the empirical relationship of percent expired oxygen to percent expired carbon dioxide formulated by Liddell (page 56):

$$R.Q. = \frac{(\%\ \text{Carbon dioxide liberated})}{(\%\ \text{Oxygen used})}$$

$$= \frac{\left[15.60 - 0.7051\,(O_e)\right] - 0.03}{O_i - O_e} \qquad \text{(C-1)}$$

The above estimate is then used in an equation derived by Weir (75) to determine the energy liberated per liter of oxygen utilized. He assumes that 12.5 percent of the food metabolized is protein. Weir's formulation is:

$$K = \frac{\text{Kilogram-calories}}{\text{Liter of oxygen used}} = 3.9 + 1.1(\text{R.Q.}) \qquad \text{(C-2)}$$

This formulation is the same as Liddell's (Chapter III, page 58), but does not assume that the room oxygen content O_i remains constant. Including O_i in the computation of K avoided the effects of changes in the room oxygen content, which were found to occur when the laboratory was closed off in order to use the internal air conditioning system. The greatest change recorded during one five hour test was 0.4 percent.

The average volume of air expired over the last five minutes of the test is computed by:

$$\bar{V} = \text{average volume per minute (L./min.)} = \frac{V}{5}\,. \qquad \text{(C-3)}$$

This volume is then corrected to a dry, standard pressure and temperature by the following formulation from Consolazio et al. (26:6), with the assumption that the expired air is saturated at 25° C.:

$$\bar{V}_{STP} = \bar{V} \times \frac{B - 23.76}{760\left[1 + 0.00367(T)\right]} \quad . \qquad \text{(C-4)}$$

The average metabolic energy expenditure rate is then computed as follows:

$$E = \text{(Kilogram-calories/minute)}$$

$$= \bar{V}_{STP} \times \frac{O_i - O_e}{100} \times K \quad . \qquad \text{(C-5)}$$

Example Calculation of E_{inc}

The following computations illustrate the application of the aforementioned estimating technique for incremental metabolic energy expenditure rate E_{inc}. The data is obtained from the data sheet, Figure C-3, with percent oxygen readings corrected to standard pressure and temperature:

$V = 33.5$ liters/5min.

$O_e = 20.80\%$ (corrected to STP)

$O_i = 16.40\%$ (corrected to STP)

$B = 734$ mm. Hg.

$V = 36.8$ liters/5min

$O_e = 20.80\%$ (corrected to STP)

$O_i = 16.35$ (corrected to STP)

$B = 734$ mm. Hg.

$T = 25°C.$

$t_{rr} = 14$ sec.

$T_{ar} = 1$ sec.

$t_r = 15$ sec.

$T = 25°C.$

$t_{ra} = 7.5$ sec.

$t_{aa} = 7.5$ sec.

$t_a = 15$ sec.

The average metabolic energy expenditure rate E_r for the <u>resting segment</u> is estimated as follows:

$$R.Q. = \frac{\left[15.60 - 0.7051(16.4)\right] - 0.03}{(20.8 - 16.4)}$$

$$= \frac{4.05}{4.40} = \underline{.920}$$

(By equation C-2):

$$K = 3.9 = 1.1(0.920) = 4.91 \text{ Kcal/liter } O_2$$

(By equation C-3):

$$\bar{V} = \frac{33.5}{5} = 6.70 \text{ liters/min.}$$

(By equation C-4):

$$\bar{V}_{STP} = 6.70 \times \frac{(734 - 23.76)}{760(1 + 0.00367(25))}$$

$$= 6.70 \times \frac{710.24}{829.7} = 5.73 \text{ liters/min.}$$

(By equation C-5):

$$\bar{E}_r = 5.73(0.044)\ 4.91$$

$$\bar{E}_r = \underline{\underline{1.238 \text{ Kcal/min.}}}$$

The average metabolic energy expenditure rate $\bar{E}_a$ for the active segment is estimated as follows:

(By equation C-1):

$$R.Q. = \frac{\left[15.60 - 0.7051(16.35)\right] - 0.03}{(20.8 - 16.35)}$$

$$= \frac{40.6}{44.5} = 0.913$$

(By equation C-2):

$$K = 3.9 + 1.1(0.913) = 4.91 \text{ Kcal/liter } O_2$$

(By equation C-3):

$$\bar{V} = \frac{36.8}{5} = 7.36 \text{ liters/min.}$$

(By equation C-4):

$$\bar{V}_{STP} = 7.36 \times \frac{710.24}{829.7} = 6.30 \text{ liters/min.}$$

(By equation C-5):

$$\bar{E}_a = 6.30 \times 0.0445 \times 4.91 = \underline{\underline{1.375 \text{ Kcal/min.}}}$$

The incremental metabolic energy expenditure rate E_{inc} is estimated as follows:

$$E_{inc} = \frac{\left[E_a \times t_a\right] - \left[E_r \times t_r\right]}{(t_{aa} - t_{ar})}$$

$$E_{inc} = \frac{\left[1.375 \times 15\right] - \left[1.238 \times 15\right]}{(7.5 - 1.0)}$$

