AN ABSTRACT OF THE THESIS OF

Charles Willard Novak for the degree of Master of Science

in Education presented on January 19, 1981

Title: EXTERNAL AND INTERNAL WORK OF A T-6 PARAPLEGIC PROPELLING A WHEELCHAIR AND ARM CRANKING A CYCLE ERGOMETER: CASE STUDY

Abstract approved: Redacted for Privacy

(John M. Dunn)

The purpose of this investigation was to compare the results of two methods of gathering data on the stress of wheelchair propelling at equivalent work loads and to account for differences in physiological responses with a mechanical analysis of wheelchair propelling. Physiological data collected were heart rate, systolic blood pressure, and rate-pressure product. A biomechanical cinematography analysis was used to determine external work in wheelchair propelling. Ergometer settings determined external work in arm cranking cycle ergometry. A *t*-test of equivalent external work loads indicated that heart rate was not different between the two exercise modes at the .05 level of significance. The *t*-tests did indicate a significant difference in systolic blood pressure and rate-pressure product at the .05 level of significance. The biomechanical analysis of wheelchair propelling established that an increase in external work

was accompanied by a decrease in the range of motion and an increase in the speed of movement. During cycle ergometry the range and speed of movement remained the same while the resistance was increased. Results of the study established that while heart rate for equivalent external work loads was the same for wheelchair propelling and arm cranking cycle ergometry, systolic blood pressure and rate-pressure product were not the same.

External and Internal Work of a T-6 Paraplegic Propelling a Wheelchair and Arm Cranking a Cycle Ergometer: Case Study

by

Charles Willard Novak

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed January 19, 1981

Commencement June 1981

APPROVED:

Redacted for Privacy

Professor of Physical Education
in charge of major

Redacted for Privacy

Dean of Education

Redacted for Privacy

Dean of Graduate School

Date thesis is presented January 19, 1981

Typed by Lyndalu Sikes for Charles Willard Novak

TABLE OF CONTENTS

Table of Contents (continued)

LIST OF FIGURES

List of Figures (continued)

LIST OF TABLES

EXTERNAL AND INTERNAL WORK OF A T-6 PARAPLEGIC PROPELLING A WHEELCHAIR AND ARM CRANKING A CYCLE ERGOMETER: CASE STUDY

CHAPTER I

INTRODUCTION

Recent legislation mandated equal opportunity for participation in all levels of education and employment by persons with handicapping conditions. Implementation of legislation has removed many physical barriers which previously denied equal access to persons with handicapping conditions. However, while physical barriers were receiving attention and modification, few studies defined the physiological fitness required of wheelchair bound persons which would enable them to benefit from the removal of those architectural barriers.

This study investigated two methods of determining fitness to perform wheelchair activity by comparing the external work production and internal energy cost of arm activity at varying work loads. Comparison of external and internal work performed in a wheelchair to external and internal work performed by arm cranking a cycle ergometer provided information based on established techniques as to the stress of operating a wheelchair. A mechanical analysis of work performed during wheelchair pushing at varying speeds helped to explain the physiological changes which were found.

Purpose of the Study

The purpose of this investigation was to compare the results of two methods of gathering data on stress of wheelchair propelling at equivalent work loads and to account for the differences in physiological responses with a mechanical analysis of wheelchair propelling.

The study was a replicated case study. The results of the study were essentially comparative and sought to explain internal work on the basis of the external biomechanics involved.

Significance of the Study

The effect of arm work of wheelchair bound persons in wheelchair activity and the internal physiological response to that work has not been well defined due to a lack of established evaluation techniques. One method used to describe internal effects of arm work has been to measure physiological responses to arm cranking a cycle ergometer. Another method used to describe the effects of arm work has been to measure physiological responses to wheelchair ambulation on a smooth level surface.

An assumption was made that performance of a given amount of external work would produce similar internal responses whether that work was performed on a cycle ergometer or while propelling a wheelchair. If the two methods of evaluation were equivalent, performance of a given amount of work on a cycle ergometer should have produced identical internal effects to the performance of the same amount of work in wheelchair activity. If the internal effects of doing the same amounts of work in cycle ergometry and wheelchair ambulation were not equal, then a mechanical analysis of work performed would help to explain the differences.

Methodology and Delimitations

A case study design was selected to describe the external and internal work of wheelchair propelling. The subject of this investigation was an adult male paraplegic with 20 years experience in wheelchair ambulation. Internal physiological work was reflected by changes in heart rate and blood pressure at the selected velocities. External work was determined by changes in forces applied to the wheelchair and the resultant chair velocities as obtained through cinematography. Data related to physiological and mechanical adjustments at different velocities were compared with data obtained from working at various loads on a cycle ergometer.

Criterion measures for internal work were heart rate and blood pressure changes at various work intensities in both wheelchair propelling and cycle ergometry. Criterion measures for external work were changes in work load as determined from velocities and accelerations during wheelchair ambulation and as determined from ergometer settings in cycle ergometry.

Hypotheses

Hypotheses advanced were that the values for each internal work parameter would change as a result of external work load performed. The null hypothesis was assumed for each internal work parameter for three external workloads. Mean values for heart rate, systolic blood pressure, and rate-pressure product for wheelchair ambulation for each of three external work loads were set equal to $\overline{X}_1$. Mean values for heart rate, systolic blood pressure, and rate-pressure product for cycle ergometry for three equivalent work loads were set equal to $\overline{X}_2$. The null hypothesis for each internal work measure was:

$$H_o: \overline{X}_1 = \overline{X}_2$$

In effect, then, this null hypothesis was used for each of three internal work parameters measured in three external work loads.

A paired observation two-tailed t-test was used to determine acceptance or rejection of the null hypothesis. If the null hypothesis was rejected then the two methods of gathering internal work data must produce different results on the physiological system.

Limitations

A comparison of the relationship between the results of two methods of gathering information on internal physiological responses of a wheelchair bound person to arm work was the goal of this study. The investigator recognized that interpopulation comparisons or generalizations were not possible on the basis of the results from measures taken on one subject. The use of such measures was acceptable since relative changes in internal physiological data related to external work performance were the important statistics.

The study was an in-depth observation of a T-6 paraplegic propelling a wheelchair. The researcher recognized that different disability levels other than the mid-thoracic involvement of the subject might have different abilities relative to work performance. More work needs to be done describing the responses of subjects with different disability levels to standard work loads. The case study methodology was selected for this study because the nature of the mechanical analysis did not lend itself to large population studies. Furthermore, the investigation was viewed as a necessary step for determining future test protocols which could be shown to be valid.

Summary

No standard methods existed for determining stress of wheelchair activity or fitness to perform wheelchair ambulation. While at least two methods received some use in evaluating internal cost of external work performance, the validity of either method as a criterion instrument was unknown. As more wheelchair bound individuals entered the public schools and mainstream of the labor force, the necessity of having a valid instrument to determine fitness to perform wheelchair activity increased. This study supplied comparative information concerning two methods generally utilized to access the physiological stress of wheelchair propelling.

Definition of Terms

External work - As used in the present study "external work" referred to the total mechanical work produced which was composed of forces from active muscular contraction as well as elastic recoil energy from stretched contracted muscle.

Handicapped - "Handicapped" referred to any individual who had a disability which resulted in a hindrance to employment or education. The specific handicap of concern in this case study was paraplegia. The subject of the study was a T-6 paraplegic. The term T-6 paraplegic referred to an individual with a traumatic lesion at the level of the sixth thoracic vertebra resulting in loss of both motor and sensory innervation from the abdomen to the feet.

Internal work - Also referred to as physiological work and internal energy cost, "internal work" described work of the heart and vascular system required to supply blood and oxygen to actively metabolizing tissues and was characterized by rate-pressure product (RPP).

Occlusion - "Occlusion" described a condition in which extra-arterial pressure is greater than internal arterial pressure thereby reducing blood flow through a vessle.

Stress - "Stress" referred to increased internal work due to external work performance or an excited emotional state or some combination of the two.

Stroke - "Stroke" as used in this study referred to an application of force with the arms to the drive wheel of a wheelchair.

Wheelchair pushing, propelling, driving, walking, using, ambulation, propulsion - The preceeding terms were used in this study synonymously and referred to any act which resulted in the purposeful movement of a wheelchair by its user.

CHAPTER II

REVIEW OF RELATED LITERATURE

The primary purpose of this replicated case study was to compare the internal work of wheelchair propelling to the internal work of arm cranking cycle ergometry at equivalent external work loads. A mechanical analysis was used to help explain the physiological effects of wheelchair ambulation. Initially the review of literature focused on the value of the study related to recent legislation. Next, a comparison of external and internal work as determined by mechanical and physiological analyses was presented. Physiological stress of arm work as compared to leg or total body work was then described. The review concluded with a discussion of information related specifically to wheelchair propulsion.

Legislation

With regard to the equality of opportunity for handicapped people to participate in various activities, a common practice has been to measure compliance by the numbers of individuals mainstreamed. Physiological responses to work loads imposed upon wheelchair users often have been overlooked or disregarded.

Two major pieces of federal legislation mandated the incorporation into society of handicapped persons to the greatest extent appropriate for each individual. In its ninety-third session, the United States Congress passed into law the Rehabilitation Act of 1973. Part of the declaration of purpose of that Act was to, "promote and expand employment opportunities in the public and private sectors for handicapped individuals and to place such individuals in employment" (81). Also declared as purpose was to:

> evaluate existing approaches to architectural and transportation barriers confronting handicapped individuals, develop new such approaches, enforce statutory and regulatory standards and requirements regarding barrier-free construction of public facilities and study and develop solutions to existing architectural and transportation barriers impeding handicapped individuals (81, p. 845).

The recognition of a need to promote and expand opportunities and to consider placement of handicapped individuals in suitable employment was long overdo. The directive to evaluate and modify "existing approaches to architectural and transportation barriers confronting handicapped individuals" (81) has needed clarification.

A question was raised as to the nature of a transportation barrier. Was a transportation barrier only to be considered some physical, structural impedence to the free rolling of a wheelchair on a smooth level surface? Or was a transportation barrier also being considered to be some physiological limitation associated with a mode of transportation, for example wheelchair pushing? The position of this investigator was that a mode of transportation may constitute a transportation barrier. One wondered taking this position, whether the objectives of the Rehabilitation Act of 1973 were, in fact, being met solely with the modification of external barriers. Paragraphs 4 and 6 of section 301 of the Act state:

> (4) it is of critical importance to this Nation that equality of opportunity, equal access to all aspects of society and equal rights guaranteed by the Constitution of the United States be provided to all individuals with handicaps;
>
> (6) it is essential that recommendations be made to assure that all individuals with handicaps are able to live their lives independently and with dignity, and that the complete integration of all individuals with handicaps into normal community living, working, and service patterns be held as the final objective (81, p. 870 as amended 1976).

Were equality of opportunity, equal access or equal rights really obtainable when the nature of the physiological stress of transporting one's self was not clearly identified? Could the objectives of the act have been attained without some study of the physiological difficulty of the effort required to effectuate the act?

The Education for all Handicapped Children Act of 1975 also was enacted to ensure that all handicapped individuals received a free appropriate public education and were afforded the opportunity to participate to the greatest extent possible in the least restrictive environment (28). Specifically included in the Act were provisions for physical education. Section 121a. 307 indicated clearly that every handicapped child would participate in some type of physical education activity.

With regard to various handicapping conditions, what was the nature of the physiological stress of a given activity? How were teachers to know the difficulty of the activities of children who used different modes of transportation? Answers to these questions should have been obtained and should have been published in the literature for wheelchair bound persons to enjoy equality of opportunity.

There was little information concerning the physiological stress of wheelchair propulsion. In the light of recent legislation mandating removal of barriers to transportation, attention has focused on equality of opportunity to participate. Little information appeared concerning the physiological equality for opportunity after the removal of physical transportation barriers. Studies of possible modes of wheelchair transportation should have been initiated. The primary purpose of this study was to compare two methods of obtaining data relative to the physiological and mechanical work conducted in propelling a wheelchair. The study helped to provide some basis for comparison of specific modes of transportation. The biomechanical analysis provided valuable information which helped to explain the results of the study.

External and Internal Work Revealed by Mechanical and Physiological Analyses

As early as 1939, T. K. Cureton described the importance of cinematographic analysis as an aid in athletic research (18). Recent technological advances enabled researchers to identify with precision the physical and mechanical properties involved in a variety of human performances. Current techniques have permitted analysis of movement patterns to determine forces responsible for those actions. Refinements in high speed cinematography provided detailed description of movement patterns advancing the study of kinematics (15, 36, 43, 57, 61, 63). Through kinematics, human motion was described in terms of segment relationships and sequences of segment patterns. The kinetics or forces necessary for given movements have been determined when segment masses and centers of gravity were used in conjunction with kinematic information (1, 19, 36, 41, 42, 43, 48, 61, 85). The dual role of kinematics and kinetics of human motion has allowed researchers to study performance in terms of efficiency of energy expenditure and to derive implications enabling individuals to enhance performance based upon changing sequencing of segments and/or force production in a given sequence.

Sinning and Forsythe (73) utilized detailed kinematic analysis to describe running step patterns at a variety of linear velocities. Other researchers utilizing kinetic and kimematic descriptions of running techniques have determined the most efficient body posture for sustained running (16, 75). One of the recent studies utilizing kinetic and kinematic descriptions as an aid in athletic research was a paper by McMahon and Green (55). In McMahon's study, kinetic data concerning the elastic recoil of tissues in the leg during running as determined by strain-gauge platform (12) was related to kinematic data obtained by cinematography. The study was a description of the elastic bounce of the body on surfaces of varying compliance. The application of the study was the determination of surface compliance which was optimal for running at greater efficiency.

Further applications of biomechanics cinematography analysis in obtaining kinetic and kinematic descriptions have been conducted with various activities including jumping and throwing (2), kicking (64), walking (59), the golf swing (11, 47, 84), and the pole vault (22, 40). The vast majority of biomechanics cinematography analyses have been performed with non-disabled average or above average athletes. The purpose of studies such as those mentioned above has been to analyze efficiency of a performer or group of performers so that implications might be made of a precise nature to enable the subject to become more proficient in a given task.

Possibly due to the lack of emphasis in education for the wheelchair bound student or perhaps due to the complexity of a variety of conditions associated with the functioning of the human machine, research literature has been practically void of performance studies of the wheelchair bound person. The majority of what little direct application of mechanical or physiological analysis that appeared in the literature concerning the handicapped population has been done in hospital or clinic situations and has dealt with the analysis or effects of prostheses on performance of simple motor skills (23, 24, 50, 89).

Recently Glaser (35) utilized cinematography analysis to study the kinetics of wheelchair propulsion as performed by non-handicapped subjects for the purpose of determining mechanical efficiency of the task. Steadward (77) also utilized cinematography analysis to describe the kinematics of wheelchair propulsion of a variety of subjects with different levels of spinal cord lesion. Glaser's work provided meaningful information about the mechanics of wheelchair propulsion, however, he used a non-handicapped population as the subjects of his study. Steadward's study was performed with subjects well adapted to wheelchair ambulation, however, the cinematography analysis was limited to a kinematic description of segment and joint actions. Little information has appeared in the literature on the kinetics and kinematics of external work performed by the chronic wheelchair user. Development of such information seemed crucial to determine the extent to which an educational experience might be considered appropriate.

While biomechanics cinematography proved useful in describing the kinetics of external work, another area of study has been utilized to determine the effects of forces and motions. In a study published in 1964, Cavagna, et al. (16) defined external and internal work performed in running as components of total mechanical work. The term external work referred to the total mechanical work of mobilization, recognizing that the external work performed was composed of forces from active muscular contraction as well as elastic recoil energy from stretched contracted muscle. Consideration of elastic recoil energy as related to running had much importance. The elastic recoil variable amounted to nearly half the total mechanical work performed (12, 13, 15, 79).

The term internal work referred to the work of the heart and vascular system required to supply blood and oxygen to actively metabolizing tissues. Heart rate and blood pressure determinations have been used as measures of the internal cost of external work. Heart rate and blood pressure determinations have been used to estimate oxygen demand by the participating musculature as well as the proportion of the total musculature utilized (20, 21, 33, 34, 52, 66, 87).

The performance of a given amount of external work has been shown to require a given amount of internal energy production (7, 20, 21, 68, 70). In the human body the production of energy was described as being accomplished by combustion of oxygen (38, 39). The combustion of oxygen, or oxygen uptake, has been shown to be directly related to heart rate (5, 6, 52, 65, 66, 68) (see Figure 1).

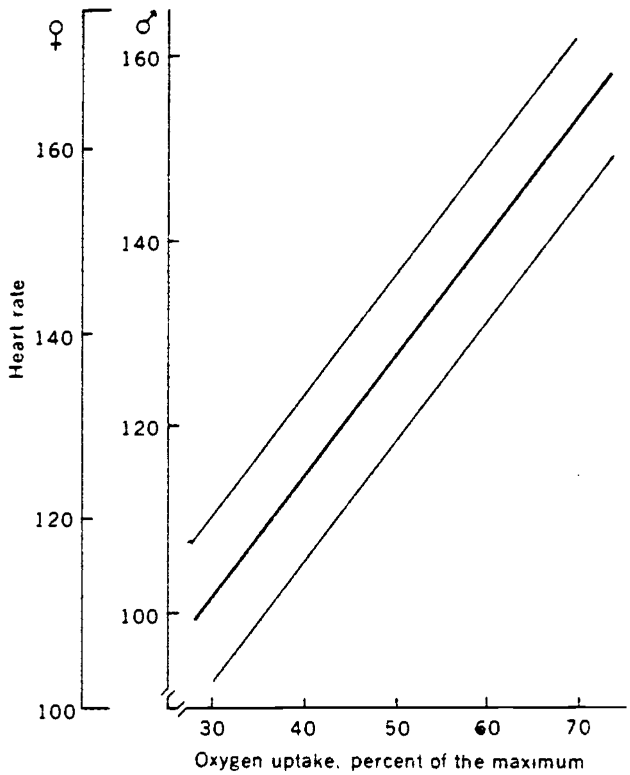

Figure 1. Relationship between heart rate during work (bicycle ergometer) and oxygen uptake expressed in percentage of subject's maximal aerobic power. (From P. O. Astrand and Ryhming, 1954).

