

AN INVESTIGATION OF VARIOUS MEASURES USED
IN FOOTBALL HELMET EVALUATION

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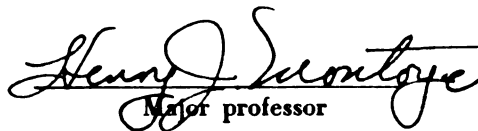
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ABSTRACT

AN INVESTIGATION OF VARIOUS MEASURES USED IN FOOTBALL HELMET EVALUATION

by Richard C. Nelson

The purpose of this study has been to evaluate and compare certain measures used in the evaluation of football helmets. This was accomplished by relating the findings of the medical research on brain injury to the information secured from the impact test data.

Thirty-nine football helmets were impacted by a pendulum striker at four velocities (12, 15, 18, and 21 feet/sec.). The helmets, mounted on a wooden head, were struck at four positions; front, back, side, and top. Two accelerometers, one placed on the back of the pendulum and the other inside the wooden head were employed. The output from the accelerometer circuits was fed into a dual trace oscilloscope. A Polaroid camera, mounted on the face of the instrument, was used to record the acceleration-time curves for both acceleration of the head and deceleration of the pendulum striker.

The photographs were projected and plotted on graph paper. Four measures were determined for both acceleration and deceleration: (1) peak or maximum acceleration, (2) rate of change of acceleration, (3) time duration of acceleration, and (4) kinetic energy.

Richard C. Nelson

The interrelationship of these four measures for acceleration of the head was determined from the plots of the six combinations or pairs of measures. The acceleration values were plotted against those for deceleration to determine to what degree they are related.

It is concluded that, the front and back positions responded similarly as did the top and side. Peak acceleration, rate of acceleration, and kinetic energy increased with an increase in impact velocity, while the fourth measure, time duration of acceleration, decreased. A positive relationship was noted for peak, rate, and kinetic energy. These three measures were negatively correlated with time duration of acceleration. These findings indicate that the measurement of peak acceleration alone is sufficient under these testing conditions. The acceleration values were directly related to those for deceleration. This was especially true of time duration, peak acceleration, and rate. On the basis of these results, it is concluded that observing the phenomenon of deceleration of the striker at impact is unnecessary for this type of helmet testing.

AN INVESTIGATION OF VARIOUS MEASURES USED
IN FOOTBALL HELMET EVALUATION

by
Richard C. Nelson

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DEDICATION

This dissertation is dedicated to my wife, Inez, and to our two children, Holly and David, who joined us during the past three years.

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CHAPTER I

INTRODUCTION AND STATEMENT OF THE PROBLEM

Introduction

The percentage of football fatalities due to head and spine injuries has risen steadily from 66% in 1947 to 80% in 1959.(3) As a result, concern has been shown by the medical profession and other groups directly associated with the game of football. These facts have, in turn, stimulated investigation in the area of football headgear, but unfortunately, an insufficient amount of work has been done to date. Much of this work has been hampered by the absence of explicit criteria upon which to base the comparison and evaluation of football helmets.

Statement of the Problem

The purposes of this study were to: (1) attempt to relate the medical research evidence to the impact test data; (2) to determine what relationships exist, if any, between the four measures of acceleration of the head (peak acceleration, rate of acceleration, time duration of acceleration, and kinetic energy absorbed by the head); and (3) to examine the relationship of the acceleration and deceleration values.

The impact test data were obtained by the use of a free swinging pendulum to deliver blows of varying magnitudes to different positions of the helmet.

Justification of the Study

The over-all problem of protecting the head and brain from injury is extremely complex. Despite extensive investigation by members of the medical profession the exact mechanism of concussion is still not fully understood. There is sufficient evidence, however, that acceleration (or deceleration) of the head at impact is one of the most important factors in brain injury. Other factors that appear to be related are the duration of acceleration, kinetic energy absorbed by the head, rate of application of the energy, the rise or fluctuation in intracranial pressure at impact and the time duration of this pressure.

On the basis of these findings investigators have developed various impact testing apparatuses to determine these measures. Most of these have employed some type of pendulum arrangement to impart the force to the helmet and head form. A linear accelerometer is usually mounted either within the head (to measure acceleration of the head), on the pendulum (to determine deceleration of the striker), or placed in both positions for simultaneous measurement. The following measures are obtainable under these testing conditions: peak acceleration, rate of change of acceleration, time duration of acceleration, and kinetic energy.