$$E_{inc} = \underline{\underline{0.316 \text{ Kcal/minute}}}$$

Appendix D

(Figures D-1 to D-7) E_{inc} vs. Torque

(Figures D-8 to D-13) $a_{i,\gamma}$ vs. γAngle

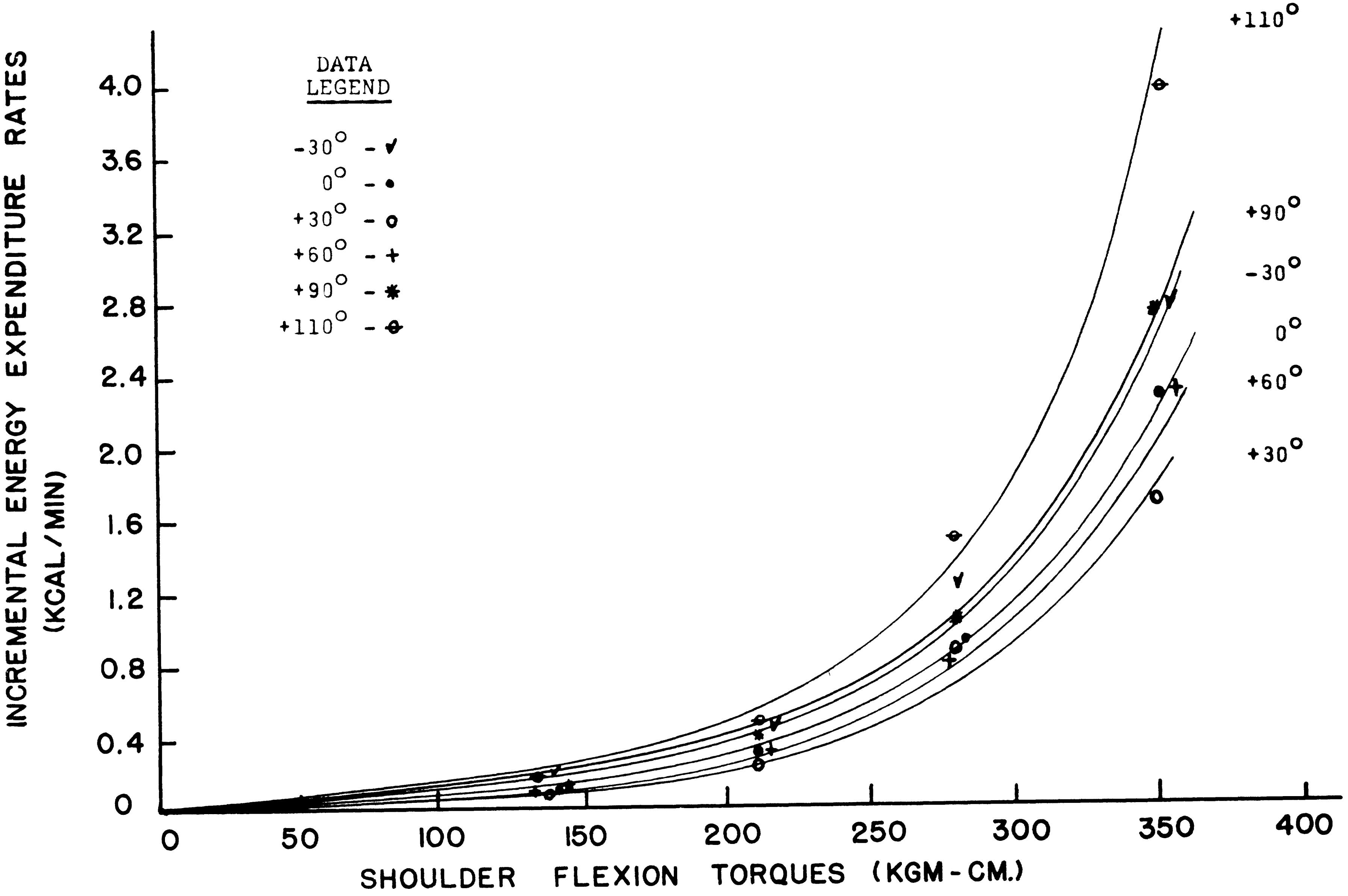


Figure D-1 F_{inc} vs. FLEXION OF ONE SHOULDER AT DIFFERENT ANGLES

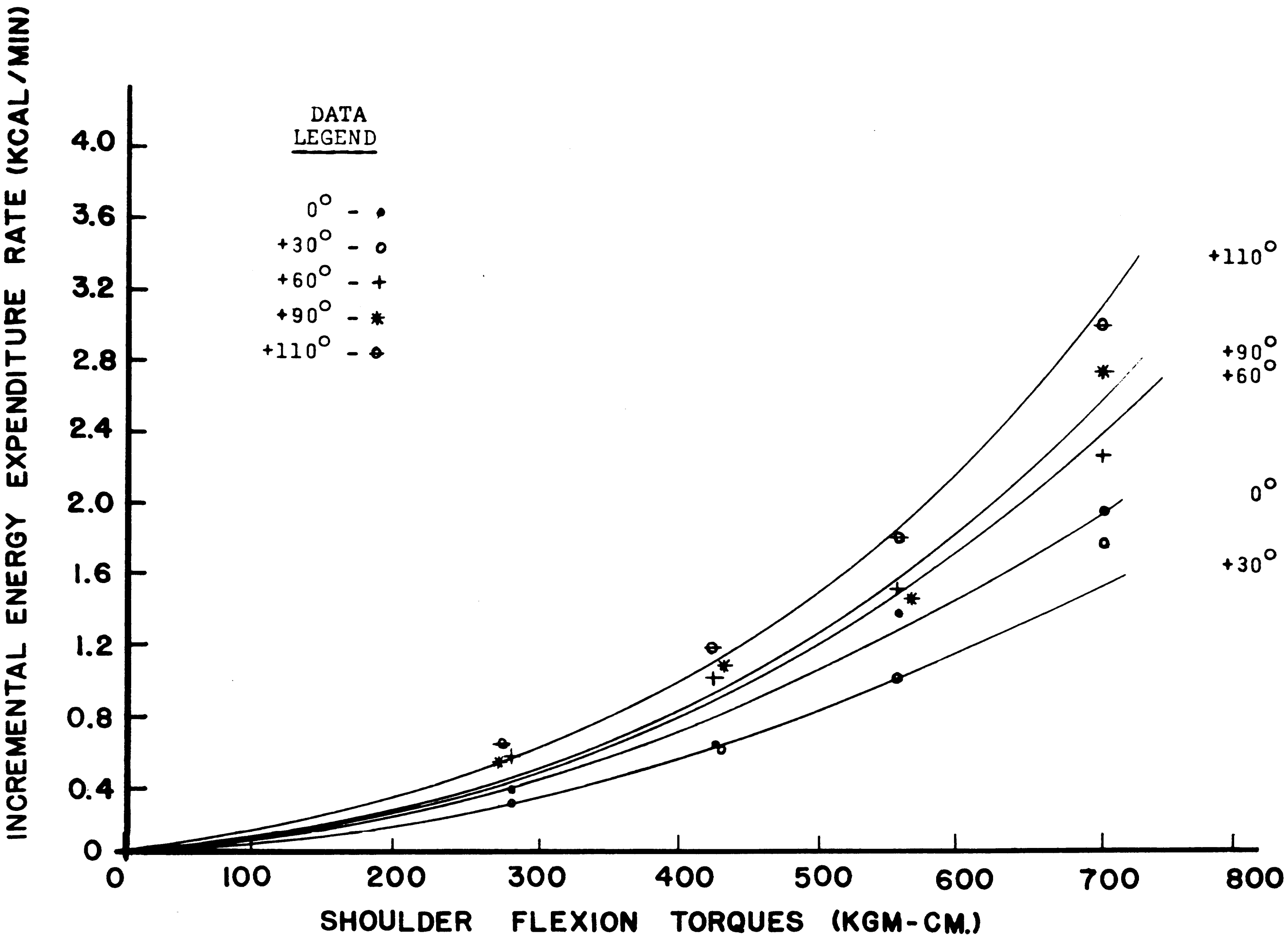


Figure D-2 E_{inc} vs. FLEXION OF BOTH SHOULDERS AT DIFFERENT ANGLES

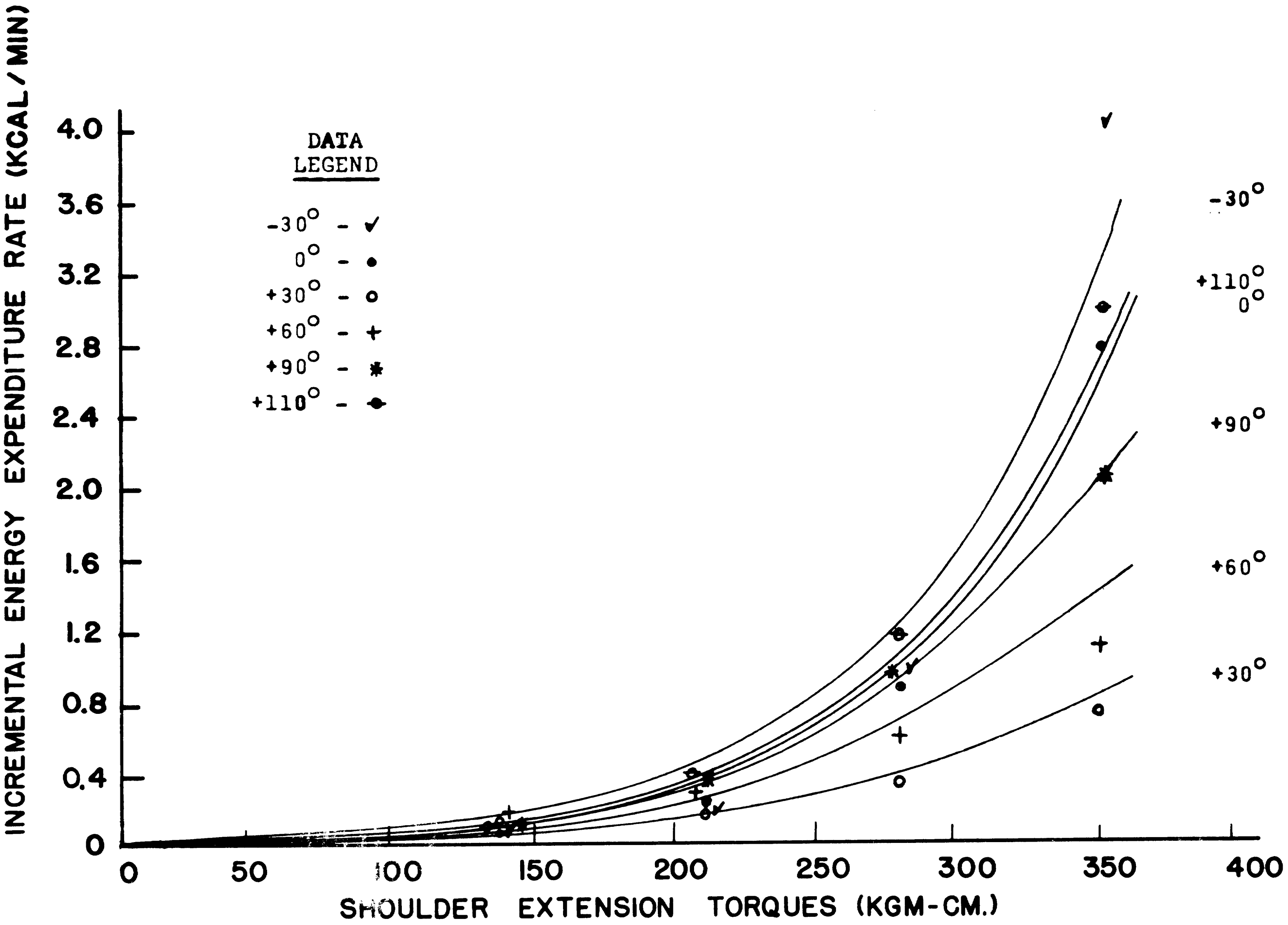


Figure D-3 Einc vs. EXTENSION OF ONE SHOULDER AT DIFFERENT ANGLES

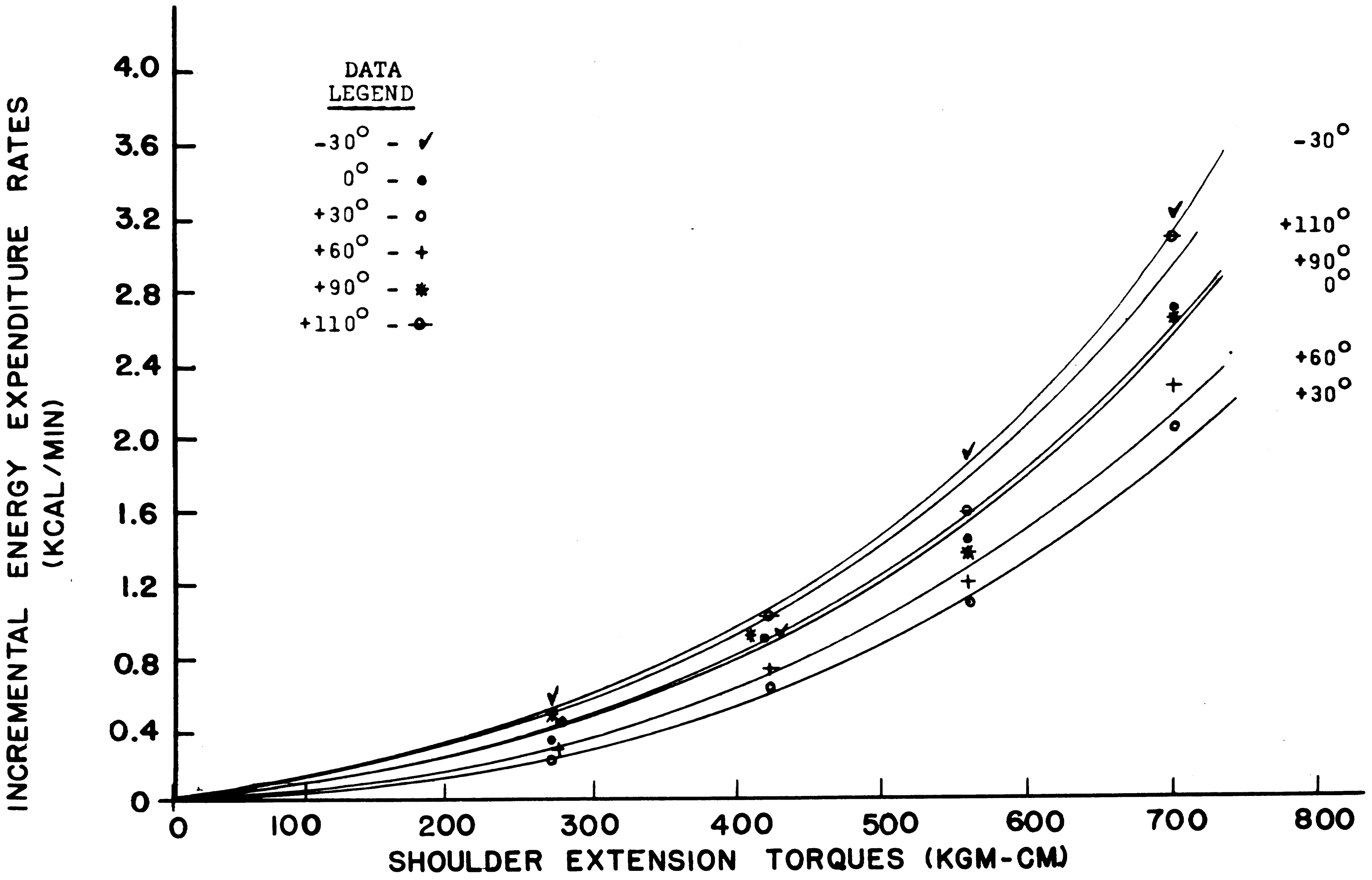


Figure D-4 E_{inc} vs. EXTENSION OF BOTH SHOULDERS AT DIFFERENT ANGLES

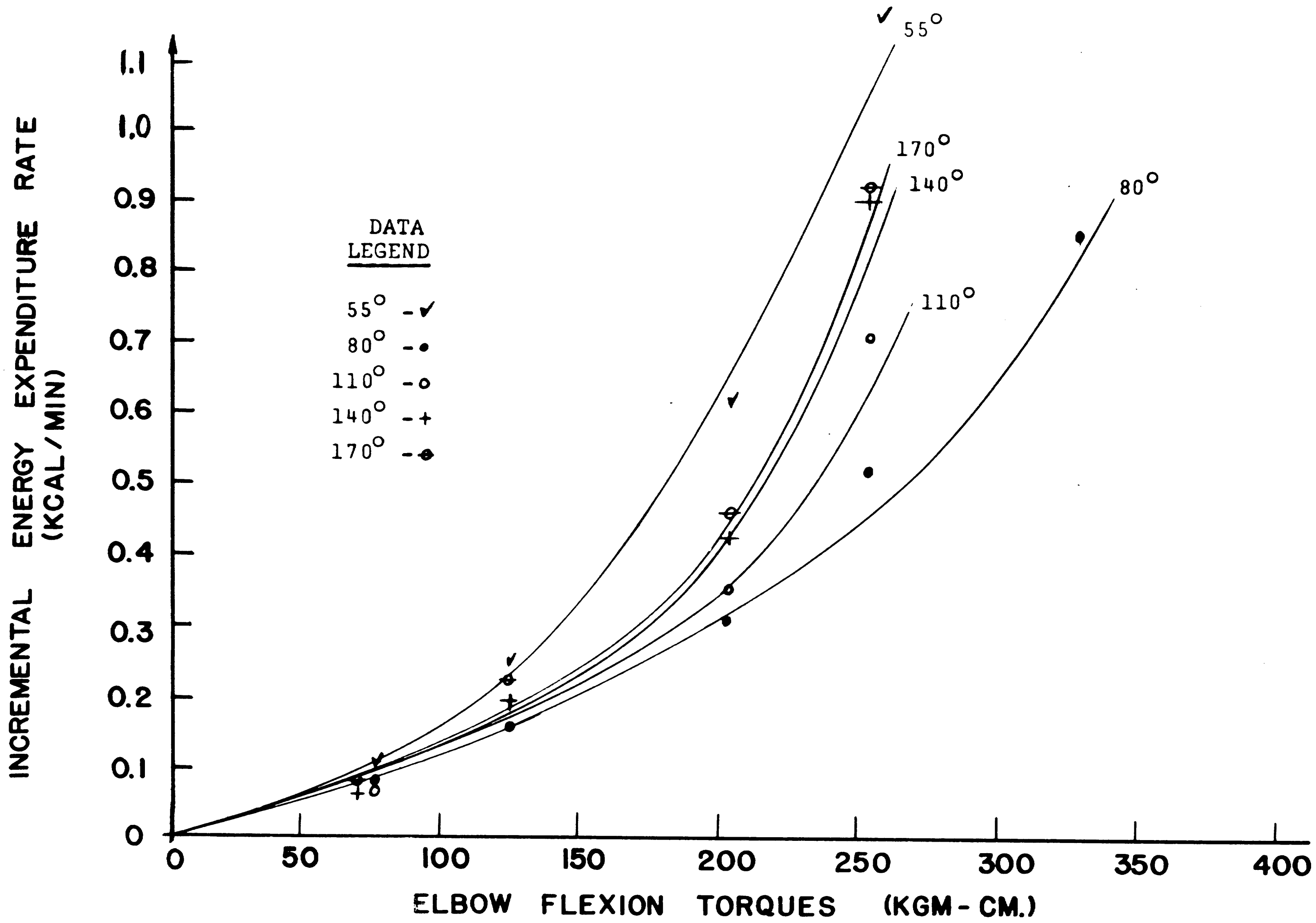