Additionally, oxygen uptake has been shown to be directly related to work load (6, 7, 8, 10, 16, 29, 49, 54). Consequently, heart rate has been shown to be directly related to work load and oxygen uptake, wherein, the relationship between workload and oxygen uptake have been shown to be direct (4, 5, 7, 20, 21, 27, 72, 87) (See Figure 2).

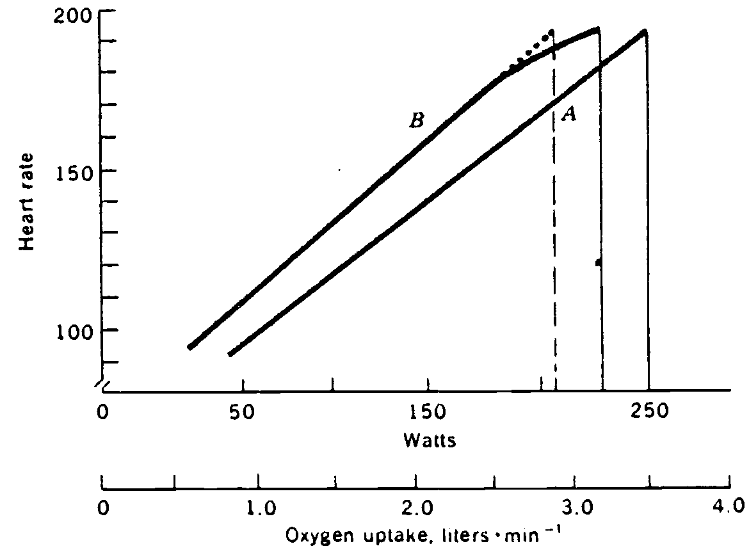

Figure 2. Relationship between heart rate and work load (in watts) and oxygen uptake (in liters$\cdot$ min^{-1}) indicating the direct relationship between work load and oxygen uptake for two different subjects, A and B (from P. O. Astrand and Rodahl, 1972).

In an individual, a given amount of external work required a given amount of internal work. Between two individuals, however, performance of a given amount of external work might have required much different internal work output. The difference would have been described relative to the efficiency of delivering an amount of oxygen to working muscle. Additionally, the ability of that muscle to extract oxygen from the circulating blood and the proportion of the total musculature involved would have been considered. (Compare subjects A and B in Figure 2.) Therefore, determining heart rate at a given work load would provide the basis for comparing the internal efficiency of performers.

While heart rate was seen to be an indicator of oxygen utilization relative to work load, the rate-pressure product (RPP), that is, the product of heart rate times systolic blood pressure, was identified as the principal determinant of myocardial oxygen utilization and internal work (67, 69). As external work increased during performance, muscle tissues demanded increasing supplies of oxygen in order to continue to work (5, 16, 52, 66).

The demand for oxygen would have been met in one of two ways. Either the oxygen concentration of arterial blood must have increased to supply tissue demands at the same rate of delivery, or the rate of delivery of a constant oxygen concentration in the blood must have increased. Investigators have reported that arterial blood that leaves the lungs is saturated to the extent of ninety-five to ninety-eight percent (20, 21, 72). Therefore, an increase in the rate of delivery appeared to account for the increased supply.

Investigators have established that as work load increased from some resting state to a higher intensity, increased work load was paralleled by increases in heart rate and systolic blood pressure (5, 6, 8, 66, 69). However, tissue demands for oxygen at relatively high rates of energy expenditure sometimes appeared to exceed the heart's ability to supply oxygen. The point at which oxygen demand exceeded the heart's ability to keep up the supply was termed maximal heart rate; the maximum rate at which the heart can beat and still result in an increased forwarding of additional amounts of oxygen to the tissues (5).

When the heart was shown to work submaximally the rate became constant at a given work load within three minutes after the onset of work (5, 6). If the work load was so great that maximum heart rate was exceeded, heart rate did not become constant but rather continued to increase throughout the work interval. Thus, heart rate served to indicate whether external work was submaximal or maximal. Since systolic blood pressure has also been shown to increase with increasing work load, RPP provided an augmented indicator of the load at which maximal heart rate was attained.

Maximal heart rate has appeared to be quite constant and predictable relative to age (5, 6, 20, 21, 49, 60, 72, 74). Therefore, a given individual performing a given work load submaximally on one occasion should have been able to perform that same work load submaximally on another occasion.

Arm Work

Researchers have compared the physiological responses of arm work to leg work. Arm work typically involved a relatively high intensity, short duration contraction on the part of a relatively small muscle group over a rather short range of motion. In contrast, walking or running involved a much lower intensity, somewhat longer duration contraction of the legs as well as the arms. Further, these segments appeared to move over a wider range of motion, resulting in heightened efficiency of movement.

In comparing arm work to leg work some similarities were apparent. Blood pressure was reported to increase in linear fashion with oxygen uptake, a fact especially observable in arm work (4, 51). Also, blood flow and oxygen uptake increased in linear fashion with the intensity of the work being performed (30, 51, 82).

A close examination of the active metabolism in the limbs revealed oxygen uptake in the arms was only seventy percent of the value for oxygen uptake in the legs (4, 6, 65, 87). The first impression from this information seemed to suggest that the arms were really not working as hard as the legs. However, further consideration of work performed and responses to that work demonstrated very different conclusions.

Several investigators have reported that maximum heart rate was lower with arm work than maximum heart rate with leg work, but the heart rate with arm work was higher than predicted from oxygen uptake. This indicated that the heart's ability to forward oxygen to the tissues and/or the tissues' ability to unload oxygen from the blood was less in arm work than leg work (4, 6, 8, 9, 29, 31, 51, 68). Considering the smaller muscle mass in the arms, tissue unloading of oxygen might have been the limiting factor.

Further reports suggested that blood pressure increased to a greater extent in arm work than leg work (4, 9, 30, 31, 62, 68). Again, due to the smaller muscle mass for a given work load, the arm muscles would have had to contract to a greater relative degree than the legs, thus increasing occlusion and consequently blood pressure.

The reports cited indicated the work of the heart was greater for arm work than for leg work as evidenced by elevated heart rate and blood pressure over that observed during leg work. Note, however, that in arm work increased cardiac output was accomplished by elevated heart rate and blood pressure but not by elevated stroke volume. Actually, stroke volume has been reported to increase little or not at all in work with the arms (9, 51). As such, arm work was not considered as efficient as leg work in terms of cardiac cost or internal work.

A variety of explanations have been suggested for the efficiency/ metabolism phenomena observed in arm versus leg work. Increased peripheral vascular resistance in the arms during work was one such explanation which accounted fairly well for the differences (4, 9, 30). Another related explanation was the effect of greater sympathetic nervous system tone during work with the arms (9, 30, 31, 62, 68).

The increased sympathetic nervous system tone might have resulted from heightened perceived exertion during work with the arms (58).

Mechanical efficiency information provided by Cavagna (13, 14, 15) suggested another possible explanation. As much as fifty percent of the total mechanical work involved in running was performed by elastic recoil energy from the stretched leg muscles at virtually no internal work cost. Regardless of the explanation(s) to which one may subscribe to interpret differences in arm and leg work, the overall effect was that arm work appeared to be less efficient than leg work resulting in greater internal work. At any given absolute work task the wheelchair user must be considered to be at a distinct disadvantage, even when considering the task of ambulation.

The Wheelchair Performer

Research cited above referred to the internal cost of arm work as related to leg work. In the non-handicapped individual who trains predominantly with leg work, the cited investigations have provided meaningful information concerning work performed with the arms, the arms being in a relatively untrained state. In the mobility limited individual whose primary means of locomotion was through the use of the arm musculature, research relating internal effects of arm work to the external work performed took on a somewhat different significance. Research literature has been noted to be almost void of information about this special group of people (34, 46).

Investigations have been completed regarding work required to propel a wheelchair on surfaces of varying compliance (88) and efficiency of wheelchair propelling as compared to equivalent cycling tasks (83). The work of both Wolfe (88) and Webb (83) indicated that wheelchair propelling was very strenuous and particularly inefficient as compared to other forms of locomotion.

In populations whose primary means of locomotion was arm musculature, information relating external work effects on internal responses differed from effects of arm work in populations whose primary locomotion was leg musculature (33, 34, 44). Certainly within the realm of possibility was the notion that the specific task of training exclusively with the arms might cause some adaptation in the musculature or mechanics of the arms toward heightened efficiency (29, 33, 35). Previously, the concept of specificity of training was not new but has only slowly gained acceptance and understanding (3, 20, 21, 25, 29, 34, 35, 49, 54, 71, 72, 80, 86).

A concept that achieved general acceptance was that cells, tissues, organs or systems adapted specifically to stress as imposed upon them. A muscle trained to move light loads quickly developed the ability to contract more quickly. A muscle trained to move very heavy loads developed the ability to move heavier loads with less strain (17, 25, 29). Adaptation was specific to the demand. A person who regularly trained to run long distances developed the ability to run long distances with a minimum of stress and strain. A person leading a sedentary lifestyle developed the ability to be sedentary. A sedentary person would not become able to run long distances by continuing sedentary lifestyle. The adaptations were very specific to the imposed demand and began at the cellular level of organization and persisted throughout the organism (20, 21, 25, 29, 71).

Also known was that a given test stressed a specific muscle group in a specific manner. The validity of that test was related to the specific nature of the test and was not necessarily extrapolated to other portions of a person's movement repertoire (3, 34, 49, 54).

Considering both test and task specificity, noteworthy was the fact that the most frequently utilized criterion instrument for comparison of external and internal work in wheelchair performers has been arm cranking a cycle ergometer (26, 34, 44, 77, 78, 90). The assumption seemed to be that the instrument was generally available, easy to operate, and had relatively constant mechanical efficiency (5).

The mechanics of cycle ergometry as cranked with the arms appeared to be quite different from wheelchair propelling. The crank shaft of the cycle ergometer was rather short (seven inches) compared to the radius of a wheelchair drive wheel (eleven inches) indicating much different torque potential developed on the two machines. Additionally, cycle ergometry as adapted for use with the arms required reciprocal application of pushing and pulling forces against the handles by the arms, whereas wheelchair propelling required that both arms simultaneously push and pull. With these points in mind, considerable doubt was cast upon comparison of physiological performance parameters of cycle ergometry as adapted for arm ergometry relative to wheelchair driving. Glaser stated that meaningful evaluation of wheelchair performance required wheelchair-type activity as the exercise mode (33, 34).

Stoboy, et al. (78) compared heart rate and pulmonary gases during wheelchair propelling with heart rate and pulmonary gases during ergometric performance to determine the physical load in Watts or kilograms per second. In reporting results of free wheelchair driving an average increase in heart rate was reported as percent increase over some average resting rate at some average velocity of driving. As reported, results indicated internal responses to only one external load. The respiratory quotient (RQ) reported for this average response to some average load was 0.92. This high RQ value indicated a rather high intensity response to that work load but gave no indication of a possible response to a lesser or greater work load.

In that portion of Stoboy's (78) study in which work load was compared to heart rate and pulmonary gases, where work load was varied, work was performed on an ergometer or during paced wheelchair propelling. Considering the specific nature of the task of arm ergometry, the validity of using the ergometer as a criterion instrument in comparison to the task of wheelchair driving was questionable. During paced wheelchair driving on a platform, there was no possibility of free wheelchair rolling, indicating that to maintain a given rate of work the performer had to build instantaneous momentum at each push, thus increasing overall work by twenty percent as reported by Stoboy (78). Specificity of the task of wheelchair driving made comparison to paced wheelchair driving questionable.

Emes (26) compared performance of wheelchair athletes to non-wheelchair athletes on specified physical fitness tests. Arm cranking of a cycle ergometer was used as criterion instrument and heart rate a criterion measure. Arm cranking of a cycle ergometer was considered an unfamiliar task to both groups of athletes, non-specific to the nature of their training. Comparison of the effects of this sort of test in the two groups of athletes reflected the degree to which the criterion instrument was inappropriate as a measure of fitness of the two groups.

Zwiren and Bar-Or (90) compared responses to exercise of wheelchair athletes, wheelchair non-athletes, normal athletes, and normal non-athletes. However, Zwiren's report utilized arm cranking of a cycle ergometer as the criterion instrument which was non-specific to the task of wheelchair driving. Comparisons and conclusions based upon this work were, therefore, questionable. Zwiren's work did report that the active wheelchair athlete responded more favorably than the sedentary wheelchair person, implying that some form of training was beneficial (90). Heightened activity seemed to provide some training effect allowing the trained individual to perform more work with less internal stress. The possibility of a training effect induced by activity supported the contention of Guttmann (37) that sports participation since World War II was the factor increasing longevity in wheelchair users. The specific internal effects of wheelchair driving related to the external work load were not clear from Zwiren's work.

Hildebrandt compared energy expenditure and cardiac response of individuals age eleven to twenty-two years and utilized wheelchair driving on a treadmill and handcranking of a cycle ergometer as criterion instruments (44). Hildebrandt noted that while energy expenditure in wheelchair propelling was less than that for walking at comparable speeds, heart rate was greater for all wheelchair confined subjects. In comparing wheelchair driving to walking Hildebrandt concluded, "The results of these studies demonstrate that in wheelchair propelling, despite a lower energy expenditure, the circulatory system is under much more load than in walking" (44). His finding further suggested that ergometric performance was similar to wheelchair driving on a treadmill. Therefore, Hildebrandt (44) suggested checking a subject's circulatory response to wheelchair propulsion by an equivalent cranking test. If wheelchair driving on a treadmill was comparable to wheelchair driving around the home, school or job the suggestion was valid. A comparative study of work performed in arm cranking of a cycle ergometer to comparable work performed during free wheelchair driving of subjects of wider age ranges seemed to be needed.

Steadward (77) compared the kinematics of wheelchair propulsion of several subjects of varying disability levels. The description of the mechanics involved in wheelchair propulsion by subjects of varying spinal disability level provided insight into possible explanations for varying internal response to imposed work load. However, Steadward did not report such responses other than to indicate qualitatively that greater effort was required to perform similar amounts of work by persons with disability at a higher spinal cord level (77).

Glaser reported results of an exercise test to evaluate fitness for wheelchair activity (33, 34). The criterion instrument utilized by Glaser was a wheelchair ergometer which consisted of a wheelchair connected to a cycle ergometer by a direct chain drive. Criterion measures recorded by Glaser included oxygen uptake, carbon dioxide output, respiratory exchange ratio, pulmonary ventilation and heart rate (33, 34). Even at fairly mild work loads the magnitude of the physiological responses indicated that the subjects were engaged in heavy exercise. This finding was in agreement with previous studies on arm work especially those studies in which arm work was compared to leg work or when work of a wheelchair confined person was compared to equivalent work of a non-handicapped person performing work with the arms. Unfortunately some of the subjects in Glaser's study were able-bodied, and therefore, Glaser indicated that responses of wheelchair confined subjects might be quite different (34). The necessity of determining carbon dioxide output, respiratory exchange ratio and pulmonary ventilation was minimized. Glaser stated, "As specialized instrumentation and techniques are required for determination, these variables may not be practical for clinical testing" (34). The indication was that submaximal heart rate and power output relationships could serve as indicators of metabolic stress and cardiorespiratory capacity.

Summary

Although biomechanics cinematography has enabled non-handicapped individuals to improve performance, increase efficiency and reduce strain, few studies have been made of the handicapped population. What little direct application of advanced techniques of movement analysis that has been done with wheelchair users has utilized non-handicapped subjects, or, when wheelchair users were studied, their disability level was not specified. From the few studies done with wheelchair users, the results indicated that wheelchair use was a stressful method of locomotion. Not only was wheelchair use more stressful than walking at comparable work loads, but those chronically adapted to wheelchair use showed more stressful responses to locomotion in their chairs than did non-handicapped individuals. Furthermore, the available evidence suggested that the higher up in the spinal cord the lesion occurred, the more stressful was the response to wheelchair activity.

Limitations of currently available data indicated that more information was needed concerning the wheelchair bound population's responses to internal and external stresses produced by work. That information was considered crucial to insure that wheelchair bound individuals could, in fact, receive appropriate educational experiences and could be afforded the opportunity to participate in the mainstream of society.

It was implied that the collection of this information must be performed in a scientific manner which could be replicated by others. Because of the vast quantity of information which was seen to be needed some method should have been established which provided some standard for data collection, interpretation, and replication. The purpose of this investigation was to compare the results of two methods of gathering data on the stress of wheelchair propelling at equivalent work loads and to account for the differences in physiological responses with a mechanical analysis of wheelchair propelling.

CHAPTER III

METHODOLOGY

The primary purpose of this investigation was to compare the results of two methods of gathering data on the stress of wheelchair propelling at equivalent work loads and secondarily to account for the differences in physiological responses with a mechanical analysis of wheelchair propelling. A replicated case study design was selected to emphasize differences associated with the method of assessment. The criteria for physiological stress or internal work of wheelchair work performance were established by Glaser (33, 34) as heart rate and blood pressure measures versus power output. Results of the two methods of assessment were compared and a mechanical analysis of wheelchair activity was utilized to account for the discrepancies.

Subject

The subject for the study was a thirty-seven year-old male paraplegic who has been confined to a wheelchair for twenty years due to traumatic lesion of the sixth thoracic vertebra (T-6). For the first seventeen years of wheelchair confinement the subject was not involved in any physical training, the only exercise being wheeling around the home and school environments. For the last three years the subject has participated on a professional wheelchair basketball team. Workouts for the team include one hour per day, three days per week practice in winter months during the regular season with no organized activity in the summer. At the time of testing the regular season of basketball was not in session and the subject was involved in no organized training. On an irregular basis averaging no more than once a week the subject wheeled a distance of two miles. By his own admission this routine was insufficient to maintain a fitness level consistent with the energy requirements imposed by the demands of the regular basketball season.

During the period in which the study was conducted the subject was considered to be in good health by his physician and was under no medication. At the suggestion of the Oregon State University Human Subjects Committee the personal physician of the subject was presented with and signed a form indicating his approval of the subject's participation in the study. (See Appendix A for the approval of the Human Subjects Committee.) The subject also signed an informed consent document (Appendix B).