There is at present no information available as to the existing relationships between these measures. Although assumptions have been made concerning the direct relationship between acceleration and deceleration at impact (41) no data have been reported to substantiate this assumption. Knowing how these measures are related would enhance the understanding of the phenomenon occurring at impact. In addition this information could lead to the simplification of future helmet testing techniques.

Limitations of the Study

1. The results of this study are, of course, limited to football headgear.
2. The helmets were impacted at four distinct positions. It is possible that a different response would have been observed had other areas of the helmet been hit.
3. The results are further limited to test apparatuses having a helmet-head mass to pendulum mass ratio of approximately 2.6 to 1 (.38 slug to .15 slug), and a flat surface striker moving at the four velocities specified.
4. The fact that the data have been collected under laboratory conditions is a further limitation. Whether these conditions simulate those found in the normal football environment is open to question.

CHAPTER II

REVIEW OF RELATED LITERATURE

The problems of skull fracture and brain concussion have challenged medical research workers for many centuries. Much of the earlier work in this area was primarily of a theoretical nature, since adequate research tools had not been developed. The recent improvement in laboratory techniques and instruments has opened the way to more fruitful investigation. The review of the medical literature relating to brain injury will be discussed in the first section.

Protective headgear research has expanded considerably during the past 25 years. Much of this work has come about as a result of improved laboratory instrumentation and the application of sound principles of mechanics. Although only a limited amount of research has been done on football helmets, extensive work has been conducted on aircraft, motorcycle, and racing headgear. The second portion of this review contains the material relating to these investigations.

Skull Fracture and Brain Concussion

The lack of relationship between skull fracture and brain concussion has been well established. (45,37,26) Lissner, et al., stated, "There is no direct correlation

between severity of cerebral damage and linear skull fracture." (37,p.68) Fatalities due to concussion frequently occur with no fracture of the skull present. Likewise, skull fracture may occur with no concussive effect experienced. The fact that a small amount of energy is dissipated by fracturing the skull may account for the absence of concussion.(23)

A review of the case histories on football fatalities indicates that skull fracture rarely occurs in this sport. During the last fourteen seasons 125 football fatalities have resulted from head injuries. Of this total, eleven skull fractures were reported. Six of these occurred in sandlot games in which the player was not wearing a helmet. Three of the remaining five were victims of fracture in the basal region of the skull.(3) Gay (15) in his report on fifteen football head injuries observed no fractures, and only one death resulting from the injury incurred.

Lewin and Kennedy (36), in their report on nine motorcycle deaths, observed that in two cases in which the victim had worn a crash helmet, no signs of scalp marks or skull fracture were present. Of the seven deaths in which helmets had not been worn, six showed skull fracture and all seven suffered surface bleeding.

Further evidence that minimal protection is needed to prevent skull fracture was reported by Cole, MacNamee, and Herget.(2) In their experimental work on Rhesus monkeys,

concussion was induced by firing a shell against a steel plate placed against the animal's head. It was noted that a layer of sponge rubber one centimeter thick inserted between the plate and head was sufficient to prevent fracture of the skull.

These findings substantiate Gross's (19) contention that most protective helmets currently in use provide reasonable protection from scalp laceration and skull fracture. He suggests (18) that the primary function of the helmet is to provide protection from brain concussion in case of impact.

Brain concussion is defined as a state of post-traumatic unconsciousness associated with palor and shock-like state. It may be of varying intensity from a completely recoverable state to that of continued coma and death. (32, p.128) Research workers in the field of medicine, with assistance from technicians from other fields, have extensively investigated the mechanism of brain concussion. Despite this intensified effort, the phenomenon is still not fully understood.

It is generally agreed that brain concussion is usually produced in one of two ways: acceleration (or deceleration) of the head, and compression of the intracranial contents caused by inbending or crushing of the skull. (7, 8, 26, 28, 29, 30, 31, 35) "Acceleration concussion" refers to cases in which the head is either

accelerated or decelerated. It is associated with an increase in intracranial pressure at the point of impact and a decrease (negative) on the opposite side of the head. (16, 22, 28) Compression concussion occurs with the head more or less fixed while the increase in pressure is uniform throughout the cranial cavity. (16, 22, 28)

Denny-Brown and Russell (6, 8) in their work on cats and monkeys observed that in using a light pendulum to strike the animal concussion did not occur when the head was fixed. However, if the head was allowed to move as little as 3 mm. concussion was produced. They concluded that compression concussion required much greater force than acceleration concussion to produce the same effect.