Figure D-5 E_{inc} vs. FLEXION OF ONE ELBOW AT DIFFERENT ANGLES

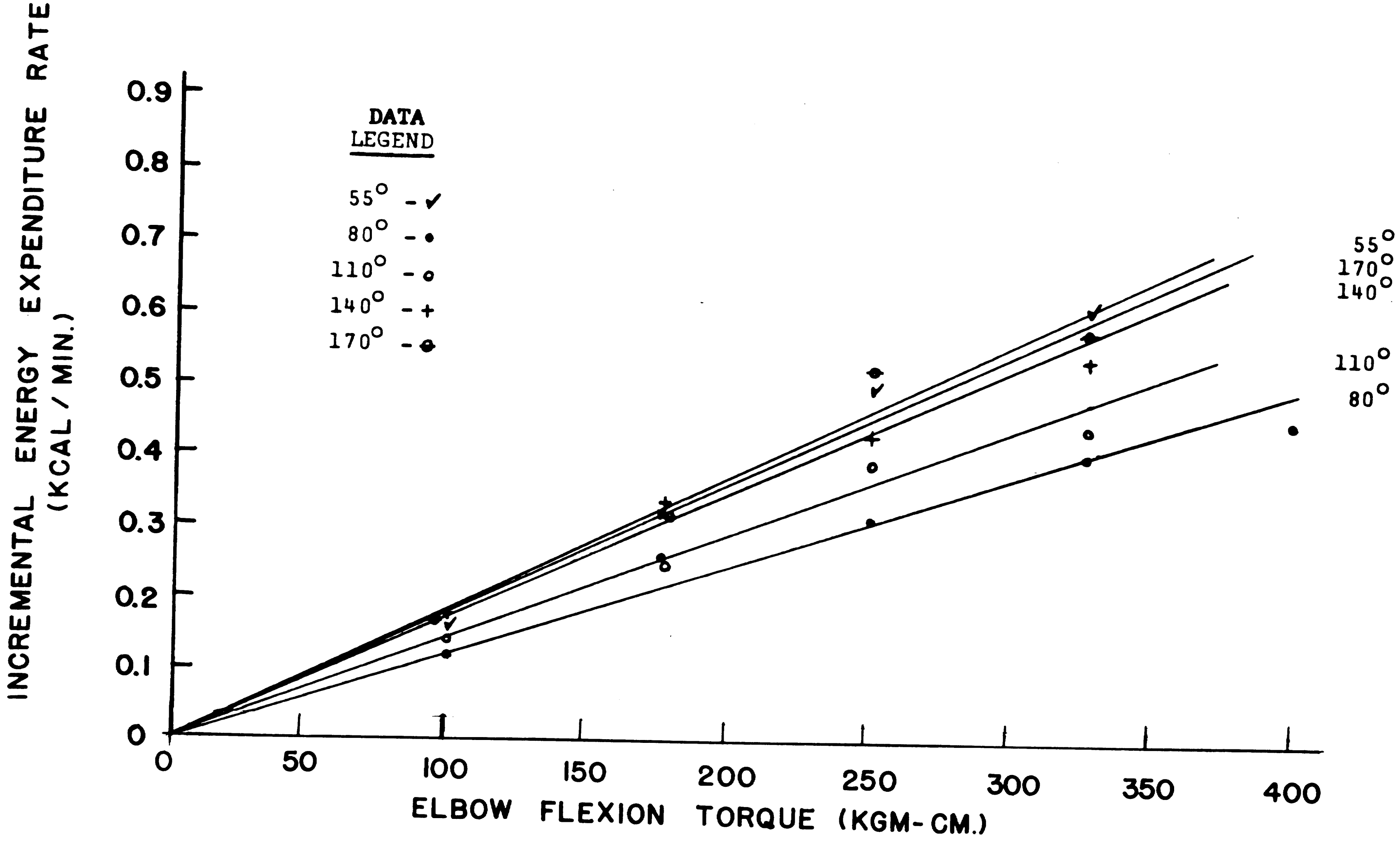


Figure D-6 E_{inc} vs. FLEXION OF TWO ELBOWS AT DIFFERENT ANGLES

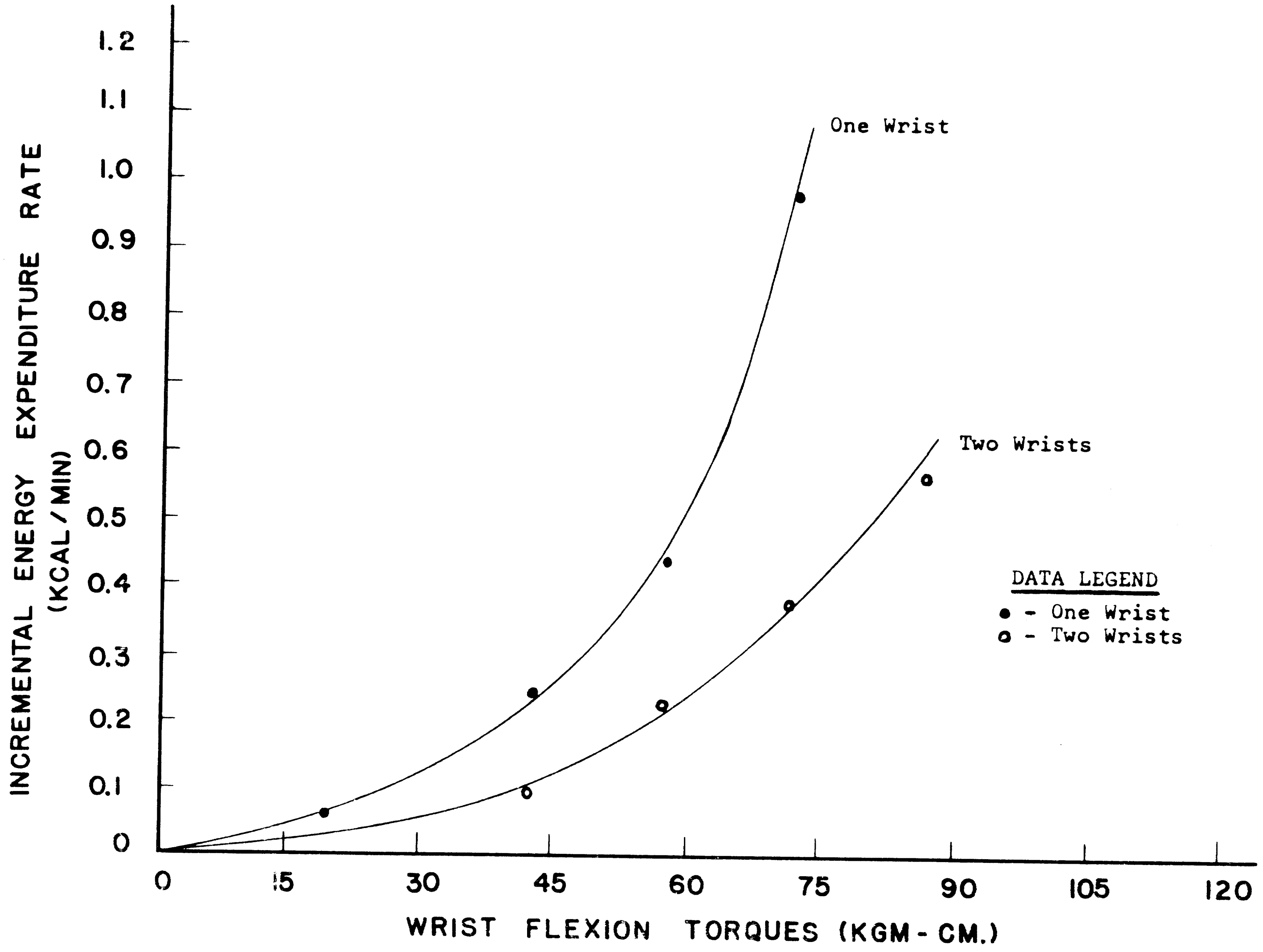


Figure D-7 E_{inc} vs. COMPARISON OF ONE WRIST AND TWO WRIST FLEXIONS

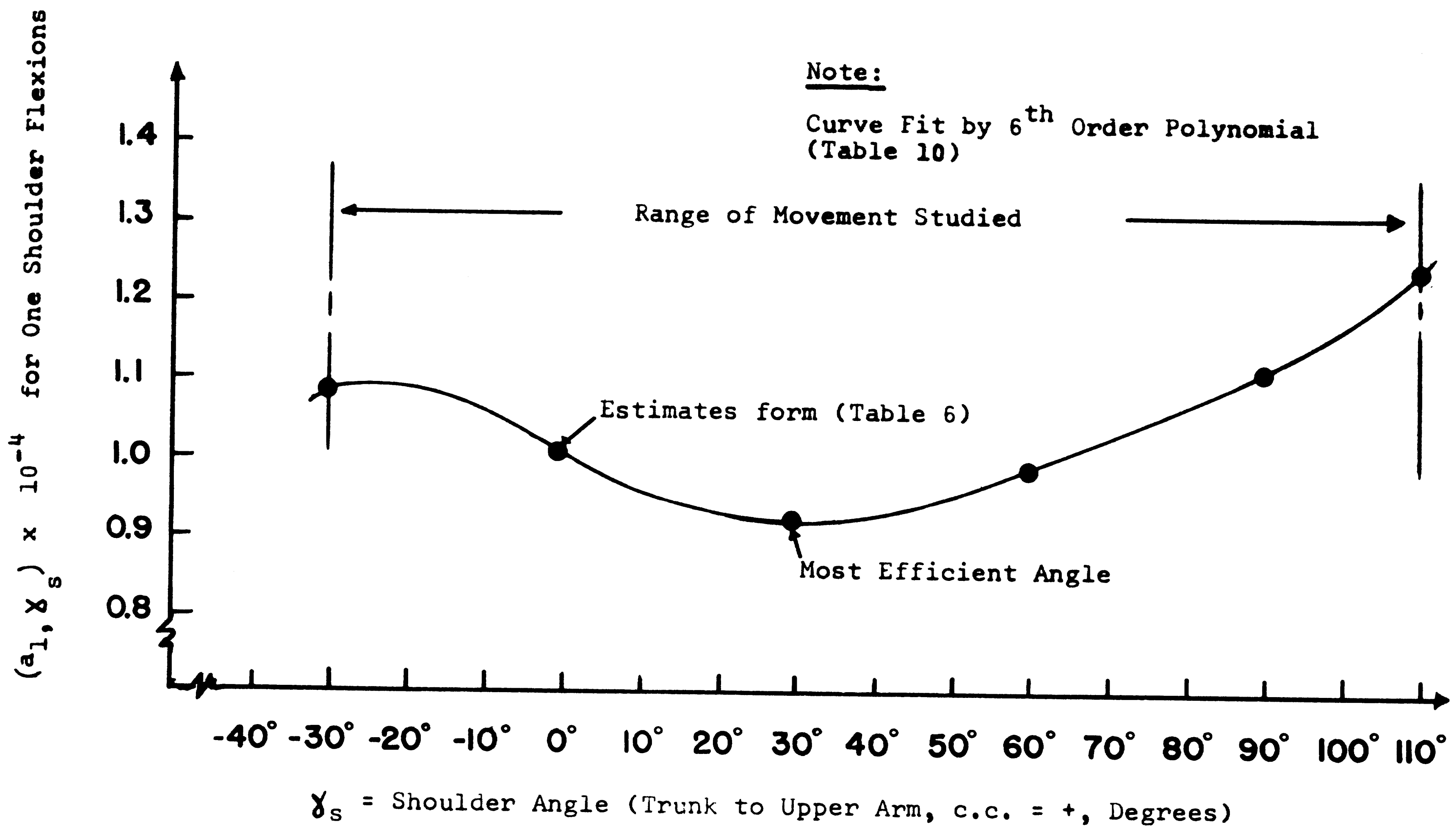


Figure D-8 ANGLE EFFECT ON a_{1,γ_s} PARAMETER IN ONE SHOULDER FLEXION MODEL

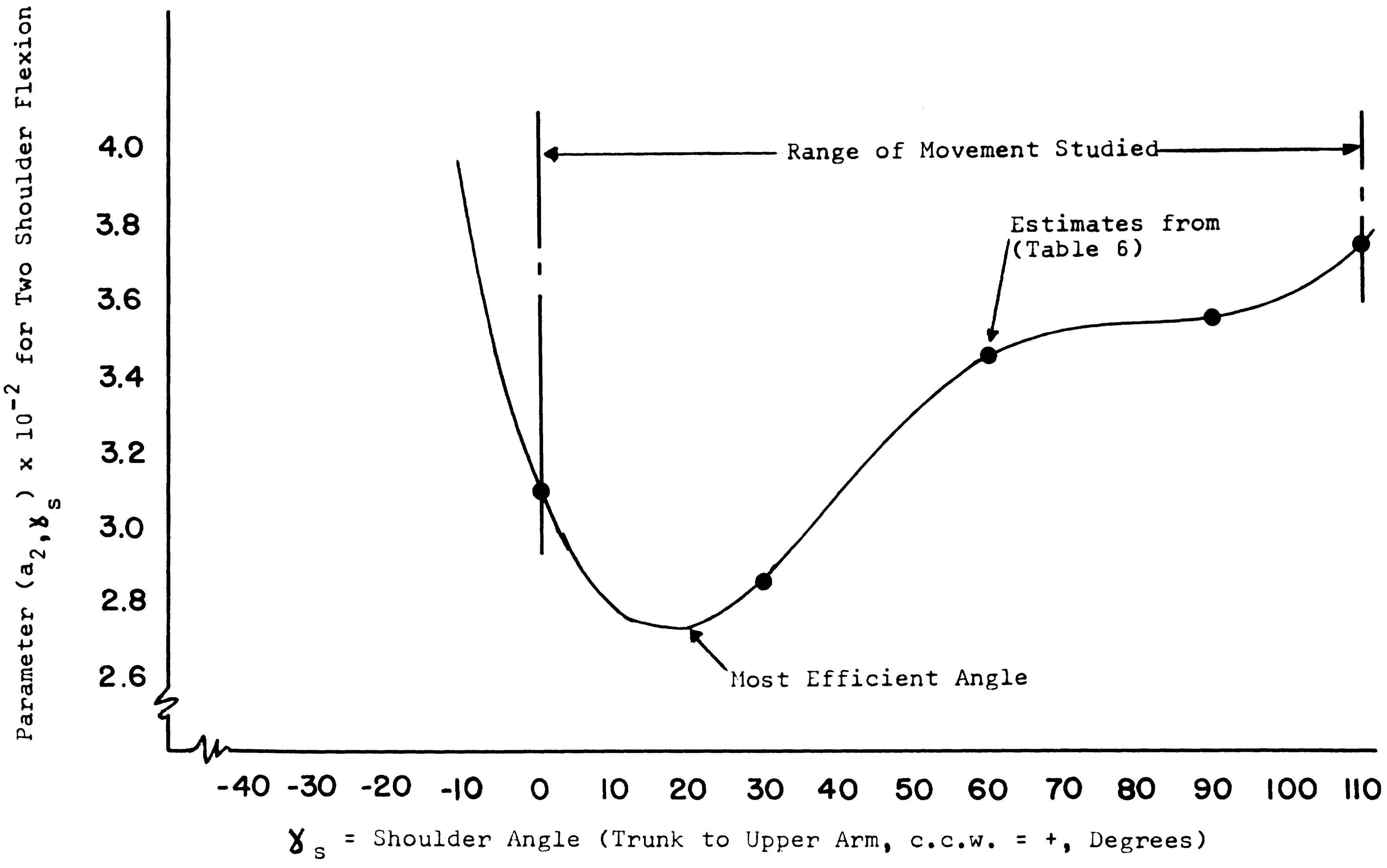


Figure D-9 ANGLE EFFECT ON a_{2,γ_s} PARAMETER IN TWO SHOULDER FLEXION MODEL

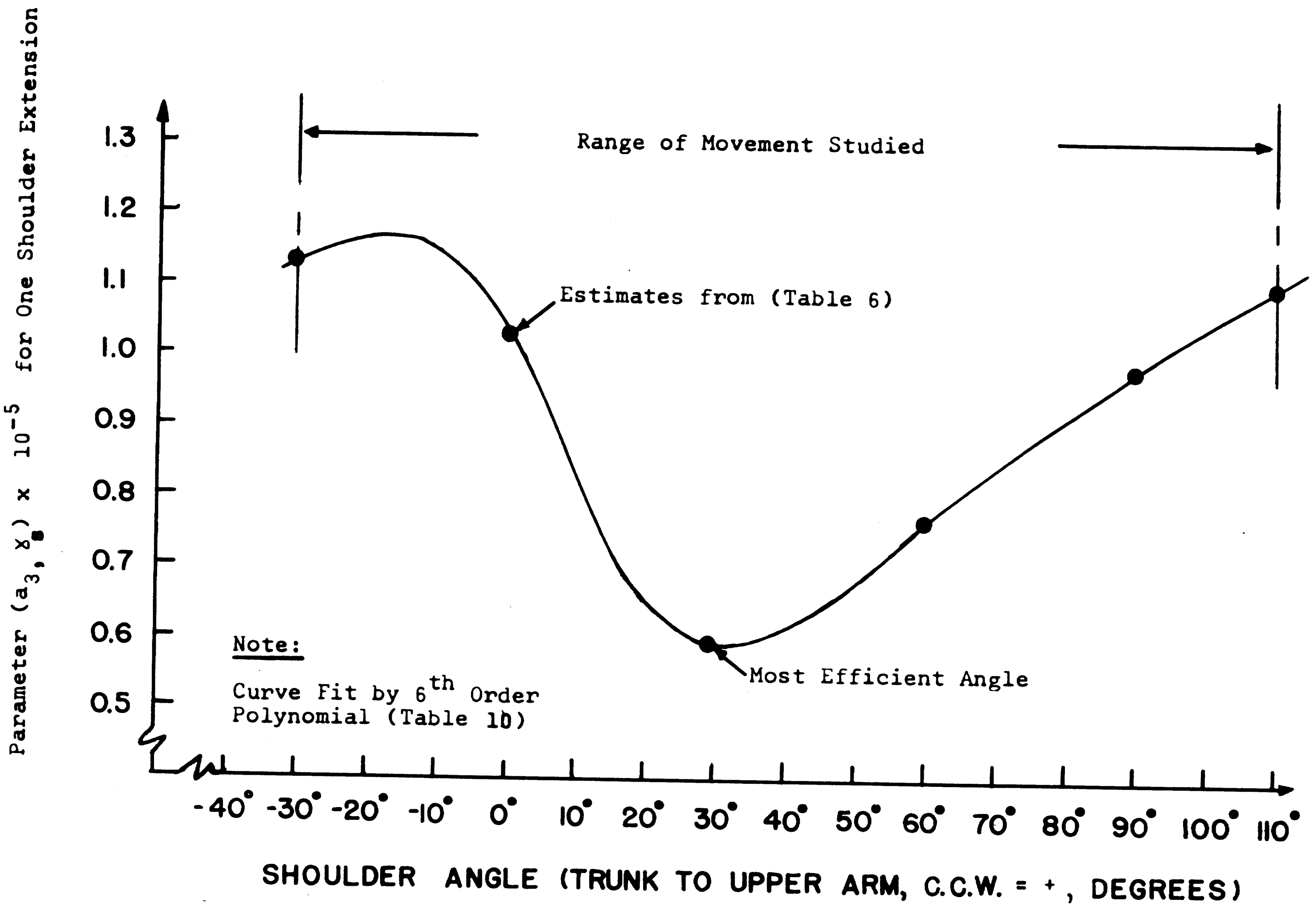


Figure D-10 ANGLE EFFECT ON a_3, γ_s PARAMETER IN ONE SHOULDER EXTENSION MODEL