Equipment

Kinetic data for wheelchair propelling was obtained following the method described by Plagenhoef (63). To determine precisely external work in free wheelchair propelling a cinematography record of movement of the subject was obtained with a sixteen millimeter Locam high speed camera operated at four hundred frames per second. A technician from the Oregon State University photo service operated the camera. Filming was performed against a grid background on a basketball court. A two hundred foot circumference track for the subject to follow was marked on the court. A stop watch also was used to determine the average time taken to complete a circuit on the marked track.

Internal work was determined by recording two physiological performance variables. Heart rate during performance was monitored by use of a telemetering transmitter and receiver connected to a Sanborn Electrocardiograph (ECG) monitoring unit. Blood pressure was measured with a Higgs sphygmomanometer.

From the product of the two physiological performance variables, systolic blood pressure and heart rate, rate-pressure product (RPP) was determined. Sarnoff (67) identified RPP as the principle determinant of myocardial oxygen utilization. As such RPP served as both a measurement of physiological response to imposed work as well as an indicator of the degree to which the subject was stressed relative to maximal predicted values for his age. Thus RPP served as an exercise response measurement and as an exercise duration endpoint.

For determination of external work in arm cranking of a cycle ergometer, a Monarch cycle ergometer was the criterion instrument.

The cycle ergometer located in the Exercise Physiology Laboratory at Oregon State University, Department of Physical Education, was fixed to a table so the subject could operate it with his arms while seated in his wheelchair. Internal work was determined from heart rate and blood pressure as recorded on a Sanborn ECG and by a Higgs sphygmomanometer, respectively.

Procedure

Wheelchair Propelling

Two surface electrodes were attached to the chest of the subject. A two lead telemetering transmitter was attached to the electrodes to obtain a telemetry modified Blackburn CM-5 tracing on the Sanborn ECG monitoring unit. Marks were made on the subject with a body marking pen to locate joint axes on the cinematographic film. All marks were made on the subject's right upper extremity. Marks were placed at the location of the axis of rotation of the proximal aspect of the humerus, at the elbow, at the wrist and at the distal aspect of the third metacarpal. The distances between the marks were measured and recorded to provide scale to real factors for film analysis. Other physical measures including height and weight were also recorded for the purpose of kinetic analysis. The subject was allowed to rest five minutes before testing began.

During the rest interval for the subject, measurements were made of the distance from the film plane of the camera to the path marked for the subject to travel, from the camera film plane to the grid background, and from the subject's path of travel to the grid background. The height of the camera from the floor also was obtained. Other measurements taken included diameters of the large wheel, the push rim, the front wheel of the wheelchair, and the lengths of the handgrips and footrests. These measures were obtained for the purpose of determining an appropriate scale to real conversion factor for film analysis.

At the start of testing, the subject propelled the wheelchair at a comfortable pace for three minutes around the track marked on the basketball court. Heart rate was continuously monitored and recorded at the end of each minute. During the last lap of the three minute interval the subject was filmed as he passed in front of the grid backdrop. Immediately after filming, the subject's heart rate was recorded from the Sanborn ECG and the subject then stopped and blood pressure was taken and recorded. RPP was recorded for trial one.

Next, the subject propelled the wheelchair at a subjectively more hurried pace over the same track for another three minute interval. During the last lap of the three minute interval the subject was filmed as he passed in front of the grid background, heart rate was recorded from the Sanborn ECG, and blood pressure was taken and recorded as in the initial trial. Changes in RPP were calculated and noted.

Because a given work load requires a given oxygen utilization (5, 6, 8, 10, 16, 53) the fact that a second higher work load was performed was confirmed by an increase in RPP. Thus, external work was established by the kilogram-meters per minute power output of the subject in each trial and internal work was established by heart rate and blood pressure as recorded. A one week interval was allowed between observations so that any effects of fatigue from the first protocol would not contaminate results of the second.

Arm Cranking Cycle Ergometry

Three surface electrodes were attached to the subject to obtain a direct three lead Blackburn CM-5 Lead II tracing on the Sanborn ECG monitoring unit. Following a five minute rest period the test began. The subject performed three continuous progressive submaximal work loads by arm cranking a cycle ergometer for a duration of three minutes. Heart rate was recorded at the end of each minute. Following each three minute work interval, blood pressure was taken and recorded. Maintenance of heart rate and blood pressure below predicted maximal values served as criterion for establishing that each work load was submaximal. External work was established by the kilogram-meters per minute power output utilized for each submaximal work load and internal work was established by heart rate and blood pressure as recorded.

In wheelchair propelling, three heart rates and blood pressure values observed during three work trials established a relationship between internal and external work. The magnitude of the external work was determined by mechanical analysis of the cinematography record. The external work of wheelchair propelling was subsequently replicated on the cycle ergometer. Heart rates and blood pressures at these established external work loads were then recorded during arm cranking cycle ergometry. Thus, the basis for comparison of heart rate, systolic blood pressure, and rate-pressure product was the matched work rates.

Statistical Treatment

The null hypothesis was

$$H_o: \overline{X}_1 = \overline{X}_2$$

where $\overline{X}_1$ equals the value for a given physiological parameter during wheelchair pushing and $\overline{X}_2$ equals the same parameter for arm cranking cycle ergometry. The .05 level of confidence was chosen for the level of acceptance or rejection of the null hypothesis. The null hypotheses tested were:

$\underline{WL}_1$ (300 KGM/min)	$\underline{WL}_2$ (350 KGM/min)	$\underline{WL}_3$ (400 KGM/min)		
1	1	1	$H_o: \bar{X}_1 = \bar{X}_2$	for heart rate
2	2	2	$H_o: \bar{X}_1 = \bar{X}_2$	for systolic blood pressure
3	3	3	$H_o: \bar{X}_1 = \bar{X}_2$	for rate-pressure product (RPP)

Each of the above three null hypotheses were tested for the three work loads.

Data were analyzed to determine internal responses to specific external work performed, and to determine whether a difference existed between performing an amount of work by wheelchair propelling and performing a similar amount of work by arm cranking a cycle ergometer. The assumption was made that there was no difference in testing methods. A paired observation two tailed t-test was used in a treatments by trials design utilizing the following formula (76):

$$\underline{t} = \frac{\bar{D}}{S_{\bar{D}}}$$

where $\bar{D} = X_1 - X_2$

$$S_{\bar{D}} = \frac{\bar{D}^2 - \frac{1}{n}(\Sigma \bar{D})^2}{n - 1}$$

CHAPTER IV

RESULTS AND INTERPRETATION OF DATA

The purpose of this study was to compare two methods of assessing the physiological stress of wheelchair propelling and to account for differences in results of the two assessment schemes with a mechanical analysis of wheelchair propelling. The design of the investigation involved a replicated case study. Results of the study were comparative and sought to explain data collected in reference to internal work on the basis of external biomechanics. Heart rate, systolic blood pressure, and rate-pressure product were compared in three equivalent work loads for wheelchair propelling and for arm cranking cycle ergometry. A paired *t*-test was used to test for significance of a difference between the two treatment procedures.

Results of t-test

Table I presents data obtained from wheelchair propelling and from arm cranking a cycle ergometer. Table II presents the values for the variables tested under the null hypotheses that no difference would be demonstrated between two methods of determining internal work for equivalent externally imposed work loads.

Table I. Data for heart rate (HR), systolic blood pressure (SBP), and rate-pressure product (RPP) for workload 1 (WL_1) at 300 Kgm/min, workload 2 (WL_2) at 350 Kgm/min, and workload 3 (WL_3) at 400 Kgm/min during wheelchair propelling (X_1) and arm cranking cycle ergometry (X_2).

	WL_1 300 KGM/min		WL_2 350 KGM/min		WL_3 400 KGM/min	
	X_1	X_2	X_1	X_2	X_1	X_2
HR	122	114	146	129	168	142
SBP	238	210	242	214	246	222
RPP	28560	23730	35332	27606	41328	31524

Table II. Comparison within selected physiological variables between wheelchair propelling (X_1) and arm cranking cycle ergometry (X_2) at 3 work loads.

Physiological Variable		Activity	Work Load WL_1	WL_2	WL_3	$\bar{X}$	$\bar{D}$	$S_{\bar{D}}$	Two Tailed t
HR	wheelchair	X_1	122	146	168	145	17	5.2	3.27
	ergometer	X_2	114	129	142	128			
SBP	wheelchair	X_1	238	242	246	242	26.7	1.33	20.08[a]
	ergometer	X_2	210	214	222	215			
RPP	wheelchair	X_1	28560	35332	41328	35073	7453.3	1442.3	5.17[a]
	ergometer	X_2	23730	27606	31524	27620			

[a] Significant at .05 level   Tabular t (.05) = 4.30

Interpretation

Upon examination of Table II and Figure 3 for heart rate, the null hypothesis was accepted suggesting that no difference existed between physiological results of equivalent externally applied work loads. Results indicated that a given amount of work will require a given oxygen consumption by the skeletal muscles which, in turn, will require a given heart rate to supply oxygen to the working tissues. This finding is consistent with that of other investigators, thus establishing external validity (5, 6, 8, 10, 16, 20, 21, 27, 29, 49, 52, 53, 60, 65, 66, 68, 72, 87). The values for heart rate at the work loads under investigation were also consistent with values determined by other investigators studying wheelchair users (34, 44, 78, 90).

Inspection of the *t*-values for systolic blood pressure and rate-pressure product suggested that the null hypothesis that there was no difference between measures cannot be accepted. With the subject in the current investigation there appeared to be a statistically significant difference in systolic blood pressure and rate-pressure product for equivalent work loads as measured in free wheelchair propelling compared to cranking a cycle ergometer with the arms. As rate-pressure product reflected myocardial oxygen utilization, it appeared that arm cranking cycle ergometry was a very different task from free

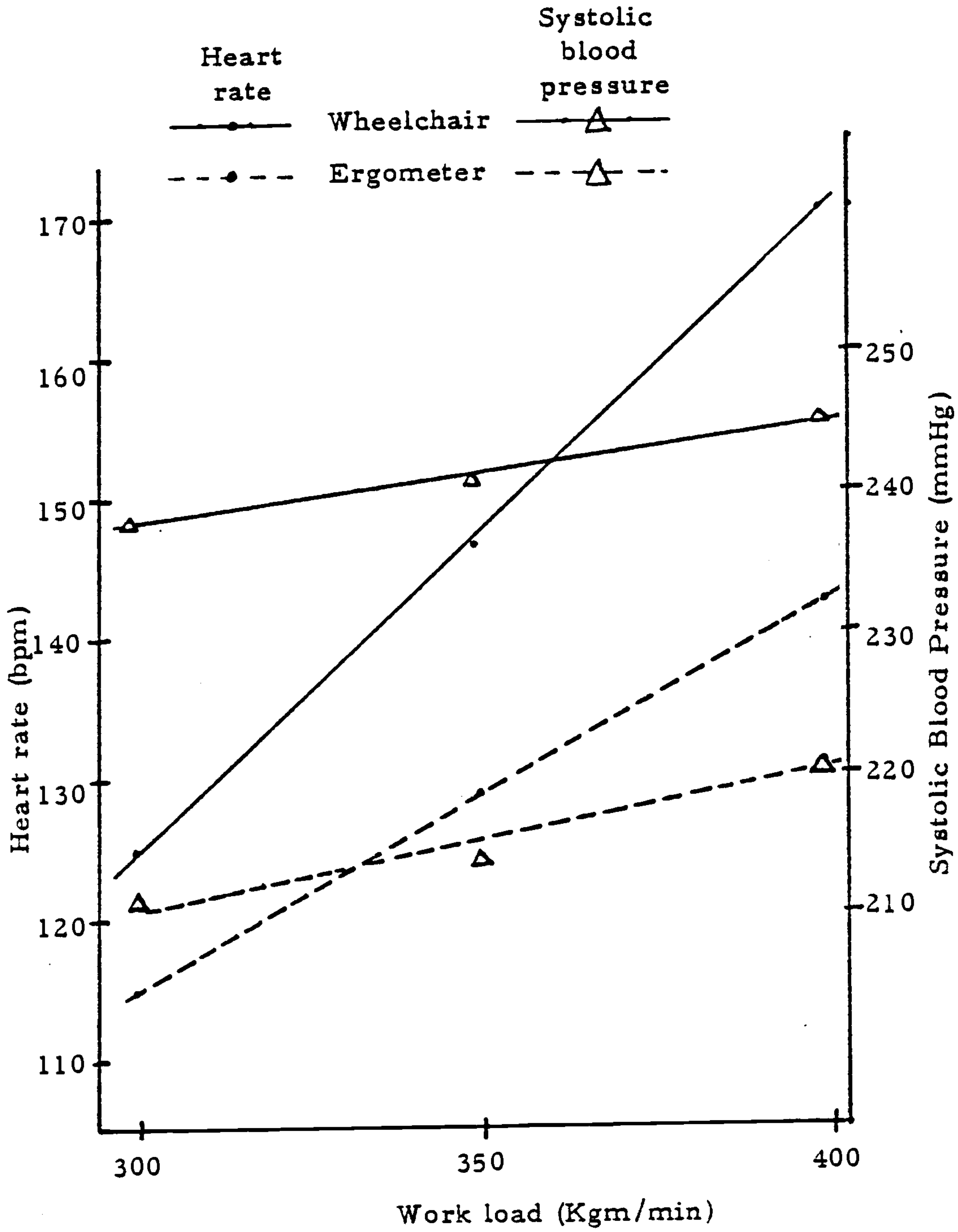

Figure 3. Relationship of heart rate and systolic blood pressure to work load in wheelchair propelling and arm cranking cycle ergometry.

wheelchair propelling in terms of the work the heart has to perform to supply oxygen to the muscles performing the task. Greater systolic blood pressure in wheelchair propelling and consequent greater rate-pressure product indicated that, for equivalent amounts of external work, the heart of a subject was under much greater physiological stress during wheelchair propelling than in arm cranking cycle ergometry.

Mechanical Analysis of Wheelchair Propelling

Table III presents the data for the subject recorded just prior to filming the wheelchair propelling trials. Figure 4 shows point-line drawings made from the high speed film record indicating the action of the near-side arm, forearm and hand. The four-by-four grid shown in Figure 4 were drawn from the film corresponding to the four inch-by-four inch grid board which was placed six feet away from the subject with respect to the position of the camera. Figure 5 depicts the point-line drawings placed uniaxially at the shoulder joint. The Figure indicates dramatic differences in segment path and segment relationships from Trial 1 at one speed to Trial 2 at a greater speed.

Measurements of segment lengths were made from the point-line drawings and those scalar values are presented in Table IV. From Table IV the scale length of the segments was found to be most

Table III. Physical measures of subject and apparatus.

Subject

Age 37 years   Sex Male   Height 6ft 1 in

Subject weight 165 lbs   Wheelchair weight 58 lbs

Total weight 223 lbs

Length of humerus 11-1/4 in
Length of forearm 11-3/4 in
Length of hand (axis to 3rd knuckle) 3-1/2 in

Apparatus

Diameter of back wheel 24 in
Diameter of push rim 19-3/4 in
Diameter of front wheel 5 in
Length of handgrip 3-1/2 in
Length of footrest 6-1/8 in

Distance from camera to subject 27 ft 7 in
Distance from camera to grid board 33 ft 7 in
Distance from subject to grid board 6 ft
Height of camera from floor 3 ft 10-1/2 in

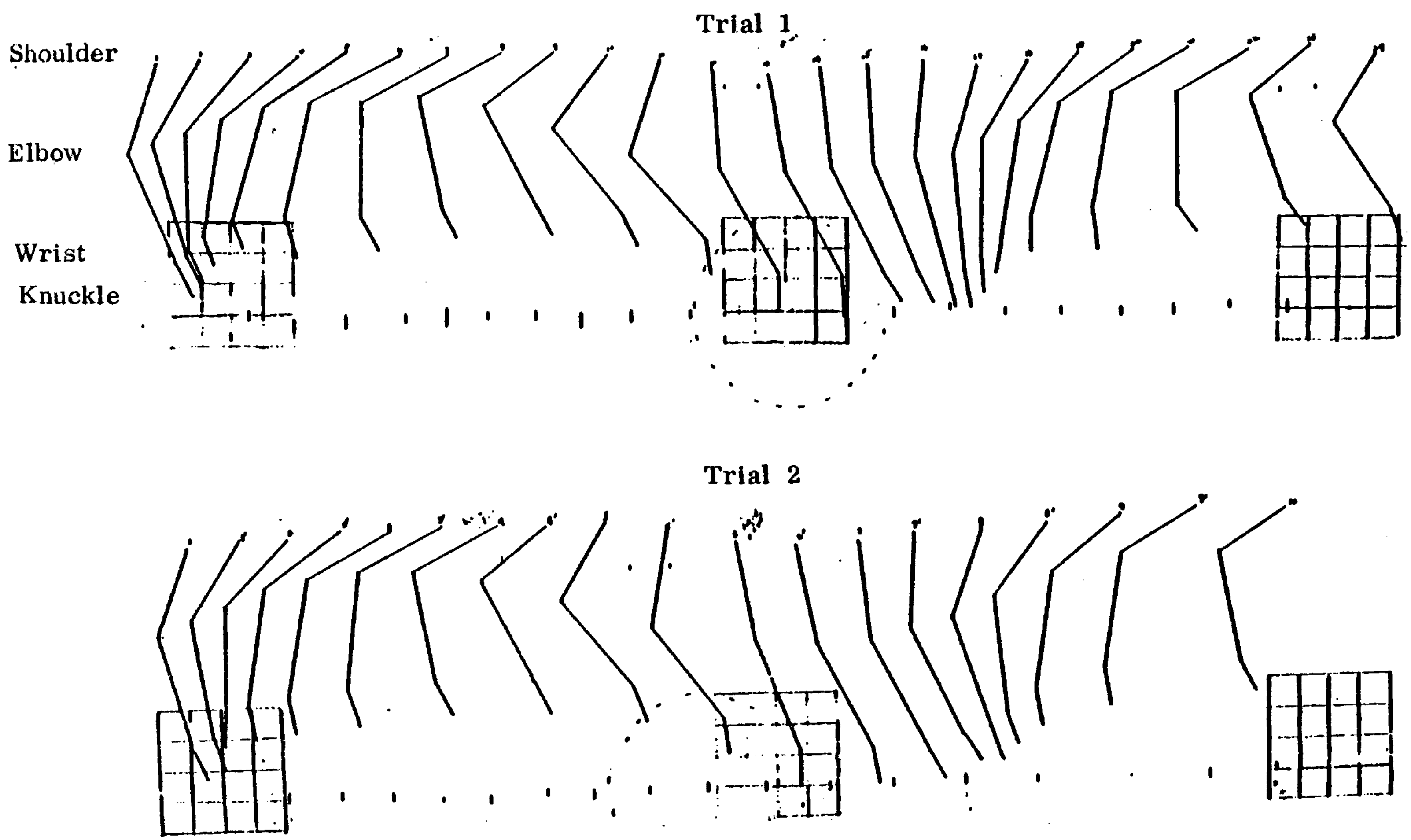

Figure 4. Point-line drawings made from high-speed film record indicating action of near-side arm, forearm and hand in film Trials 1 and 2.