More recent investigations have failed to substantiate this conclusion. Gurdjian and co-workers, in their experiments on dogs (25, 26, 29) reported that, for a given blow, the degree of injury decreased as the freedom of motion of the head increased. Groat, et al. (17, p.125) in their work with cats reported that, "A blow that caused concussion in the movable head demolished the fixed head."

Other theories have been advanced to explain the mechanism of brain injury. Eden (12) suggests that there are two ways in which the brain may be injured by a blow to the head: (1) a generalized effect in which the force is transmitted throughout the skull to the brain as a whole, and (2) a localized bruising effect characterized by signs

of focal damage or contusion to the brain. In addition, the important factor determining the presence or absence of concussion (assuming adequate momentum) is the area of the skull struck.

Holbourn (35) as a result of his work with cats theorized that, in addition to compression, concussion was caused by rotational acceleration. He further suggested that linear acceleration was of little importance, since it brought about no appreciable relative movement between parts of the brain. The limitation in his work lies in the fact that he did not observe the movement of the brain when the head was impacted nor did he attempt to differentiate between rotational and linear acceleration. No measures of either of these factors were reported. Further he related the mechanical factors to shear-strains (tearing) of the brain and not to concussive symptoms or effects.

In their work with Rhesus monkeys, Cole and fellow investigators (2) used a different approach to the problem. A lipiodal injection was administered to the brain of the animal. This substance formed globs which were recorded radiographically. During impact, changes in the shape of these globs were observed indicating a disbursing of the brain matter away from the point of impact. Autopsies later revealed that the site of injury was at this point. This phenomenon occurred in a time before much, if any, movement (acceleration) had taken place. They concluded that, "Brain

injury, without skull fracture during an intense local blow, is caused by a local circulation of brain substance resulting from stresses transferred through the skull to the brain."(2, p.32)

A more recent theory, based on hydrodynamic principles, has been advanced by Gross.(20) He photographed closed test tubes which were accelerated by a sharp blow. Whenever the tensile force of the blow exceeded the tensile strength of the liquid, gaseous cavities were formed. This process, which he called "cavitation," may occur at the point of impact (coup cavitation), or on the opposite side (contrecoup). He proposed that the violent collapsing of these cavities is the principle cause of brain damage when the human head is accelerated.

Regardless of which type of concussion is produced (acceleration or compression) the physiological changes; namely, a sudden rise in blood pressure, loss of the corneal reflexes, reduction in respiration, and unconsciousness, are the same. Gurdjian and Webster (26) found, for blows caused by a pendulum, there was no essential difference of response phenomena between the fixed and the movable head. This observation applied even when the skulls were actually penetrated by bullets.(25) Other studies have shown that acceleration and compression invoke similar physiological responses. (17, 55) The findings do not, however, suggest that acceleration concussion is necessarily identical with the effects of brief compression.

Although the relative importance of these two mechanisms of concussion has not been firmly established, it appears that acceleration concussion occurs more frequently in accidents as well as in football. Courville (50,p.40-41) states,

It has now come to be recognized that compression concussion resulting from pressure or a blow to the head, which is more or less fixed in position, is relatively mild or may be absent altogether. On the other hand, concussion produced by acceleration or deceleration of the head (acceleration concussion) is of a more serious degree.

Other investigators (56,46,14,6) concluded that acceleration concussion is the type that occurs most frequently in falls and other accidents. Gurdjian and Webster stated, however, that pure compression or acceleration concussion are rare (26), and that they usually coexist.(27) They further insist that it is impossible to have acceleration injury without some compression effect due to inertia of the head or the object struck.(28) Foltz (14), however, contends that acceleration concussion differs fundamentally from the various types of compression concussion.

Pudenz and Sheldon, in their classic experiment on monkeys (43), added further evidence of the movement of the brain at impact. In their study, the tops of the monkeys' skulls were removed and replaced by a transparent lucite dome. After the animals recovered from the surgery, the investigators took high speed movies of the brain as the head was subjected to varying blows. They concluded that

(1) when the head was free to move at impact the cortex rotated mainly in the sagittal and horizontal planes; (2) if the head was fixed, little or no motion took place; (3) for all blows inflicted, the parietal and occipital parts of the brain moved farther than the frontal and temporal parts, and (4) brain movement is much greater following blows in the parietal and temporal than in the frontal and occipital regions.

Evidence of the importance of rotational acceleration in the contre-coup injury is offered by Goggio.(16) He stated that the fronto-temporal area is most frequently involved in contre-coup injury because this is the roughest surface of the inside of the skull. Rotation rather than linear force frequently accompanies the blow. On the other hand, Russell (46) contends that contre-coup injury is due simply to the tearing away of the brain from its meninges by its own momentum.