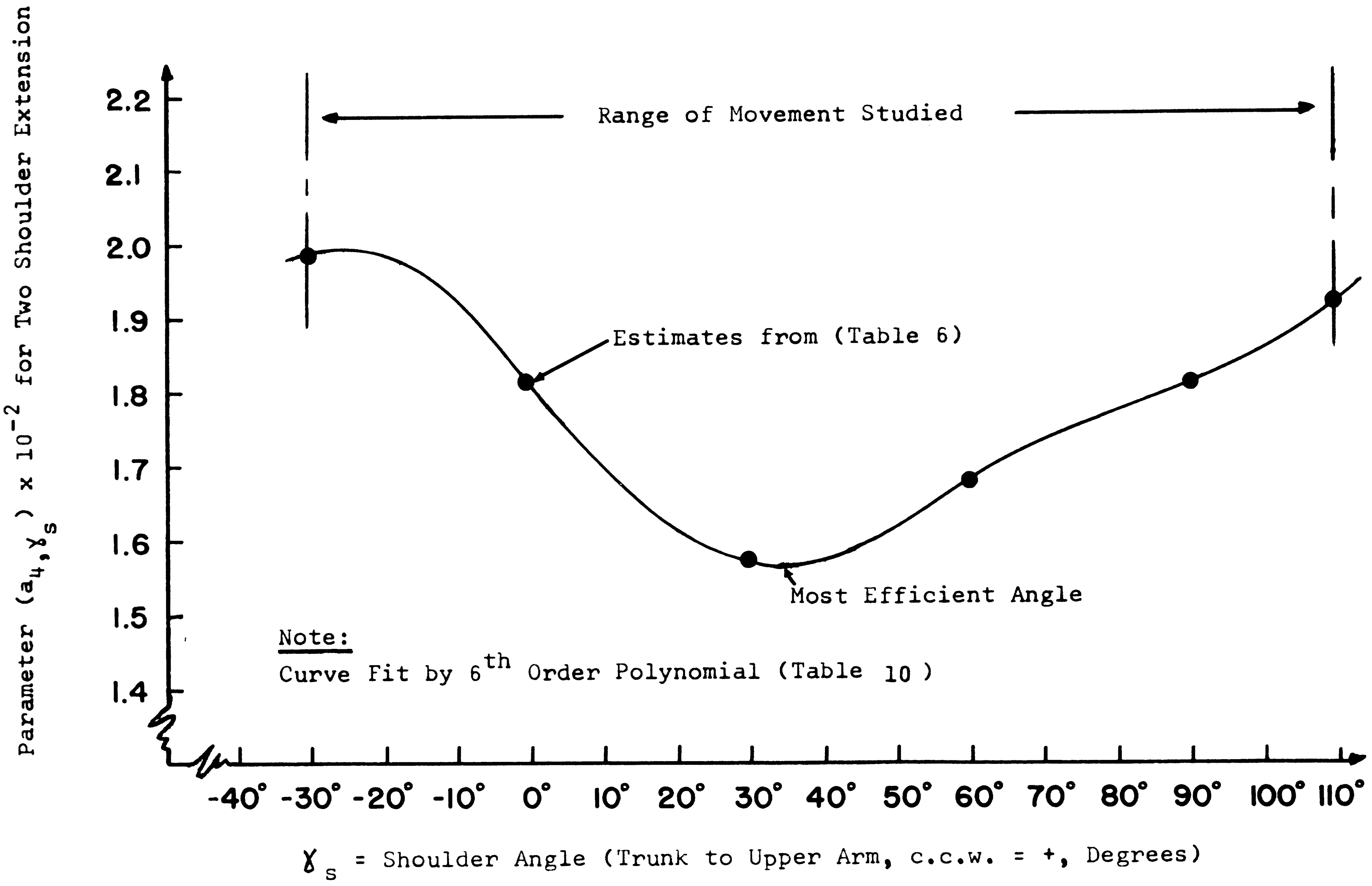


Figure D-11 ANGLE EFFECT ON a_{4,γ_s} PARAMETER IN TWO SHOULDER EXTENSION MODEL

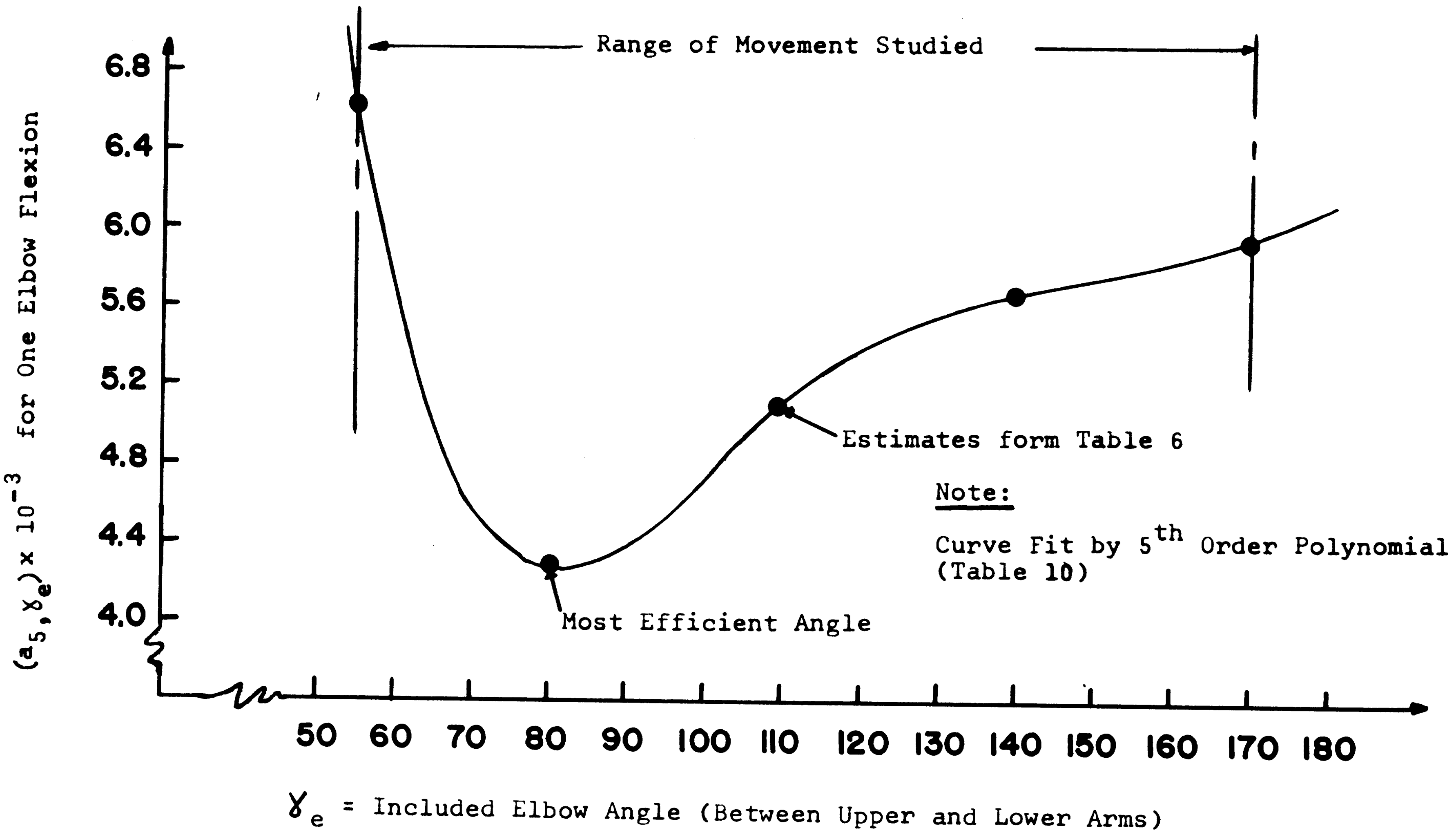


Figure D-12 ANGLE EFFECT ON a_{5,γ_e} PARAMETER IN ONE ELBOW FLEXION MODEL

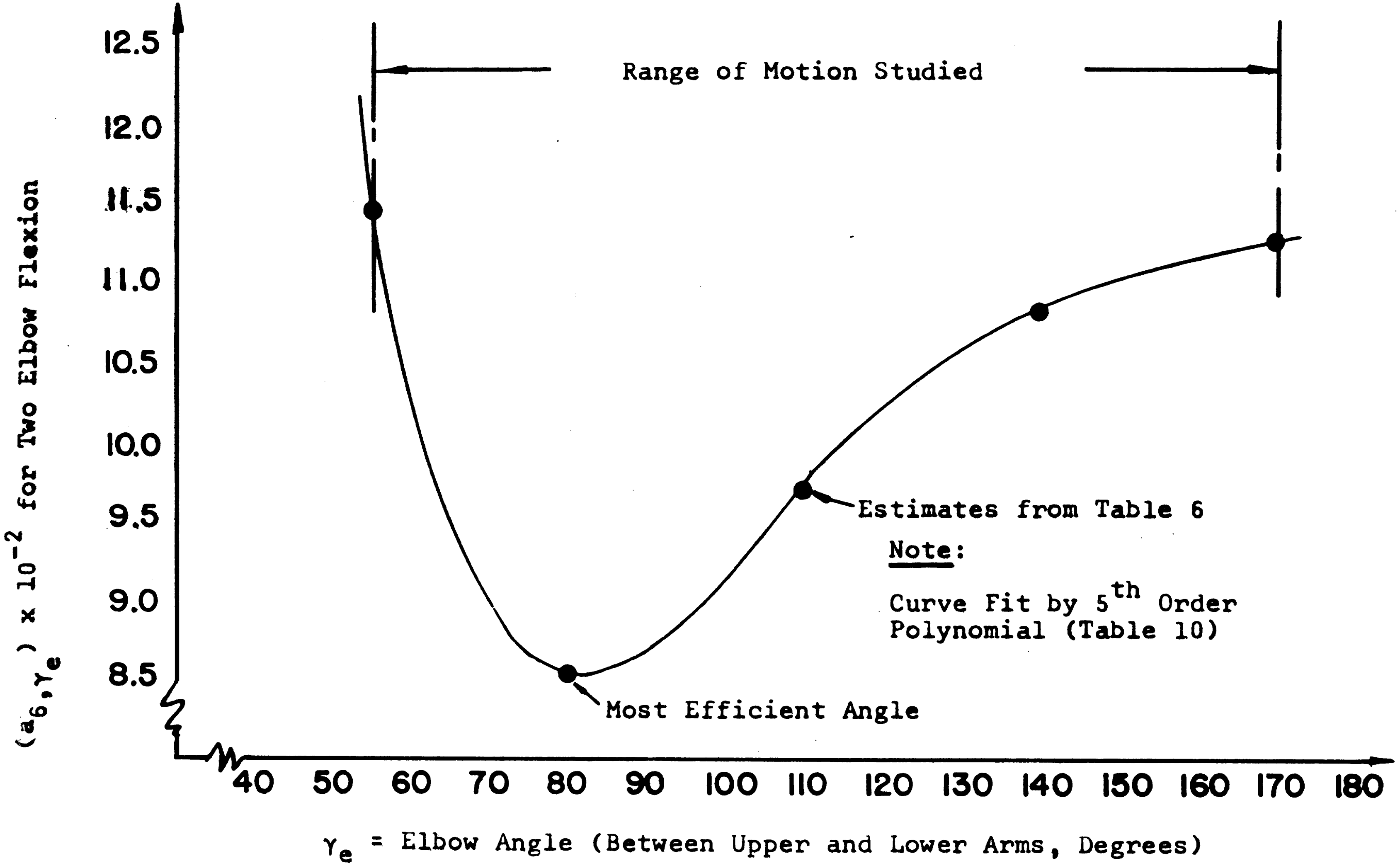


Figure D-13 ANGLE EFFECT ON a_{6,γ_e} PARAMETER IN TWO ELBOW FLEXION MODEL

Appendix E

Glossary of Variables

This glossary contains those variables which are generally referred to throughout the body of the text. The order of presentation follows the order of appearance.