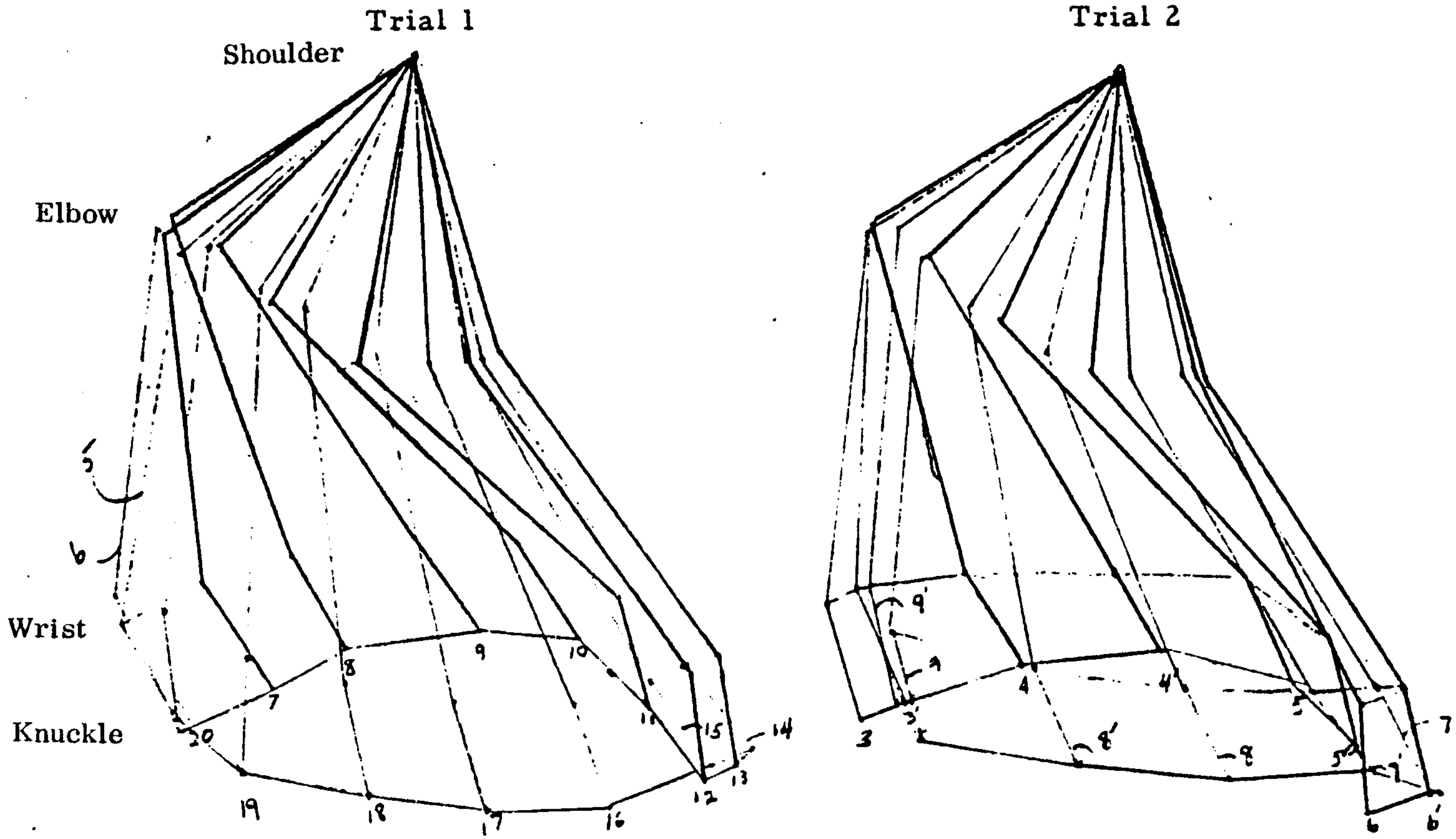

Figure 5. Uniaxial presentation of point-line drawings from film Trials 1 and 2.

Table IV. Segment lengths (scale values - inches).

Trial 1 (frames)	1	2	3	4	5	6	7	8	9	10
Humerus	1.48	1.50	1.52	1.56	1.58	1.58	1.54	1.46	1.38	1.44
Forearm	1.88	1.85	1.86	1.87	1.85	1.85	1.80	1.80	1.78	1.78
Hand	.58	.59	.58	.50	.46	.68	.60	.51	.55	.55

Trial 1 (frames)	11	12	13	14	15	16	17	18	19
Humerus	1.55	1.58	1.57	1.57	1.56	1.54	1.45	1.43	1.42
Forearm	1.79	1.86	1.85	1.84	1.84	1.87	1.84	1.85	1.85
Hand	.56	.54	.59	.56	.55	.55	.58	.56	.55

Trial 1 (frames)	20	21	22	23	24
Humerus	1.42	1.38	1.32	1.23	1.23
Forearm	1.84	1.83	1.79	1.73	1.66
Hand	.53	.67	.50	.54	.54

Trial 2 (frames)	1	1'	2	2'	3	3'	4	4'	5	5'
Humerus	1.48	1.49	1.46	1.49	1.51	1.48	1.49	1.34	1.43	1.52
Forearm	1.83	1.85	1.81	1.84	1.84	1.82	1.78	1.78	1.75	1.80
Hand	.56	.52	.38	.56	.58	.61	.55	.58	.58	.54

Trial 2 (frames)	6	6'	7	7'	8	8'	9	9'	10
Humerus	1.58	1.58	1.57	1.53	1.46	1.40	1.40	1.39	1.26
Forearm	1.85	1.84	1.84	1.84	1.79	1.83	1.83	1.81	1.72
Hand	.53	.58	.63	.51	.57	.53	.59	.58	.52

stable at frame thirteen for Trial 1 and at frame six for Trial 2. These frames correspond to that position when the subject's plane of travel was most nearly perpendicular to the filming angle of the camera, therefore, scale to real conversion factors were derived from known lengths.

Table V presents scale positions measured from the point-line drawings from an origin at frame thirteen in Trial 1 and at frame six in Trial 2. Table VI presents real positions of the segments as determined from the scale positions of Table V and the scale-to-real conversion factor. From the real positions presented in Table V, real linear displacements were calculated and the linear displacement result appear in Table VII. From linear displacements of Table VII and from the time interval between successive frames, linear velocities of shoulder, elbow, wrist and knuckle were calculated. The linear velocities appear in Table VIII. Figures 6 and 7 graphically illustrate linear velocities of the segments for Trials 1 and 2 respectively. Velocity of the segments was greater in Trial 2 than in Trial 1 even though time to develop the greater velocity was reduced in the second Trial.

From Table VIII the change in linear velocity of the joints was calculated and the results appear as acceleration in Table IX. Values for linear acceleration of the joints for Trials 1 and 2 are presented graphically in Figures 8 and 9. During the power production phase,

Table V. Scale positions (inches).

Trial 1 (points)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Shoulder																				
Horizontal	-9.70	-9.02	-8.27	-7.50	-6.75	-5.90	-5.15	-4.35	-3.50	-2.68	-1.88	-1.06	-0.20	0.62	1.36	2.23	3.05	3.83	4.63	5.46
Vertical	4.47	4.55	4.56	4.60	4.67	4.60	4.60	4.64	4.64	4.58	4.50	4.35	4.25	4.33	4.37	4.43	4.38	4.45	4.57	4.62
Elbow																				
Horizontal	-10.15	-9.78	-9.27	-8.70	-8.03	-7.31	-6.52	-5.63	-4.62	-3.55	-2.31	-0.97	0.07	0.78	1.43	2.08	2.67	3.12	3.71	4.32
Vertical	3.08	3.25	3.42	3.63	3.81	3.89	3.88	3.96	3.82	3.46	3.14	2.77	2.74	2.80	2.85	2.93	3.00	3.21	3.51	3.79
Wrist																				
Horizontal	-9.44	-9.25	-9.22	-9.00	-8.54	-7.73	-6.55	-5.27	-3.83	-2.47	-1.20	-0.08	0.94	1.58	2.12	2.57	2.83	3.10	3.31	3.88
Vertical	1.36	1.50	1.55	1.80	2.05	2.09	2.09	2.20	2.25	2.10	1.69	1.15	1.12	1.15	1.18	1.14	1.17	1.39	1.69	2.00
Knuckle																				
Horizontal	-9.15	-9.00	-8.98	-8.84	-8.38	-7.54	-6.26	-5.06	-3.56	-2.48	-1.20	-0.08	0.94	1.58	2.11	2.56	2.84	3.10	3.42	3.86
Vertical	0.86	0.98	1.08	1.36	1.63	1.46	1.56	1.76	1.78	1.59	1.14	0.63	0.54	0.71	0.69	0.61	0.62	0.85	1.14	1.49

Trial 1 (points)	21	22	23	24
Shoulder				
Horizontal	6.33	7.25	8.20	9.22
Vertical	4.65	4.63	4.70	4.56
Elbow				
Horizontal	5.12	6.13	7.27	8.55
Vertical	3.96	3.96	3.91	3.50
Wrist				
Horizontal	4.81	6.13	7.80	9.44
Vertical	2.16	2.18	2.29	2.11
Knuckle				
Horizontal	4.81	6.13	8.79	9.43
Vertical	1.50	1.80	1.88	1.62

Trial 2 (points)	1	1'	2	2'	3	3'	4	4'	5	5'	6	6'	7	7'	8	8'	9	9'	10
Shoulder																			
Horizontal	-8.93	-8.11	-7.37	-6.52	-5.76	-4.97	-4.12	-3.36	-2.44	-1.49	-0.43	0.50	1.47	2.34	3.38	4.40	5.54	6.72	8.10
Vertical	4.48	4.57	4.54	4.64	4.60	4.67	4.64	4.62	4.63	4.48	4.30	4.23	4.26	4.38	4.41	4.47	4.56	4.66	4.61
Elbow																			
Horizontal	-9.44	-8.92	-8.39	-7.75	-7.09	-6.29	-5.44	-4.40	-3.17	-1.79	-0.19	0.78	1.62	2.24	2.89	3.54	4.45	5.53	7.04
Vertical	3.09	3.33	3.53	3.80	3.09	4.00	3.97	3.81	3.45	3.00	2.75	2.71	2.74	2.83	3.04	3.35	3.71	3.97	3.94
Wrist																			
Horizontal	-8.97	-8.63	-8.45	-8.17	-7.45	-6.53	-5.16	-3.64	-2.16	-0.74	0.46	1.58	2.40	3.00	3.42	3.69	4.14	5.20	7.31
Vertical	1.36	1.51	1.72	1.98	2.12	2.20	2.23	2.23	2.10	1.58	1.04	1.07	1.12	1.24	1.35	1.54	1.91	2.20	2.25
Knuckle																			
Horizontal	-8.73	-8.46	-8.45	-7.97	-7.35	-6.34	-4.91	-3.40	-1.93	-0.67	0.43	1.67	2.69	3.25	3.61	3.85	4.23	5.28	7.52
Vertical	0.48	1.03	1.35	1.44	1.54	1.61	1.75	1.72	1.56	1.03	0.49	0.52	0.56	0.84	0.82	1.06	1.33	1.64	1.80

Table VI. Real positions (feet).

Trial 1 (points)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Shoulder																			
Horizontal	-5.34	-4.96	-4.55	-4.73	-3.71	-3.25	-2.83	-2.39	-1.93	-1.47	-1.03	-0.58	-0.11	0.34	0.75	1.23	1.68	2.11	2.55
Vertical	2.46	2.50	2.51	2.53	2.57	2.53	2.53	2.55	2.55	2.52	2.48	2.39	2.34	2.38	2.40	2.44	2.41	2.45	2.51
Elbow																			
Horizontal	-5.58	-5.38	-5.10	-4.79	-4.42	-4.02	-3.59	-3.10	-2.54	-1.95	-1.29	-0.53	0.04	0.43	0.79	1.14	1.47	1.72	2.04
Vertical	1.69	1.79	1.88	2.00	2.10	2.14	2.13	2.18	2.10	1.90	1.73	1.52	1.51	1.54	1.57	1.61	1.65	1.77	1.93
Wrist																			
Horizontal	-5.19	-5.09	-5.07	-4.95	-4.70	-4.25	-3.60	-2.90	-2.11	-1.36	-0.66	-0.04	0.52	0.87	1.17	1.41	1.56	1.71	1.82
Vertical	0.75	0.83	0.85	0.99	1.13	1.15	1.15	1.21	1.24	1.16	0.93	0.63	0.62	0.63	0.65	0.63	0.64	0.76	0.93
Knuckle																			
Horizontal	-5.03	-4.95	-4.94	-4.86	-4.61	-4.15	-3.44	-2.78	-1.96	-1.36	-0.66	-0.66	0.52	0.87	1.16	1.41	1.56	1.71	1.88
Vertical	0.47	0.54	0.59	0.75	0.90	0.80	0.86	0.97	0.98	0.87	0.63	0.35	-.30	0.39	-.38	-.34	-.34	-.47	-.63

Trial 1 (points)	20	21	22	23	24
Shoulder					
Horizontal	3.00	3.48	3.99	4.51	5.07
Vertical	2.54	2.56	2.55	2.59	2.51
Elbow					
Horizontal	2.37	2.82	3.37	4.00	4.70
Vertical	2.08	2.18	2.18	2.15	1.93
Wrist					
Horizontal	2.13	2.65	3.37	4.29	5.19
Vertical	1.10	1.19	1.20	1.26	1.16
Knuckle					
Horizontal	2.12	2.65	3.37	4.83	5.19
Vertical	-.82	-.83	-.99	1.83	0.89

Trial 2 (points)	1	1'	2	2'	3	3'	4	4'	5	5'	6	6'	7	7'	8	8'	9	9'	10
Shoulder																			
Horizontal	-4.91	-4.46	-4.05	-3.59	-3.17	-2.73	-2.27	-1.85	-1.34	-0.82	-0.24	0.28	0.81	1.29	1.86	2.42	3.05	3.70	4.46
Vertical	2.46	2.51	2.50	2.55	2.53	2.57	2.55	2.54	2.55	2.46	2.37	2.33	2.34	2.41	2.43	2.46	2.51	2.56	2.54
Elbow																			
Horizontal	-5.19	-4.91	-4.61	-4.26	-3.90	-3.46	-2.99	-2.42	-1.74	-0.98	-0.10	0.43	0.89	1.23	1.59	1.59	2.45	3.04	3.87
Vertical	1.70	1.83	1.94	2.09	2.15	2.20	2.18	2.10	1.90	1.65	1.51	1.49	1.51	1.56	1.67	1.84	2.04	2.18	2.17
Wrist																			
Horizontal	-4.93	-4.75	-4.64	-4.49	-4.10	-3.59	-2.84	-2.00	-1.19	-.65	0.25	0.87	1.32	1.65	1.88	2.03	2.28	2.86	4.02
Vertical	0.75	0.83	0.95	1.09	1.17	1.21	1.23	1.23	1.16	0.87	0.57	0.59	0.62	0.68	0.74	0.85	1.05	1.21	1.24
Knuckle																			
Horizontal	-4.80	-4.65	-4.65	-4.38	-4.04	-3.49	-2.70	-1.87	-1.06	-0.37	0.24	0.92	1.48	1.79	1.99	2.12	2.33	2.90	4.14
Vertical	0.26	0.57	0.74	0.79	0.85	0.89	0.96	0.95	0.86	0.57	0,27	0.29	0.21	0.46	0.45	0.58	0.73	0.90	0.99

Table VII. Linear Displacements of joints (feet).