Courville (4), in a more thorough study of the coup-contre-coup mechanism observed that this type of injury occurred only when the moving head strikes a stationary or relatively stationary object. The coup injury is manifest at the point under impact, and contre-coup in the area diametrically opposite. The frontal area appeared to be the most vulnerable to injury. If the blow is struck in the frontal region, coup injury develops. However, if impact occurs in the occipital region, contre-coup injury occurs

(injury in the frontal area). This was explained by the fact that the tips of the fronto-temporal lobes lay enclosed in a bony pocket having irregular walls.

The use of electronic equipment in recent investigations has made possible the measurement of the following factors in impact: acceleration of the head, time duration of acceleration, intracranial pressure and its time duration, the kinetic energy absorbed. In most of these animal studies, an attempt was made to associate one or more of these factors either with concussive effect or actual brain damage.

Lissner and co-workers (37) suggest that the total injurious effect is due to the absorption of energy by the head, with the magnitude of the energy and its rate of absorption being the important factors. They further state, that if the accidental input of energy into the human head can be kept below 400 inch pounds, a considerable reduction in fatalities and serious injuries will result. In a closely related study by Gurdjian and Webster (26,27), it was concluded that the quantity of energy absorbed by the head in an optimum period of time determined the intensity of the physiologic response. This was found to be true whether the head was fixed or free to move. In the experimental animal (dog), 200 inch pounds absorbed by the head in .001 to .002 seconds or less caused profound patho-physiologic effects, usually resulting in death. Lombard, et al. (40), pointed out that the effect of the absorption of a given amount of

energy is dependent upon the accompanying maximum acceleration of the head.

Gurdjian and co-workers attempted to relate degree of concussive effect with acceleration of the head and increase in intracranial pressure. (28, 30, 31, 33) They attached a linear accelerometer to the side of the dog's head opposite the point of impact, and mounted a pressure gauge on each side of the head. The animal was then struck with a hammer and the acceleration-time curve and pressure changes were recorded by use of electronic oscilloscopes. Their results indicated there is little relationship between magnitude of acceleration and physiological response evoked at the time of impact. However, the time duration of the acceleration did appear to be related to the degree of clinical effects. The greater the time duration, the more serious the concussive effect. Also, the magnitude of the pressure alone did not determine the concussive effect obtained, but time duration of pressure was also significant. In other words, the same affect was obtained with high pressure over a short period of time as with lower pressure over a longer time.

It should be noted that because of the type of blow inflicted, compression concussion was primarily being produced. The authors found that skull deformation was so great that the pressure due to this deformation was of primary significance and positive pressures were generally measured opposite the point of the blow as well as on the same side

of the blow (of the 23 dogs tested only three developed negative pressure on the side opposite the point of impact). The fact that peak acceleration was not related to concussive effect is not surprising since the greater the crushing of the skull, the lower the resulting acceleration would be, and the greater the compression of the brain. .

As a result of this work, these investigators concluded that acceleration and deceleration of the head produced clinical effects by causing an increase in pressure of the intracranial contents and this pressure increase in turn causes the injurious effect.(31) This may hold true only for compression concussion since other studies (8, 14, 58, 6) have shown that acceleration concussion is not accompanied by an increase in intracranial pressure. Gurdjian and fellow investigators further examined the importance of the elevation of intracranial pressure and its time duration. (29) To do this, they applied pressure directly to the dural sac through an opening in the skull. Again, the time duration as well as the maximum pressure appeared to be related to the concussive effect. Walker, Kollross, and Case (55), while using a similar technique found that the rapid changes in pressure constituted the most important factor in causing the resultant concussion. Whether this type of stimulus is present in acceleration concussion, however, is open to question. Foltz (14) in his work with cats and monkeys reported that experimental variation of

compression concussion can be devised in which the intracranial contents are directly compressed through an opening in the skull in a variety of ways, but this technique does not simulate acceleration concussion. The fact that mechanically increasing the pressure produces the same results as inflicting a blow to the fixed head (compression concussion) (47), casts further doubt as to the applicability of these results to acceleration concussion.