E_{inc} - The incremental (above rest) metabolic energy expenditure per minute during performance of a designated static activity, expressed in Kilogram-calories per minute, or Kcal/min. (pages 64-68). (Subscripts may be included to designate specific muscle group actions or articulation angles.)

σ_e - The standard deviation of the error in a single estimate of E_{inc}, which is assumed (based on empirical data) to be a specific function of the value of E_{inc} (page 74).

T - Resultant torque during the following muscle group actions, as determined by biomechanical equations of Appendix A, expressed in Kilogram-centimeters:

SFT1 or SFT2 - Shoulder flexion torque with one or both shoulders

SET1 or SET2 - Shoulder extension torque with one or both shoulders

EFT1 or EFT2 - Elbow flexion torque with one or both elbows

WFT1 or WFT2 - Wrist flexion torque with one or both wrists

E_W - Transformed E_{inc} values used as dependent variables in various regression models. The transformation assumes that the standard deviation of the error of E_{inc} is a function of the value of E_{inc}. The resulting relationship used is (page 92):

$$E_W = \frac{\log[2.147 + 7.963E_{inc}]}{0.07963} - 4.1673$$

$a_{i\gamma m}$ - Empirically defined parameter which reflects the value of E_W for the m^{th} individual sustaining a known torque, requiring the i^{th} muscle group action (page 104), at a γ articulation angle (page 108). (For the first subject the m subscript was not included, and for wrist flexions the γ subscript was also excluded.)

b_i - Empirically defined exponent which represents the relative change in E_W for a given change in the resultant torque during the i^{th} muscle group's action (page 103).

e_{AB} - Empirically defined coefficient which reflects the value of E_{inc} conserved by subjects when torques at two adjacent articulations exist simultaneously (page 137). Its effect on E_{inc} is based on the cross-product of the adjacent articulation torques.

d_{im} - Empirically defined subject difference parameter derived from ratio of $a_{i\gamma m}$ coefficients for m^{th} subject and first subject (page 161).

E_D - The incremental (above rest) metabolic energy expenditure per minute of performance of a designated dynamic activity, expressed in Kilogram-calories per minute (page 178).

P - Empirically derived parameter whose value, when raised to the power of the angular velocity, reflects the increase in E_D (above the equivalent static E_{inc}) caused by the angular velocity of the arm segments rotating about the elbow or shoulder (page 186).

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