Trial 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Shoulder																				
Horizontal	.38	.41	.42	.42	.46	.42	.44	.46	.46	.44	.45	.32	.45	.41	.48	.45	.43	.44	.46	.48
Vertical	.04	.01	.02	.04	-.04	0	.02	0	.03	-.04	-.09	-.05	.04	.02	.04	-.03	.04	.06	.03	.02
Elbow																				
Horizontal	.20	.28	.31	.37	.40	.43	.49	.56	.59	.66	.76	.57	.39	.36	.35	.33	.25	.32	.33	.45
Vertical	.10	.09	.12	.10	.04	-.01	.05	-.08	-.02	.17	.21	-.01	.03	.03	.04	.04	.12	.16	.15	.10
Wrist																				
Horizontal	.10	.02	.12	.25	.45	.65	.70	.79	.75	.70	.62	.56	.35	.30	.24	.15	.15	.11	.31	.52
Vertical	.08	.02	.14	.14	.02	0	.06	.03	-.08	-.23	.30	-.01	.01	.02	-.02	.01	.12	.17	.17	.09
Knuckle																				
Horizontal	.08	.01	.08	.25	.46	.71	.66	.82	.60	.70	.60	.58	.35	.29	.25	.15	.15	.17	.24	.53
Vertical	.07	.05	.16	.15	-.10	.06	.11	.01	-.11	-.24	-.28	-.05	.09	-.01	-.04	0	.13	.16	.19	.01

Trial 1	21	22	23
Shoulder			
Horizontal	.51	.52	.56
Vertical	-.01	.04	-.08
Elbow			
Horizontal	.55	.63	.70
Vertical	0	-.03	-.22
Wrist			
Horizontal	.72	.92	.90
Vertical	.01	.06	-.10
Knuckle			
Horizontal	.72	1.46	.36
Vertical	.16	.04	-.14

Trials 2	1	1'	2	2'	3	3'	4	4'	5	5'	6	6'	7	7'	8	8'	9	9'
Shoulder																		
Horizontal	.45	.41	.46	.42	.44	.46	.42	.51	.52	.58	.52	.53	.48	.57	.56	.63	.65	.76
Vertical	.05	-.01	.05	-.02	.04	-.02	-.01	.01	-.09	-.09	-.04	.01	.07	.02	.03	.05	.05	-.02
Elbow																		
Horizontal	.28	.30	.35	.36	.44	.47	.57	.68	.76	.88	.53	.46	.34	.36	.36	.50	.59	.83
Vertical	.13	.11	.15	.06	.05	-.02	-.08	-.20	-.25	-.14	-.02	.02	.05	.11	.17	.20	.14	-.01
Wrist																		
Horizontal	.18	.11	.15	.39	.51	.74	.84	.81	.78	.66	.62	.45	.33	.23	.15	.25	.58	.16
Vertical	.08	.12	.14	.08	.04	.02	0	-.07	-.29	-.30	.02	.03	.06	.06	.11	.20	.16	.03
Knuckle																		
Horizontal	.15	0	.27	.34	.55	.79	.83	.81	.69	.61	.68	.56	.31	.20	.13	.21	.51	.24
Vertical	.31	.17	.05	.06	.04	.07	-.01	-.09	-.29	-.30	.02	.02	.15	-.01	.13	.15	.17	.09

Table VIII. Linear velocities of joints (feet/sec). (Numbers indicate intervals between successive frames)

Trial 1	1	2	3	4	5	6	7	8	9	10
Shoulder										
Horizontal	15.5	16.4	16.8	16.8	18.4	16.8	17.6	18.4	18.4	17.6
Vertical	1.6	0.4	0.8	1.6	-1.6	0	0.8	0	1.2	-1.6
Resultant	15.3	16.4	16.8	16.9	18.5	16.8	17.6	18.4	18.4	17.7
Elbow										
Horizontal	8.0	11.2	12.4	14.8	16.0	17.2	19.6	22.4	23.6	26.4
Vertical	4.0	3.6	4.8	4.0	1.6	-0.4	2.0	-3.2	-0.8	6.8
Resultant	8.9	11.8	13.3	15.3	16.1	17.2	19.7	29.9	23.6	27.3
Wrist										
Horizontal	4.0	0.8	4.8	10.0	18.0	26.0	28.0	31.6	30.0	28.0
Vertical	3.2	0.8	5.6	5.6	0.8	0	2.4	1.2	-3.2	-9.2
Resultant	5.1	1.1	7.4	11.5	18.0	26.0	28.1	31.6	30.2	29.5
Knuckle										
Horizontal	3.2	0.4	3.2	10.0	18.4	28.4	26.4	32.8	24.0	28.0
Vertical	2.8	2.0	6.4	6.0	-4.0	2.4	4.4	0.4	-4.4	-9.6
Resultant	4.2	2.0	7.1	11.7	18.8	28.5	26.8	32.8	24.4	29.6

Trial 1	11	12	13	14	15	16	17	18	19	20
Shoulder										
Horizontal	18.0	12.8	18.0	16.4	19.2	18.0	17.2	17.6	18.4	19.2
Vertical	-3.6	-2.0	1.6	0.8	1.6	-1.2	1.6	2.4	1.2	0.8
Resultant	18.3	12.9	18.8	16.4	19.3	18.0	17.3	17.8	18.4	19.2
Elbow										
Horizontal	30.4	22.8	15.6	14.4	14.0	13.2	10.0	12.8	13.2	18.0
Vertical	8.4	-0.4	1.2	1.2	1.6	1.6	4.8	6.4	6.0	4.0
Resultant	31.5	22.8	15.6	14.4	14.1	13.3	11.1	14.3	14.5	18.4
Wrist										
Horizontal	24.8	22.4	14.0	12.0	9.6	6.0	6.0	4.4	12.4	20.8
Vertical	-12.0	-0.4	0.4	0.8	-0.8	0.4	4.8	6.8	6.8	3.6
Resultant	27.5	22.4	14.0	12.0	9.6	6.0	7.7	8.1	14.1	21.1
Knuckle										
Horizontal	24.0	23.2	14.0	11.6	10.0	6.0	6.0	6.8	9.6	21.2
Vertical	-11.2	-2.0	3.6	-0.4	-1.6	0	5.2	6.4	7.6	0.4
Resultant	26.5	23.3	14.4	11.6	10.1	6.0	7.9	9.3	12.2	21.2

Trial 1	21	22	23
Shoulder			
Horizontal	20.4	20.8	22.4
Vertical	-0.4	1.6	-3.2
Resultant	20.4	20.9	22.6
Elbow			
Horizontal	22.0	25.2	28.0
Vertical	0	-1.2	-8.8
Resultant	22.0	25.2	30.1
Wrist			
Horizontal	28.8	36.8	36.0
Vertical	0.4	2.4	-4.0
Resultant	28.8	36.9	36.2
Knuckle			
Horizontal	28.8	58.4	14.4
Vertical	6.4	1.6	-5.6
Resultant	29.5	58.4	15.4

Trial 2	1	2	3	4	5	6	7	8	9
Shoulder									
Horizontal	18.0	16.4	18.4	16.8	17.6	18.4	16.8	20.4	20.8
Vertical	2.0	-0.4	2.0	-0.8	1.6	-0.8	-0.4	0.4	-3.6
Resultant	18.1	16.4	18.5	16.8	17.7	18.4	16.8	20.4	21.1
Elbow									
Horizontal	11.2	12.0	14.0	14.4	17.6	18.8	22.8	27.2	30.4
Vertical	5.2	4.4	6.0	2.4	2.0	-0.8	-3.2	-8.0	-10.0
Resultant	12.3	12.8	15.2	14.6	17.7	18.8	23.0	28.3	32.0
Wrist									
Horizontal	7.2	4.4	6.0	15.6	20.4	29.6	33.6	32.4	31.2
Vertical	3.2	4.8	5.6	3.2	1.6	0.8	0	-2.8	-11.6
Resultant	7.9	6.5	8.2	15.9	20.5	29.6	33.6	32.5	33.3
Knuckle									
Horizontal	6.0	0	10.8	13.6	22.0	31.6	33.2	32.4	27.6
Vertical	12.4	6.8	2.0	2.4	1.6	2.8	-0.4	-3.6	-11.6
Resultant	13.8	6.8	11.0	13.8	22.0	31.7	33.2	32.6	29.9

Trial 2	10	11	12	13	14	15	16	17	18
Shoulder									
Horizontal	23.2	20.8	21.2	19.2	22.8	22.4	25.2	26.0	30.4
Vertical	-3.6	-1.6	0.4	2.8	0.8	1.2	2.0	2.0	-0.8
Resultant	23.3	20.9	21.2	19.4	22.8	22.4	25.3	26.1	30.4
Elbow									
Horizontal	35.2	21.2	18.4	13.6	14.4	14.4	20.0	23.6	33.2
Vertical	-5.6	-0.8	0.8	2.0	4.4	6.8	8.0	5.6	-0.4
Resultant	35.6	21.2	18.4	13.7	15.1	15.9	21.5	24.2	33.2
Wrist									
Horizontal	26.4	24.8	18.0	13.2	9.2	6.0	10.0	23.2	6.4
Vertical	-12.0	0.8	1.2	2.4	2.4	4.4	8.0	6.4	1.2
Resultant	29.0	24.8	18.0	13.4	9.5	7.4	12.8	24.1	6.5
Knuckle									
Horizontal	24.4	27.2	22.4	12.4	8.0	5.2	8.4	22.8	9.6
Vertical	-12.0	0.8	0.8	6.0	-0.4	5.2	6.0	6.8	3.6
Resultant	27.2	27.2	22.4	13.8	8.0	7.3	10.3	23.8	10.2

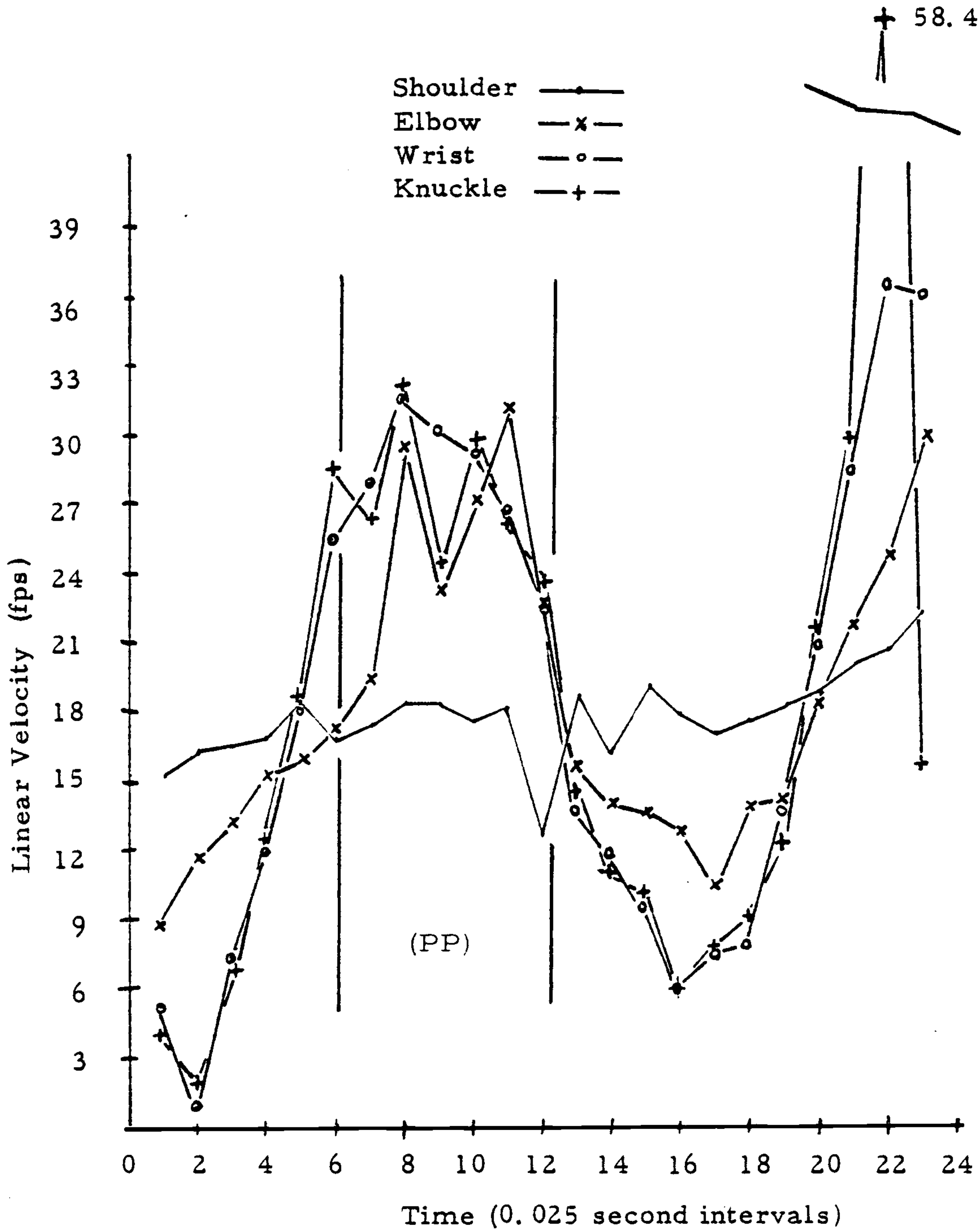

Figure 6. Linear velocities of joints during Trial 1.
PP = Propulsion Phase

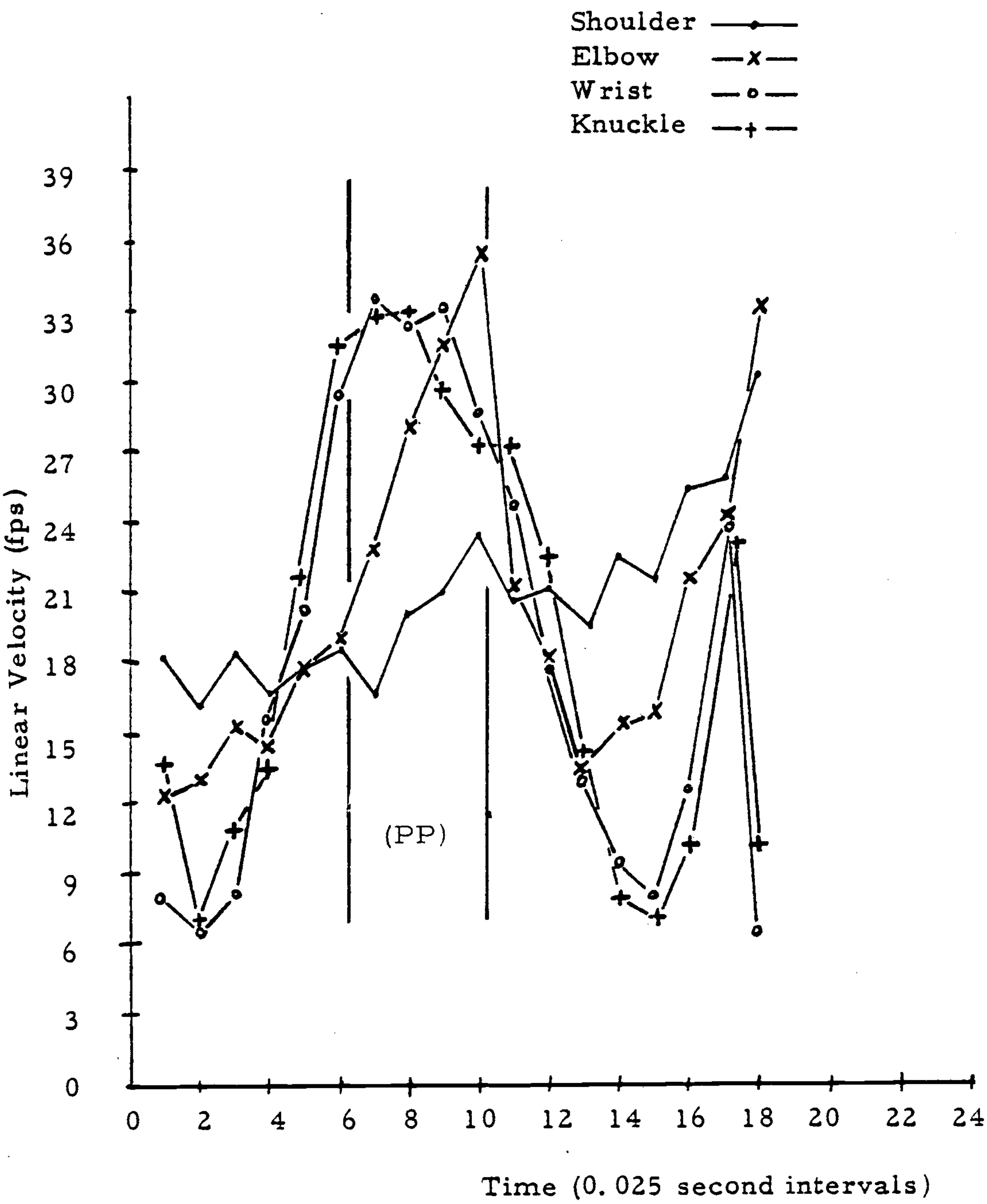

Figure 7. Linear velocities of joints during Trial 2.
PP = Propulsion Phase

Table IX. Linear acceleration of joints (feet/sec/sec). (Numbers indicate intervals between successive velocity intervals.)

Trial 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Shoulder	1.1	0.4	0.1	1.6	-1.7	0.8	0.8	0	-0.7	0.6	-5.4	5.2	-1.7	2.9	-1.3	-0.7	0.5
Elbow	2.9	1.5	2.0	0.8	1.1	2.5	10.2	-6.3	3.7	4.2	-8.7	-7.2	-1.2	-0.3	-0.8	-2.2	3.2
Wrist	-4.0	6.3	4.1	6.5	8.0	2.1	3.5	-1.4	-0.7	-2.0	-5.1	-8.4	-2.0	-2.4	-3.6	1.7	0.4
Knuckle	-2.2	5.1	4.6	7.1	9.7	-1.7	6.0	-8.4	5.2	-3.1	-3.2	-8.9	-2.8	-1.5	-4.1	1.9	1.4

Trial 1	18	19	20	21	22
Shoulder	0.6	0.8	1.2	0.5	1.7
Elbow	0.2	3.9	3.6	3.2	4.9
Wrist	6.0	7.0	7.7	8.1	-0.7
Knuckle	2.9	9.0	8.3	28.9	-43.0

Trial 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Shoulder	-1.7	2.1	-1.7	0.9	0.7	-1.6	3.6	0.7	2.4	-2.6	0.3	-1.8	3.4	-0.4	2.9	0.8	4.3
Elbow	0.5	2.4	-0.6	3.1	1.1	4.2	5.3	3.7	3.6	-14.4	-2.8	-4.7	1.4	0.8	5.6	2.7	9.0
Wrist	-1.4	1.7	7.7	4.6	9.1	4.0	-1.1	0.8	-4.3	-4.2	-6.8	-4.6	-3.9	-2.1	5.4	11.3	-17.6
Knuckle	-7.0	4.2	2.8	8.2	9.7	1.5	-0.6	-2.7	-2.7	0	-4.8	-8.6	-5.8	-0.7	3.0	13.5	-13.6