Protective Headgear Research

Recent improvement in helmet testing techniques has resulted in extensive research on many types of protective headgear. Most of these investigations have utilized a pendulum arrangement to administer blows to the helmet which is mounted either on a wooden or metal head. Linear accelerometers are mounted either on the pendulum or attached to, or secured within, the head form. An electronic oscilloscope is generally used to portray either maximum acceleration or the whole acceleration-time curve, while motion or still pictures are taken at the time of impact. From these records the following measurements are obtained: peak acceleration, rate of change of acceleration, time duration of acceleration, and the change in velocity (area under the acceleration-time curve). The relative importance of these measures for use in comparing and evaluating helmets is yet to be determined.

The Cornell Aeronautical Laboratory (9), under the direction of Edward Dye, measured two components of the blow: magnitude of energy and concentration of pressure on the head. The report stated that blows, in terms of kinetic energy, was believed to be the important factor. In a later report, however, Dye (11) suggested that several component effects of the blow received through the helmet by the head must be considered collectively to make an accurate evaluation of the helmet. These were: (1) linear acceleration of the head, (2) rate of change of linear acceleration, (3) distribution of force received by the head, (4) angular acceleration of the head, (5) rate of angular acceleration, and (6) intensity of negative pressure within the brain fluid. Under the existing test apparatus only the first five of these can be determined.

Since no explicit criteria for head protection are available, Strand (54) made the assumption that the following characteristics were desirable: (1) minimum peak acceleration, (2) maximum energy absorption by the helmet, (3) minimum tendency to "bottom-out" against the head, and (4) uniform protection over the entire head. He concludes by stating that other factors, such as rate of change of acceleration and duration of the peak acceleration, must be considered in a final determination of adequacy of the helmet protection at a particular point.

The importance of maximum acceleration has been emphasized by Lombard, et al. (38, 40) and Snively. (49) The latter investigator believes that along with acceleration of a low order, the energy should be dissipated over a broad base in terms of time. Mindlin, (42) in his report on the "Dynamics of Package Cushioning," concluded that if the outer container is adequate, the survival of a packaged item in a drop test depends upon the form of the acceleration-time curve and the magnitude of the maximum acceleration that cushioning permits the packaged item to reach. In his work on aviation protection helmets, Hendler (34) implies the importance of rate of change of acceleration. For even though the three curves in Figure 1 have the same area, magnitude, and total duration of acceleration, the dynamic effect would be quite different. The curve with the steepest upward slope (rate of change of acceleration) would elicit the greatest dynamic effect.

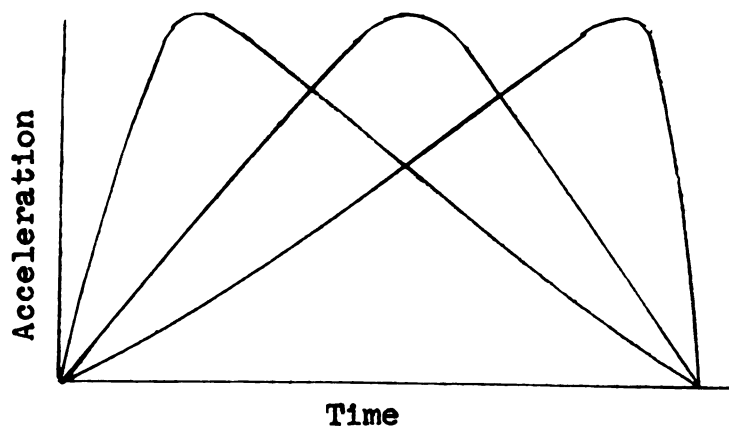


Fig. 1. Acceleration vs Time

The only data available on human tolerance to acceleration of the head has been reported by Lombard and co-investigators.(41) In this experiment they measured deceleration and rate of deceleration of the pendulum striker at impact. The subjects wore various types of protective headgear, and were hit from the front, back, side, and top. The velocity of the pendulum was steadily increased until the subject voluntarily quit. Pendulums of 13 and 9.4 pounds (approximating the weight of the human head) were used. The highest deceleration tolerated for each position were: Top--34G, Front--38G, Side--25G, and Back--35G. The limitation of this study lies in the assumption that deceleration of the pendulum can be considered equal to acceleration of the head (which was not measured). The authors implied the forces are equal and opposite. However, when two objects collide, it is the momentum, not the force, which is conserved. Because of this, the G values reported are of limited value.

Although Stapp's (52) investigation of human tolerance to deceleration involved the whole body, his work is worth noting. The subjects were mounted on a movable sled which was propelled at high speed and then suddenly stopped. The author determined that 40G at a rate of 12,000 G per second rate of application for .12 seconds could be endured without irreversible damage if the body is adequately restrained.