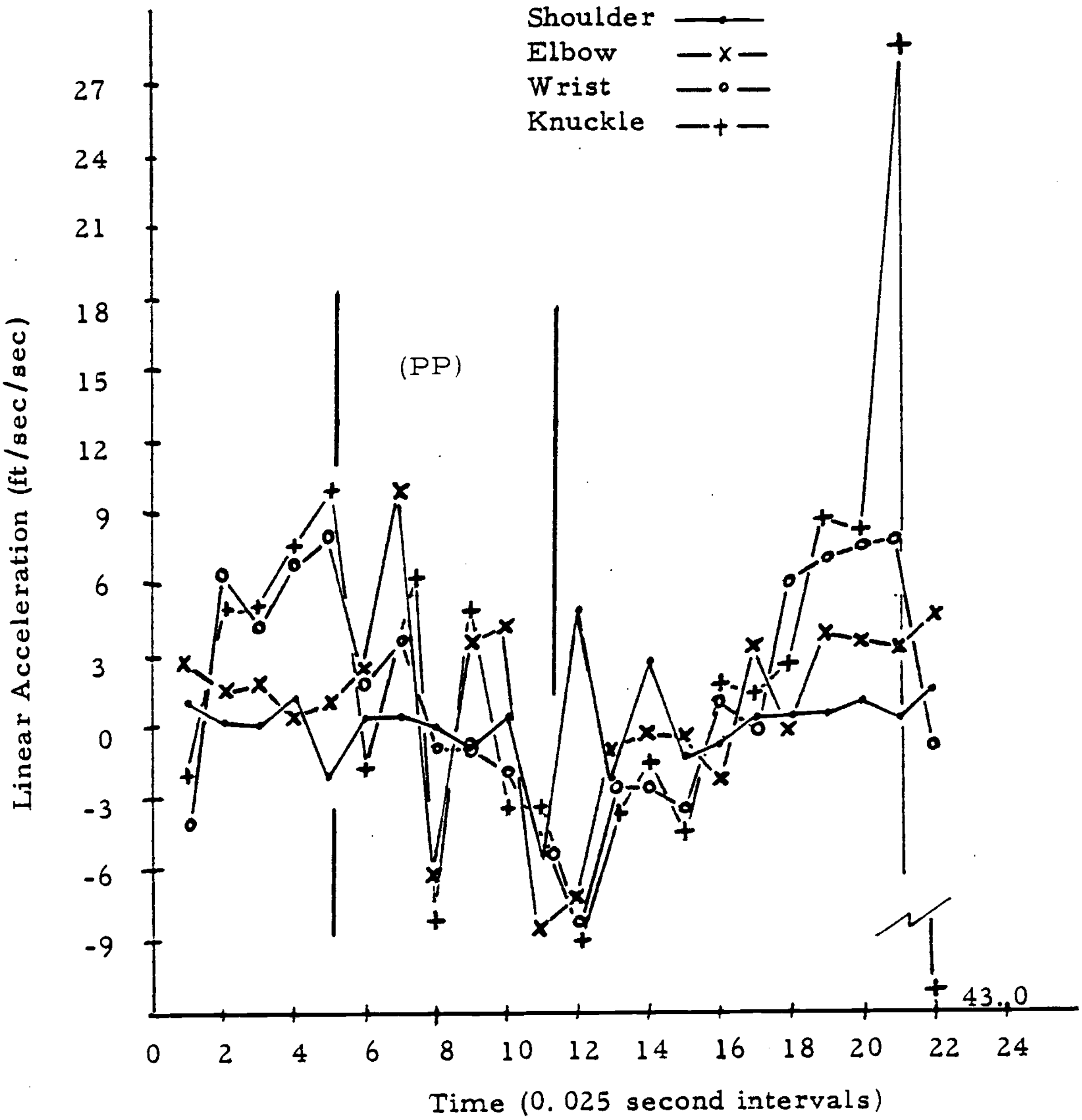

Figure 8. Linear acceleration of the joints during Trial 1.
PP = Propulsion Phase

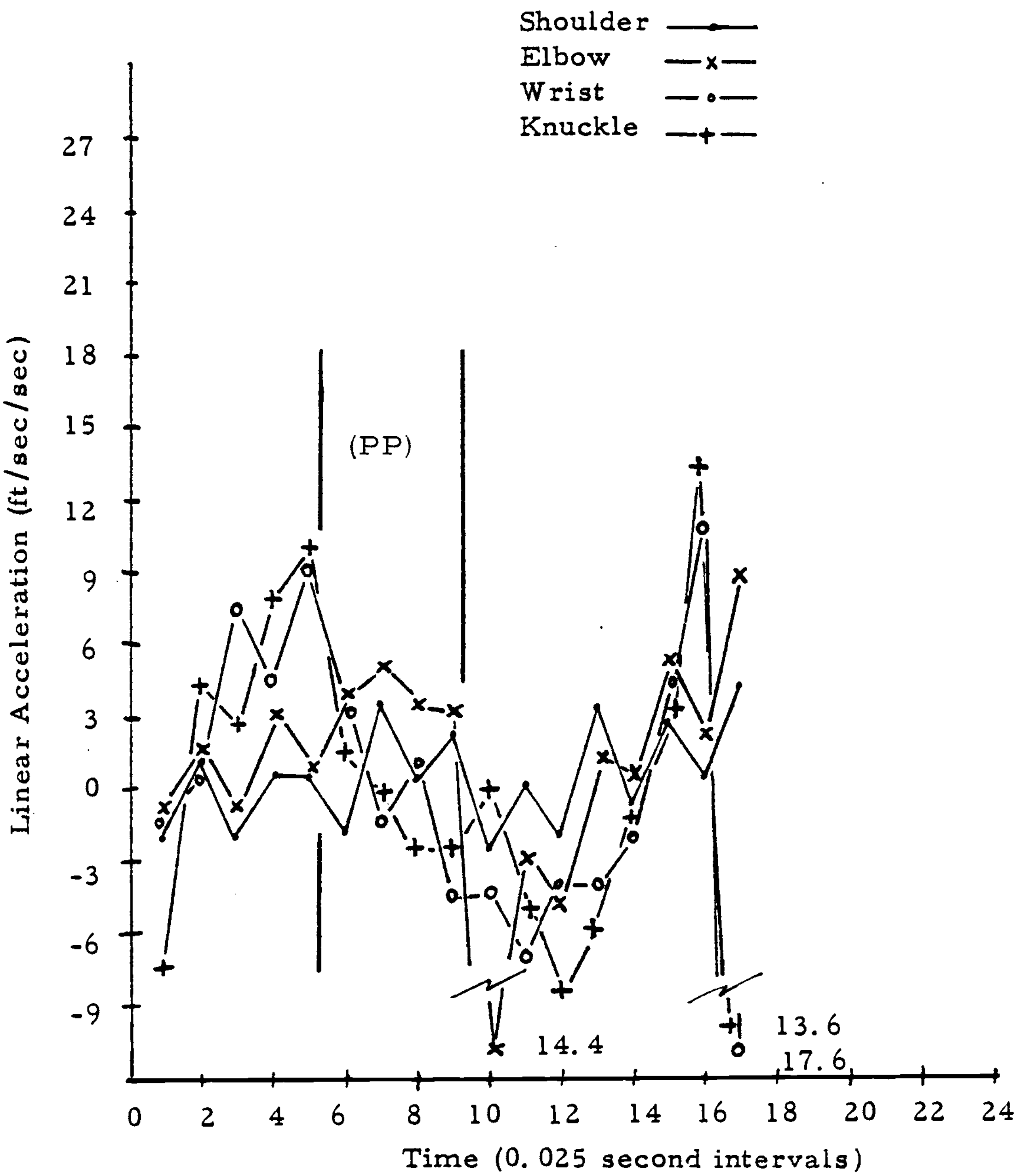

Figure 9. Linear acceleration of the joints during Trial 2.
PP = Propulsion Phase

frames 5 through 11 in Trial 1 and frames 5 through 9 in Trial 2, linear acceleration for the elbow was greater in the slower Trial, Trial 1. Also, while wrist and knuckle had higher peak acceleration at the beginning of Trial 2, elbow, wrist, and knuckle all had greater acceleration during force production phase in Trial 1. The greater acceleration may be explained by these segments having proportionately lower velocity in recovery and during initial force production.

Table X presents the segment orientation of the arm, forearm and hand. Table XI gives the relationship between the segments, that is, the elbow angle and wrist angle for Trials 1 and 2. Data in Table XI together with Figure 5 established that while the total displacement of the arm was greater in Trial 1, the elbow angle had greater extension in Trial 2. Data in Table XI and Figure 5 indicated that while the range of motion of the arm was greater at a slower pace, the portion of arm action which applied power to the wheel, that is, arm extension, was greater at the higher pace.

From Table X, Segment Orientation, and from the time interval between successive frames, angular velocity of the segments was calculated and is presented in Table XII. Angular velocity of the segments is presented graphically in Figures 10 and 11 for Trials 1 and 2 respectively. The most dramatic difference in angular velocity of the segments between the two Trials was the marked increase in angular velocity of the hand immediately following and prior to the

Table X. Segment orientation (degrees). Vertical downward is zero; clockwise direction is negative.

Trial 1 (frames)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Humerus	-19	-31	-41	-51	-57	-63	-63	-62	-54	-38	18	3	9	6	2	-6	-16	-31	-41	-59	-61
Forearm	23	46	0	-10	-16	-14	-1	12	27	39	41	28	28	26	22	14	9	-2	-10	-19	-10
Hand	28	28	25	21	20	17	29	26	30	25	7	-1	3	32	26	15	11	4	-10	-1	6

Trial 1 (frames)	22	23	24
Humerus	-60	-51	-32
Forearm	0	18	33
Hand	37	39	20

Trial 2 (frames)	1	1'	2	2'	3	3'	4	4'	5	5'	6	6'	7	7'	8	8'	9	9'	10
Humerus	-21	-34	-46	-55	-63	-64	-64	-53	-31	-12	9	10	6	-4	-20	-38	-52	-60	-58
Forearm	15	9	-2	-11	-12	-8	9	26	38	36	21	26	26	24	18	4	-11	-11	9
Hand	24	20	-2	13	9	17	28	26	20	6	-3	9	26	34	20	18	8	7	26

Table XI. Relationship between segments (degrees).

Trial 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Elbow Angle	138	132	138	138	139	130	119	106	100	104	121	154	161	160	160	159	158	150	148	140	130
Wrist Angle	176	169	155	150	144	149	150	165	178	193	214	208	206	175	177	180	175	175	180	166	164

Trial 1	22	23	24
Elbow Angle	120	112	115
Wrist Angle	143	162	193

Trial 2	1	1'	2	2'	3	3'	4	4'	5	5'	6	6'	7	7'	8	8'	9	9'	10
Elbow Angle	143	138	136	135	129	123	117	112	111	133	168	163	159	151	142	137	138	131	112
Wrist Angle	171	169	180	157	160	156	162	180	198	210	204	198	180	171	177	167	161	162	163

Table XII. Angular velocity of segments (degrees/sec). Clockwise direction is positive; counter-clockwise is negative.

Trial 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Humerus	-480	-400	-400	-240	-240	0	40	320	640	800	840	240	-120	-160	-320	-400	-600	-400	-560	-240	-40
Forearm	-280	-640	-400	-240	80	520	520	600	480	80	-520	0	-80	-160	-320	-360	-280	-320	-200	200	400
Hand	0	-120	-160	-40	-120	480	-120	160	-200	-720	-320	160	1160	240	-440	-160	-280	-560	360	280	1240

Trial 1	22	23
Humerus	360	760
Forearm	720	600
Hand	-80	-600

Trial 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Humerus	-520	-480	-360	-320	-40	0	440	880	760	840	40	-160	-400	-640	-720	-560	-320	80
Forearm	-240	-440	-360	-40	160	680	680	480	-80	-600	200	0	-80	-240	-560	-600	0	800
Hand	-160	-880	600	-160	320	440	-80	-240	-560	-360	480	680	320	-560	-80	-400	-40	760

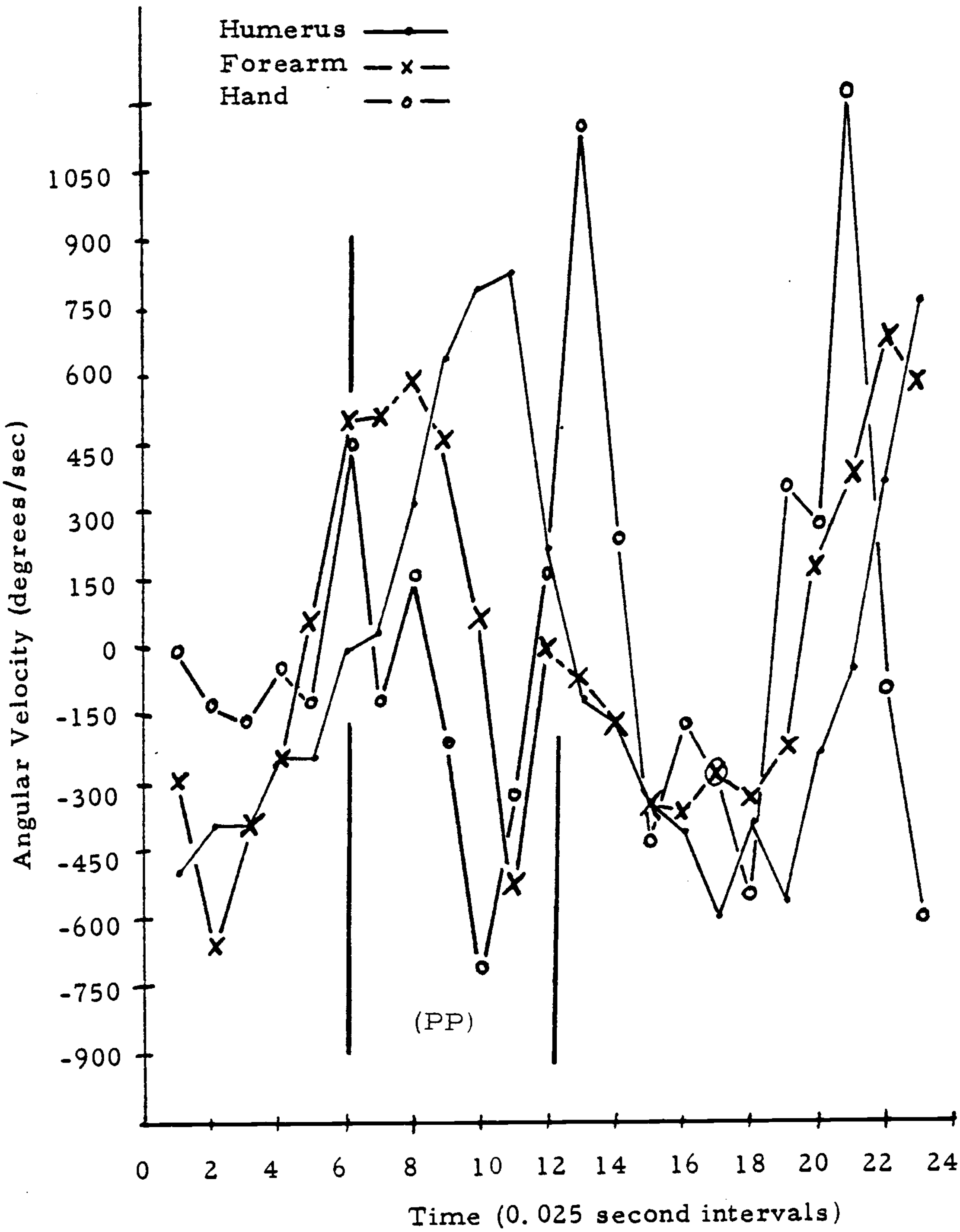

Figure 10. Angular velocity of the segments during Trial 1.
PP = Propulsion Phase

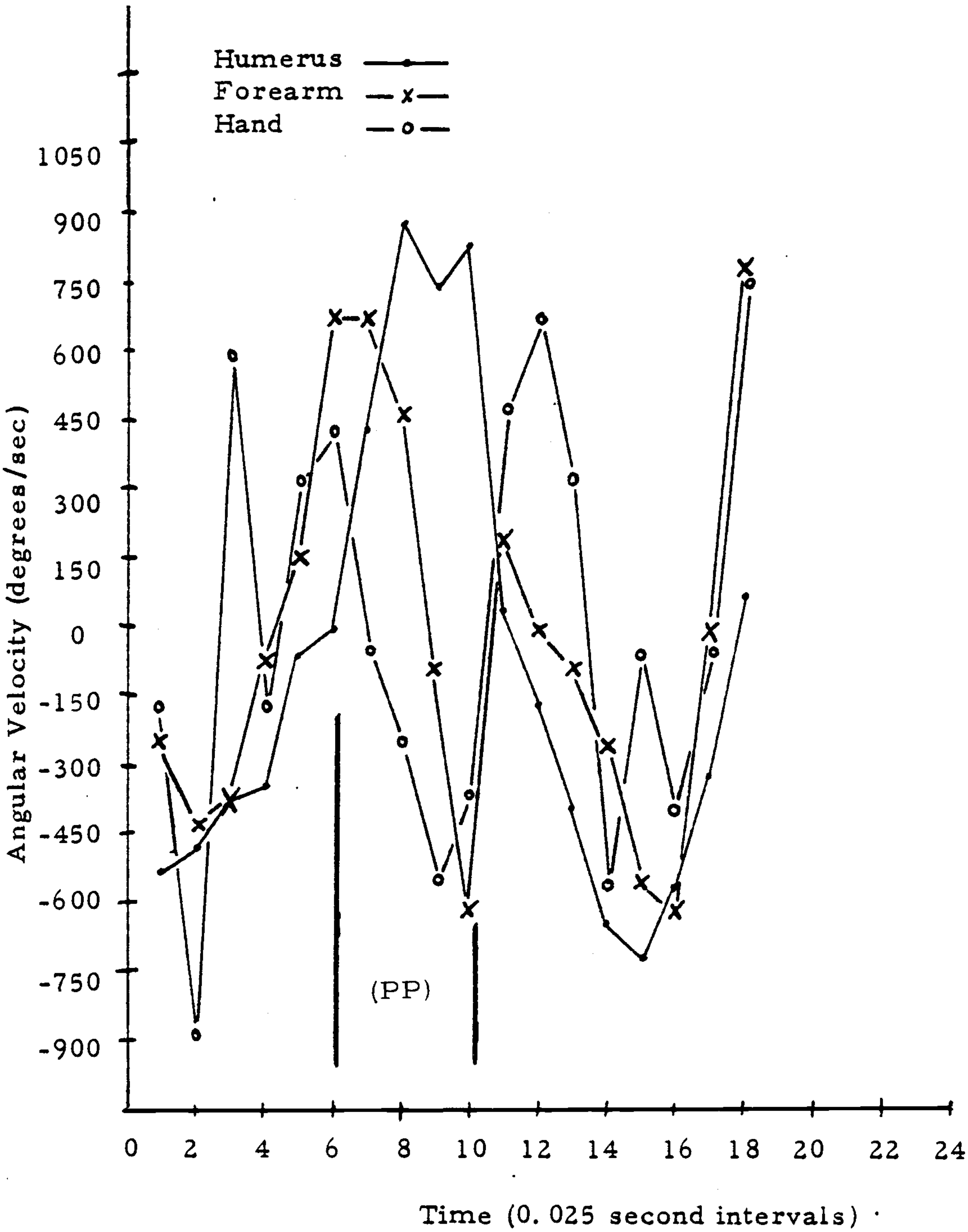

Figure 11. Angular velocity of the segments during Trial 2.
PP = Propulsion Phase

propulsive phase. The increase in hand angular velocity was much greater in Trial 1, the slower pace. A greater elastic component or whipping action seemed to occur at the lower velocity of travel while at the greater velocity of travel, the hand appeared under more controlled tension. This controlled tension could have created greater systolic blood pressure.

Angular acceleration of the segments was computed and is presented in Table XIII. Angular acceleration is presented graphically in Figures 12 and 13. Again, angular acceleration of the hand appeared greatest at the end of the propulsive phase. Note in Figure 12 that angular acceleration of the hand increased dramatically at the end of the propulsive phase and just as dramatically decreased immediately afterward. This phenomenon was absent from Figure 13. Information presented here seemed to confirm the results noted in angular velocity data. That is the hand appeared to operate under a greater elastic component or whipping action at lower velocities of travel and seemed to be under greater controlled tension at higher velocities.

Table XIV summarized work-power relationships from the previous data for Trials 1 and 2.

Interpretation

Comparing mechanical data from Table XIV with physiological data from Tables I and II revealed some facts which were summarized

Table XIII. Angular acceleration (radians/sec/sec).

Trial 1 (intervals)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Humerus	55.8	0	111.7	0	167.5	27.9	195.5	223.4	111.7	27.9	-418.9	-251.3	-27.9	-111.7	-55.8	-139.6	139.6
Forearm	-251.3	167.5	111.7	223.4	307.2	0	55.8	-83.7	-279.2	-418.9	363.0	-55.8	-55.8	-111.7	-27.9	55.8	-27.9
Hand	-83.7	-27.9	83.7	-55.8	418.9	-418.9	195.5	-251.3	-363.0	279.2	335.1	698.1	-977.4	-139.6	195.5	-83.7	-195.5

Trial 1 (intervals)	18	19	20	21	22
Humerus	-111.7	223.4	139.6	279.2	279.2
Forearm	83.7	279.2	139.6	223.4	-83.7
Hand	642.3	-55.8	670.2	-921.5	-363.0

Trial 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Humerus	27.9	83.7	27.9	195.5	27.9	307.2	307.2	-83.7	55.8	-558.5	-139.6	-167.5	-167.5	-55.8	111.7	167.5	279.2
Forearm	-139.6	55,8	223.4	139.6	363.0	0	-139.6	-390.9	-363.0	558.5	-139.6	-55.8	111.7	-223.4	-27.9	418.9	558.5
Hand	-502.6	1033.2	-530.6	335.1	83.7	-363.0.	-111.7	-223.4	139.6	586.4	139.6	-251.3	-614.3	335.1	-223.4	251.3	558.5

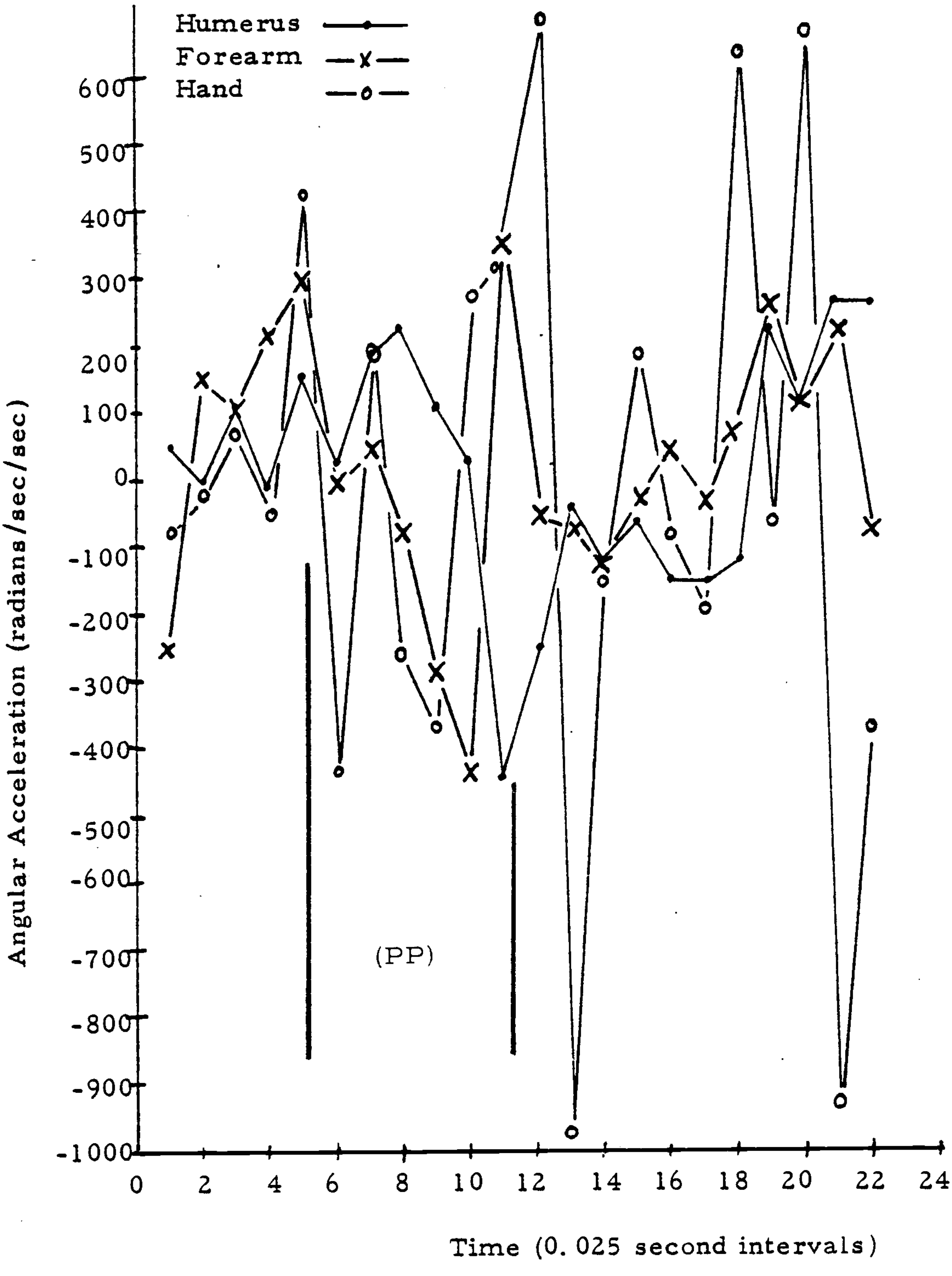

Figure 12. Angular acceleration of the segments during Trial 1.
PP = Propulsion Phase

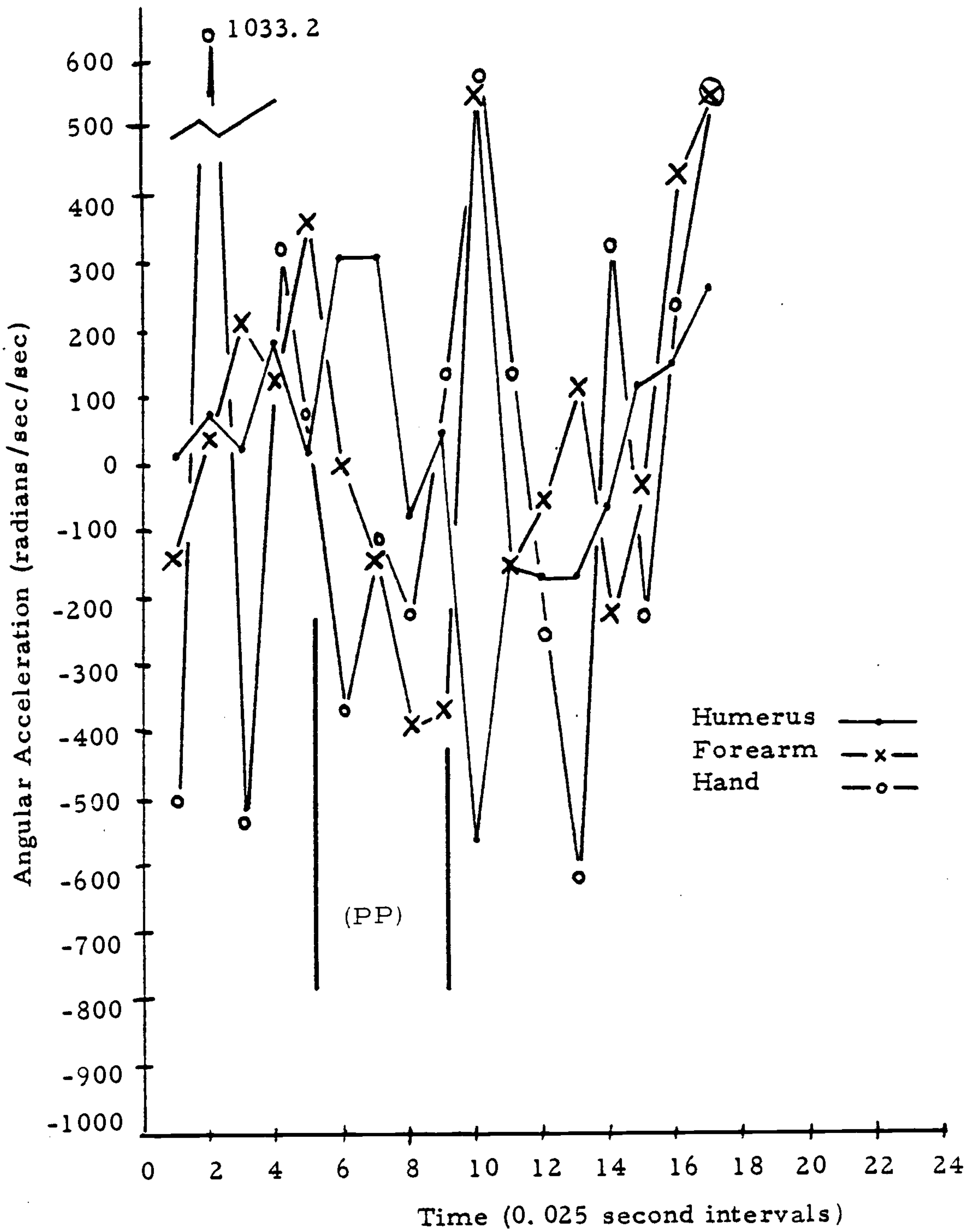

Figure 13. Angular acceleration of the segments during Trial 2.
PP = Propulsion Phase

Table XIV. Work-power relationships.

	Work (ft/lbs)	$\bar{t}$ (sec)	$\bar{s}$ (ft/sec)	Power (ft.lbs/sec)
Trial 1	42,370	34.14	22.0	1241.1
Trial 2	42,370	26.33	25.9	1609.2

	Power/stroke (ft.lbs/sec/stroke)	Work/stroke (ft.lbs/stroke)	KgM/min/stroke	Distance/stroke (ft/stroke)
Trial 1	35.46	1210.57	294.67	5.42
Trial 2	48.04	1264.78	399.34	5.67

	# Strokes/Lap	Revolutions/stroke (wheel)
Trial 1	35	.864
Trial 2	33.5	.903

in Table XV. Data for Trial 1 in Table XIV corresponded to Work Load 1 in Tables I and II and Trial 2 in Table XIV corresponded to Work Load 3 in Tables I and II. From Trial 1 to Trial 2 in Table XIV power per stroke and work per stroke both increased 35. 5% while heart rate in Tables I and II increased 37. 7%, a comparable increase. Blood pressure, on the other hand, increased 3. 4% from Work Load 1 to Work Load 3 and rate-pressure product increased 44. 7%. Obviously, myocardial oxygen utilization reflects a disproportionate increase during wheelchair propelling compared to work per stroke and power per stroke. However, when the total arm work performed on the cycle ergometer increased from 33. 3% heart rate reflected an increase of only 24. 6%. In arm cranking cycle ergometry blood pressure increased 5. 7% from Work Load 1 to Work Load 3, but rate pressure product increased 32. 8%, consistent with the 33. 3% increase in total work.

In summary, in wheelchair propelling when power per stroke and work per stroke increased 35. 5%, heart rate increased 37. 7%, blood pressure increased 3. 4% and rate-pressure product increased 44. 7%. During arm cranking cycle ergometry, when total work increased 33. 3%, heart rate increased 24. 6%, blood pressure increased 5. 7%, and rate-pressure product increased 32. 8%.

Table XV. Summary of changes in mechanical and physiological data under investigation.

Data Change	Wheelchair Propelling	Arm cranking cycle ergometry
Power per stroke increased	35.5%	---
Work per stroke increased	35.5%	---
Total work increased	---	33.3%
Heart rate increased	37.7%	24.6%
Systolic blood pressure increased	3.4%	5.7%
Rate-pressure product increased	44.7%	32.8%

Discussion

Heart rate and work load relationships were not different between methods of imposing work. This finding is in agreement with other investigators (5, 6, 7, 8, 10, 16, 29, 49, 52, 54, 65, 66, 68). External validity is therefore established. Some findings of this study, however, are novel. From the foregoing analysis of physiological data and from the mechanical analysis, certain physiological responses to imposed mechanical work loads were different for wheelchair propelling and arm cranking cycle ergometry. Blood pressure responses and rate-pressure product, or myocardial oxygen consumption, were different between the two methods. During wheelchair propelling which allowed for free movement of the limbs, increases in blood pressure were moderate. Moderate increases in blood pressure might have been due to enhanced utilization of an elastic component in the musculature as was suggested in the mechanical analysis. This possibility has been suggested by other researchers to explain enhanced power output at disproportionately less internal effort (13, 14, 15, 16, 79). The involvement of the elastic component does not explain the disproportionate increase in mycardial oxygen consumption reflected by increases in rate-pressure product.

During arm cranking cycle ergometry the increase in heart rate was rather mild with respect to the total work increase, but blood pressure increase was nearly double that observed in wheelchair propelling. This phenomenon might be explained due to the lack of involvement of an elastic muscular component. While arm cranking a cycle ergometer, a subject must work isokinetically, at one speed. When the work load is increased, pressure is added to the device externally such that the subject needs only continue working isokinetically. The increase in blood pressure, then, may be a reflection of increased muscle tension (corresponding to an increase in internal muscle pressure) required to perform the task. The moderate increase in rate-pressure product, consistent with the increase in total work, may be a reflection of the mild increase in heart rate associated with the isokinetic task.

The practically unavailing nature of wheelchair propulsion as compared to other forms of locomotion is well documented (87, 82). Recognizing the inherent inefficiency of the wheelchair as a locomotive device, one wonders why some modifications in design have not been developed to enhance locomotor efficiency of this population. Perhaps the article by Medsger (56) entitled, "The most captive consumers: At the mercy of the wheelchair barons" will serve to enlighten readers. Reasons for prolonging an archaic and inefficient design are beyond the scope of this investigation, however, the analysis does establish that wheelchair propelling has severe internal costs.

Input from the sympathetic nervous system related to the actual speed and vigor of effort may also be considerable. Certainly, the heart is very susceptible to input from the sympathetic nervous system (5, 9, 20, 21, 29, 30, 31, 32, 38, 45, 49, 52, 58, 62, 66, 68). Direct measurement of the output of the sympathetic nervous system was beyond the scope of this investigation. However, it may be postulated that an increase in sympathetic output and perceived exertion related to working isokinetically against an increasing load (as performed in cycle ergometry) might have been less than that associated with working at a constant resistance with increasing speed and vigor (as performed in wheelchair propelling). A reflection of changing nervous system activity might appear in velocity of movement as related to muscle fiber types associated with a given task. As other investigators have indicated, it may be possible that an increase in speed of movement may be associated with a shift from slow-twitch fiber types to fast-twitch fiber types through some transition period involving a proportion of both fiber types (25, 74). However, fiber type analysis was beyond the scope of this investigation.

This study suggested there was a significant difference in blood pressure and myocardial oxygen consumption as reflected by rate-pressure product between wheelchair propelling and arm cranking cycle ergometry when tasks were matched for workload. Therefore, when determining fitness to perform wheelchair activity or stress of wheelchair propelling, it appeared to make a difference whether the analysis was performed in wheelchair propelling or arm cranking cycle ergometry. Furthermore, to establish standards of performance to determine equality of opportunity to participate, it seemed that standards should have been set utilizing the equipment most nearly like the task which was to be performed. If transportation was the task, wheelchair propelling seemed the likely standard for performance. If working isokinetically against varying loads was the task, handcranking cycle ergometry seemed the likely standard for performance.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Standard techniques for evaluation of the physiological stress of performing wheelchair propelling have not been established. Heart rate response to wheelchair propelling and heart rate response to arm cranking a cycle ergometer were two methods utilized. Results of the two evaluation methods have been assumed to be equivalent. The purpose of this investigation was to compare the results of two methods of gathering data on stress of wheelchair propelling at equivalent work loads and to account for the differences in physiological responses with a mechanical analysis of wheelchair propelling.

Procedures

A male T-6 paraplegic propelled his wheelchair on a circular track at moderate and rapid velocities. Heart rate was monitored by telemetry and blood pressure was checked after three minutes of continuous working at each work load. High speed cinematography was used to record actions of the subject's arm and wheelchair to provide the basis for a mechanical analysis of wheelchair propelling.

The subject also arm cranked a cycle ergometer at work loads corresponding to the work load performed in wheelchair propelling. Heart rate was recorded and blood pressure was checked after three minutes of continuous working at each work load.

Data Analysis

Data were grouped according to work load performed. A paired *t*-test for each paired physiological statistic, heart rate, systolic blood pressure, and rate-pressure product, within each work load was performed on wheelchair propelling and arm cranking cycle ergometry. The .05 level of significance was chosen for rejection of the null hypothesis in this investigation.

The mechanical analysis was performed for descriptive purposes to help explain differences in physiological phenomena observed between wheelchair propelling and arm cranking cycle ergometry at similar work loads.

Conclusions

An analysis of the data lead to the following conclusions:

1. Heart rate did not differ significantly for given work loads between wheelchair propelling and arm cranking cycle ergometry.

2. Mean systolic blood pressure was significantly different at given work loads between wheelchair propelling and arm cranking

cycle ergometry.

3. Rate-pressure product was significantly different at given work loads between wheelchair propelling and arm cranking cycle ergometry.

4. In light of the physiological and mechanical analysis performed in this investigation, the two tasks, wheelchair propelling and arm cranking cycle ergometry, could not be considered equivalent when matched for mechanical work output.

5. When matched for mechanical work output, wheelchair propelling was significantly more costly in terms of myocardial oxygen utilization than was isokinetic arm cranking cycle ergometry.

Recommendations

This investigation demonstrated that, for the subject of the case study, wheelchair propelling and arm cranking cycle ergometry when matched for mechanical work output resulted in dissimilar physiological responses. Recommendations for further study or consideration included the following:

1. Investigations should be conducted for numerous handicapped individuals of both sexes and of different age levels. Disability level should be clearly specified and results grouped or compared accordingly.

2. For monitoring internal and external work of wheelchair propelling, a larger track should be used which has a long straight

runway and fewer turns.

3. A cycle ergometer should be used on which the subject can vary the speed at a constant pressure to correspond more nearly to wheelchair propelling.

4. A study should be performed in which subjects train by wheelchair propelling, or by cycle ergometry, or by both methods to determine training effects of both activities on a person's ability to perform wheelchair pushing.

5. Longitudinal investigations should be conducted to determine the course of fitness capacity in active and inactive wheelchair users over time.

6. In light of legal compliance with Education for all Handicapped Children Act of 1975 and the Rehabilitation Act of 1973, implications of consideration of wheelchair use as a definition of a 'transportation barrier' ought to be examined.

REFERENCES

1. Andrews, J. G. Biomechanical Analysis of Human Motion, Kinesiology IV, 32-42, 1974.

2. Ariel, G. Computerized biochemical analysis of human performance. The Athletic Journal, 54(7):54, 82, 84. March, 1974.

3. Astrand, P. O. Do we need physical conditioning? Journal of Physical Education, 129-136, March-April, 1972.

4. Astrand, P. O., B. Ekblom, R. Messin, B. Saltin, J. Stembers. Intra arterial blood pressure during exercise with different muscle groups. Journal of Applied Physiology 20(2): 253-256, March 1965.

5. Astrand, P. O., K. Rondahl. Textbook of Work Physiology. McGraw-Hill Book Company, San Francisco, 1977.

6. Astrand, P. O., B. Saltin. Maximal oxygen uptake and heart rate in various types of muscular activity. Journal of Applied Physiology 16(6):977-981, 1961.

7. Astrand, P. O., I. Rhyming. A monogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work. Journal of Applied Physiology, 7:218-221, September, 1954.

8. Berggren, G., E. H. Christensen. Heart rate and body temperature as indices of metabolic rate during work. Arbeitsphysiologie. 14:255-260, 1950.

9. Bevegard, S., U. Freyschuss, T. Strandell. Circulatory adaptation to arm and leg exercise in supine and sitting position. Journal of Applied Physiology 21(1):37-46, January 1966.

10. Campbell, D. E. Heart rates of selected male college freshmen during a season of basketball. The Research Quarterly 39(4): 880-887, December, 1968.

11. Carlsoo, S. A kinematic analysis of the golf swing, Journal of Sports Medicine and Physical Fitness, 7(2):76-82, June, 1967.

12. Cavagna, G. A. Elastic bounce of the body, Journal of Applied Physiology, 29(3):279-282, September, 1970.

13. Cavagna, G. A., B. Dusman, R. Margaria. Positive work done by a previously stretched muscle. Journal of Applied Physiology 24(1):21-32, January, 1968.

14. Cavagna, G. A., F. P. Saibene, R. Margaria. External work in walking. Journal Applied Physiology. 18(1):1-9, January, 1963.

15. Cavagna, G. A. and M. Kaneko. Mechanical work and efficiency in level walking and running. Journal of Physiology, 268(2): 467-481, June 1977.

16. Cavagna, G. A., F. P. Saibene, R. Margaria. Mechanical work in running, Journal of Applied Physiology, 19(2):249-256, March 1964.

17. Counsilman, J. E. The importance of speed in exercise, The Athletic Journal, 56(9):72-75, May 1976.

18. Cureton, T. K. Elementary principles and techniques of cinematographic analysis as aids in athletic research, The Research Quarterly, 10(1):3-24, March 1939.

19. Dempster, W. Space requirements of the seated operator, WADC Technical Report, 55-159, July 1955.

20. deVries, H. A. Physiology of Exercise for Physical Education and Athletics (2nd Ed.) Wm. C. Brown Company, Dubuque, 1976.

21. deVries, H. A. Physiology of Exercise for Physical Education and Athletics (3rd Ed.) W. C. Brown Company Publishers, Dubuque, 1980.

22. Dillman, C. J., R. C. Nelson. The mechanical energy transformations of pole vaulting with a fiberglass pole, Journal of Biomechanics, 1(3):175-183, August, 1968.

23. Drillis, R. Objective recording and biomechanics of pathological gait; Annals of the New York Academy of Science, 74:86-109, 1958.

24. Drillis, R. Photographic evaluation of prosthetics, Industrial Photographer, 5:24-25, 1956.

25. Edington, D. W., V. R. Edgerton. The Biology of Physical Activity. Houghton Mifflin Company, Boston, 1976.

26. Emes, C. G. Physical Work Capacity of Wheelchair Athletes. The Research Quarterly, 48(1):209-212, March, 1977.

27. Fardy, P. S., H. K. Hellerstein. A comparison of continuous and intermittent progressive multistage exercise testing, Medicine and Science in Sports, 10(1):7-12, 1978.

28. Federal Register, Vol. 42 (163:42478-42507, Tuesday, August 23, 1977.

29. Fox, E. L. Sports Physiology. W. B. Saunders Company, Philadelphia, 1979.

30. Freyschuss, W., T. Strandell. Limb circulation during arm and leg exercise in supine position. Journal of Applied Physiology 23(2):163-170, August, 1967.

31. Freyschuss, U., T. Strandell. Circulatory adaptation to one- and two-leg exercise in supine position. Journal of Applied Physiology 25(5):511-515, November, 1968.

32. Ganong, W. F. Review of Medical Physiology (8th Ed.) Lange Medical Publications, Los Altos, 1977.

33. Glaser, R. M., D. M. Foley, L. L. Laubach, M. N. Sawka, A. G. Suryaprasad. An exercise test to evaluate fitness for wheelchair activity. Paraplegia 16(4):341-349, February 1979.

34. Glaser, R. M., L. L. Laubach, M. N. Sawka, A. G. Suryaprasad. Exercise stress, fitness evaluation and training of wheelchair users. Proceedings of the International Conference on Lifestyle and Health, 1978. Topic: Optimal Health and Fitness for People with Physical Disabilities. (Ed.: Leon, A. S., G. J. Amundson). Department of Conferences, University of Minnesota, 1979. pp. 167-194.

35. Glaser, R. M., R. E. Young, A. G. Suryaprasad. Reducing energy cost and cardiopulmonary stresses during wheelchair activity. Federation of American Societies for Experimental Biology, 36(3):580, March 1, 1977. Abstracts of the 61st Annual Meeting, Chicago, Illinois, April 1-8, 1977.

36. Grieve, D. W., D. I. Miller, D. Mitchelson, J. P. Paul, A. J. Smith. Techniques for the Analysis of Human Movement, Princeton Book Company, Princeton, NJ, 1976.

37. Guttmann, Sir L. Textbook of Sport for the Disabled. HMTM Publishers, Aylesbury, England, 1976.

38. Guyton, A. C. Function of the Human Body, (4th Ed.) W. B. Saunders Company, Philadelphia, 1974.

39. Harper, H. A. Review of Physiological Chemistry, Lange Medical Publications, Los Altos, CA, 1971.

40. Hay, J. G. Mechanical energy relationships in vaulting with a fiberglass pole, Ergomonics, 14(4):437-448, July 1971.

41. Hay, J. G. The Center of Gravity of the Human Body. Kinesiology III, 20-44, 1973.

42. Hay, J. G. Moment of Enertia of the Human Body, Kinesiology IV, 43-52, 1974.

43. Hay, J. G. The Biomechanics of Sports Techniques, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1978.

44. Hildebrandt, G., E. D. Voigt, D. Bahn, B. Berendes, J. Kroger. Energy cost of propelling wheelchair at various speeds: Cardiac cost and effect on steering accuracy. Archives of Physical Medicine and Rehabilitation. 51(3):131-136, March, 1970.

45. Jacob, S. W., C. A. Francone. Structure and function in man. (3rd Ed.) W. B. Saunders Company, Philadelphia, 1974.

46. JAMA Medical News. 1977. Better wheelchair would benefit patients. Journal of the American Medical Association. 237 (23):2458-2459, June 6, 1977.

47. Jorgensen, T. On the dynamics of the swing of a golf club. American Journal of Physics, 38(5):644-651, May 1970.

48. Kelley, D. L. Supporting biomechanics subject matter in the undergraduate curriculum, Kinesiology IV, 1-11, 1974.

49. Lamb, D. R. Physiology of Exercise: Responses and Adaptations. MacMillan Publishing Company, New York, 1978.

50. Lamoreaux, L. W. Kinematic measurements in the study of human walking, Bulletin of Prosthetic Research, 10(15):3-84, Spring, 1971.

51. Lind, A. R., G. W. McNicol. Circulatory responses to sustained handgrip contractions performed during other exercises, both rhythmic and static. Journal of Physiology. 192(3):595-607, 1967.

52. Little, R. C. Physiology of the Heart and Circulation, Year Book Medical Publishers, Inc., 1977.

53. McArdle, W. D., L. Zwiren, J. R. Magel. Validity of the post exercise heart rate as a means of estimating heart rate during work of varying intensities. The Research Quarterly 40(3):523-528, October 1969.

54. McArdle, W. D., J. R. Magel, D. J. Delio, M. Toner, J. M. Chase. Specificity of run training on VO_2 max and heart rate changes during running and swimming, Medicine and Science in Sports, 10(1):16-20, 1978.

55. McMahon, T. A., P. R. Greene. Fast running tracks. Scientific American, 239(6):148-163, December. 1978.

56. Medsger, B. The most captive consumers: At the mercy of the wheelchair barons. The Progressive, 43(3)34-39, March, 1979.

57. Miller, D. I., K. L. Petak. Three dimensional cinematography, Kinesiology III, 14-19, 1973.

58. Moffatt, R. J., B. A. Stamford. Effects of peddling rate on maximal oxygen uptake and perceived effort during bicycle ergometer work, Medicine and Science in Sports, 10(1):27-31, 1978.

59. Muybridge, E. The Human Figure in Motion, New York: Dover, 1955.

60. Myers, C. R., L. A. Golding, W. E. Sinning. Y's Way to Fitness, Rodale Press, Inc., 1973.

61. Northrip, J. W., G. A. Logan, W. C. McKinney. Introduction to biomechanic analysis of sport, Wm. C. Brown Company, Dubuque, Iowa, 1974.

62. Nutter, D. O., R. C. Schlant, J. W. Hurst. Isometric exercise and the cardiovascular system. Modern Concepts of Cardiovascular Disease. 41(3):11-15, March, 1972.

63. Plagenhoef, S. C. Methods for obtaining kinetic data to analyze human motions, The Research Quarterly, 37(1):103-112, 1966.

64. Plagenhoef, S. Patterns of Human Motion: A Cinematographic Analysis, Prentice-Hall, Inc., Englewood Cliffs, 1971.

65. Rowell, L. B. Human cardiovascular adjustments to exercise and thermal stress, Physiological Reviews, 54(1):75-159, January, 1974.

66. Rushmer, R. F. Cardiovascular Dynamics, W. B. Saunders Company, Philadelphia, 1976.

67. Sarnoff, S. J., E. Braunwald, G. H. Welch, W. N. Stainsby, R. B. Case, R. Macruz. Hemodynamic determinants of the oxygen consumption of the heart with special reference to the tension-time index. In Work and the Heart: The First Wisconsin Conference on Work and the Heart, F. F. Rosenbaum and E. L. Belknap (Eds.), Paul B. Haeber, Inc. Medical Book Department of Harper and Brothers, New York, 1959, pp. 18-33.

68. Scheuer, J., C. M. Tipton. Cardiovascular Adaptations to Physical Training, Annual Review of Physiology, 39:221-251, 1977.

69. Scott, J. C. Physical Activity and the Coronary Circulation, Canadian Medical Association Journal, 96(12):853-866, March

70. Sears, F. W., M. W. Zemansky. College Physics, (3rd Ed.) Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1960.

71. Selye, H. The Stress of Life. McGraw-Hill Book Company, New York, 1956.

72. Sharkey, B. J. Physiology and Physical Activity, Harper and Row, San Francisco, 1975.

73. Sinning, W. E., H. L. Forsyth. Lower-limb actions while running at different velocities. Medicine and Science in Sports, 2(1):28-34, Spring, 1970.

74. Skinner, J. S., T. M. McLellan. The transition from aerobic to anaerobic metabolism. The Research Quarterly for Exercise and Sport 51(1):234-248, March, 1980.

75. Slocum, D. B., W. Bowerman. The Biomechanics of Running, Clinical Orthopaedics, 23:39-45, 1962.

76. Snedecor, G. W. Statistical Methods. Iowa State University Press, Ames, 1974.

77. Steadward, R. D. Wheelchair sports classification system. Doctoral dissertation presented to the Department of Physical Education and the Graduate School of the University of Oregon, June 1978.

78. Stoboy, H., B. W. Rich, M. Lee. Workload and Energy Expenditure During Wheelchair Propelling, Paraplegia, 8:223-230, 1971.

79. Thys, H., T. Faraggiana, R. Margaria. Utilization of muscle elasticity in exercise. Journal of Applied Physiology 32(4): 491-494, April, 1972.

80. Tornvall, G. Assessment of Physical Capabilities. Acta Physiologica Scandinavica. 53(suppl. 201):1-102, 1963.

81. United States Code, Congressional and Administrative News 93rd Congress - First session 1973. Volume 1, Laws and Legislative History, West Publishing Company, St. Paul, 1974.

82. Wahren, J. Quantitative aspects of blood flow and oxygen uptake in the human forearm during rythmic exercise. Acta Physiologica Scandinavica. 67(suppl. 269), 1966, Stockholm.

83. Webb, B. Wheelchair operation claimed more strenuous than bicycling. Paraplegia News, 30(346):5, July 1977.

84. Williams, D. The dynamics of the golf swing, Quarterly Journal of Mechanics and Applied Mathematics, 20(part 2):247-264, May, 1967.

85. Williams, M., H. R. Lissner. Biomechanics of Human Motion. W. B. Saunders Company, Philadelphia, 1968.

86. Williams, M. H., C. W. Jackson. Specificity of Training Related to Muscular Endurance, American Corrective Therapy Journal, 31(1):3-8, Jan-Feb. 1977.

87. Wilson, P. K. Adult fitness and cardiac rehabilitation. University Park Press, Baltimore, 1975.

88. Wolfe, G. A., R. Waters, H. J. Hislop. Influence of floor surface on the energy cost of wheelchair propulsion. Physical Therapy, 57(9):1022-1027, September, 1977.

89. Zuniga, E. N., L. A. Leavitt, J. C. Calvert, J. Canzoneria, C. Peterson. Gait patterns in above knee amputees. Archives of Physical Medicine, 53:373-382, 1972.

90. Zwiren, L. D., O. Bar-Or. Responses to exercise of Paraplegics who differ in conditioning level. Medicine and Science in Sports, 7(2):94-98, 1975.

APPENDICES

Appendix A

OREGON STATE UNIVERSITY

Committee for Protection of Human Subjects

Chairman's Summary of Review

Title: External and Internal Work of a T-6 Paraplegic Propelling a Wheelchair and Arm Cranking a Cycle Ergometer: Case Study

Program Director: John M. Dunn

Recommendation:

__X__ Approval

______ Provisional Approval

______ Disapproval

______ No Action

Remarks:

Letter of approval has been received from subject's physician.

Redacted for Privacy

Date: 4/16/79 Signature:

Margy Woodburn
Acting Chairman

If the recommendation of the committee is for provisional approval or disapproval, the program dirctor should resubmit the application with the necessary corrections within one month.

Appendix B

Informed Consent Form for Biomechanical and Physiological Analysis of Wheelchair Propelling

1) A high speed film study of the mechanics involved in propelling a wheelchair will be used to determine the effects on heart rate and blood pressure at different rates of travel.

2) The subject of the study will perform three trials of wheelchair propelling, each trial lasting three minutes. During the first trial the subject will be asked to propel the wheelchair at a comfortable, unhurried pace. In the second trial the subject will be asked to propel the wheelchair at a comfortable pace but more hurried. The final trial will be performed by asking the subject to travel at a pace which is more hurried still, but at less than an all-out effort. Subject in the study will be performing clothed such that the shoulder, elbow, and wrist nearest the camera will be in full view. Marks will be made at the joint axes of shoulder, elbow, and wrist. Subject will be filmed during the final lap of the three minute interval and blood pressure will be taken immediately following the filming. Heart rate will be continuously monitored by a two-lead telemetering transmitter. Subsequently the subject will be asked to perform three submaximal work loads on a cycle ergometer fixed to a table for manual operation. Blood pressure will be taken after each work load trial and heart rate will be continuously monitored.

3) Benefits to be expected from the study include a mechanical analysis of wheelchair propulsion which can be related to heart rate and blood pressure response for a given work rate. Also the subject will be provided continual ECG monitoring during performance of submaximal work loads illustrating the work of the heart under such conditions. Blood pressure monitoring under conditions of submaximal work will be an additional benefit.

4) Any questions the subject may have regarding the procedures involved will be answered by the investigator.

5) The subject is free to withdraw consent and to discontinue participation at any time with impunity.

6) The name of the subject will not appear in any written material concerning the study, and film of the subject will not be published in any manner without expressed written consent of the subject.

7) Film taken of the subject will become the property of the Oregon State University Department of Physical Education. Film may be used in research oriented classes to describe the process involved in performing a biomechanical analysis of human performance.

I have read and understand the Informed Consent Form and do give my consent to participate.

Signed Redacted for Privacy

Witness

Date __