Attempts to establish tolerance limits in terms of peak acceleration, rate of acceleration and pressure have

been made by various investigators.(11, 39, 50) The limits proposed apply only to the given test apparatus, however, and thus are of limited use. Further, since no concussion data are available on the human the technique of extrapolation from animal data has necessarily been used. As a result, the tolerance limits established for helmets to date are of little value when applied to football players or other helmet test situations.

The only research located concerning the relationship of acceleration of the head and deceleration of the pendulum striker was conducted by Edwards.(13) In this study rank order correlations were reported for a pendulum velocity of 21 feet per second at four positions. The coefficients of correlation were: Front -.016, Back .10, Top .932, and Side .90. The two measures were not secured simultaneously, however, but rather in two separate testing sessions.

Summary

It is apparent that skull fracture rarely occurs in football, especially if helmets are worn. This fact indicates that brain injury in football is primarily caused by acceleration rather than compression concussion. Because of the absence of concussion data on humans it has been necessary to apply the results of animal experimentation.

The investigations relating to acceleration concussion conclude that the magnitude (peak) of the acceleration

appears to be related to the clinical effects produced. Other factors that are apparently important include the kinetic energy and its rate of absorption as well as the changes in pressure within the cranial cavity during the time the head is accelerated. The evidence concerning the importance of time duration of acceleration is of limited value since compression of the brain was occurring during impact. No attempts have been made as yet to relate the rate of acceleration to concussive effect.

Despite the identification of these factors as being related to brain injury, their applicability to conditions involving the human head is questionable. There are no tolerance limits available for humans on any of the above mentioned factors.

CHAPTER III

EXPERIMENTAL METHOD

Testing Equipment

The helmets were mounted on a size 7-1/4 wooden head weighing 12.2 lbs. which was suspended upside down from the ceiling by two steel cables. A cast iron striker weighing 4.58 lbs. was suspended in a pendulum arrangement (Figure 2). To insure a consistent pendulum impact velocity, an adjustable electro-magnetic release was utilized. This unit, with pendulum attached, was elevated to the preassigned heights so that upon release the desired impact velocities of 12, 15, 18, and 21 ft./sec. could be achieved.

To measure deceleration of the pendulum and acceleration of the head at impact two Schaevitz type V6-750 linear accelerometers were used. One was mounted on the back of the pendulum and the second attached to an insert that was secured within the wooden head (Figure 3).

A Hewlitt Packard oscillator, model 200 cd, was utilized to establish a signal frequency of 3,000 c.p.s. at approximately 7 volts in the accelerometer circuits. These signals were fed into a Hewlitt Packard model 150 A dual trace oscilloscope. The impulse from the pendulum accelerometer was portrayed on the lower trace and the head acceleration on the upper trace. A Beattie-Varitron Polaroid

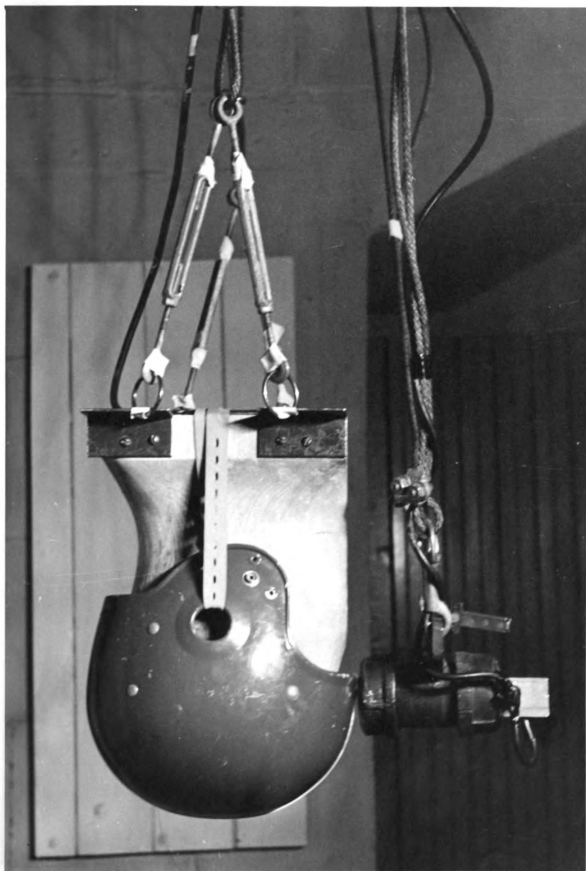


Fig. 2. Wooden Head, Helmet, and Pendulum Striker

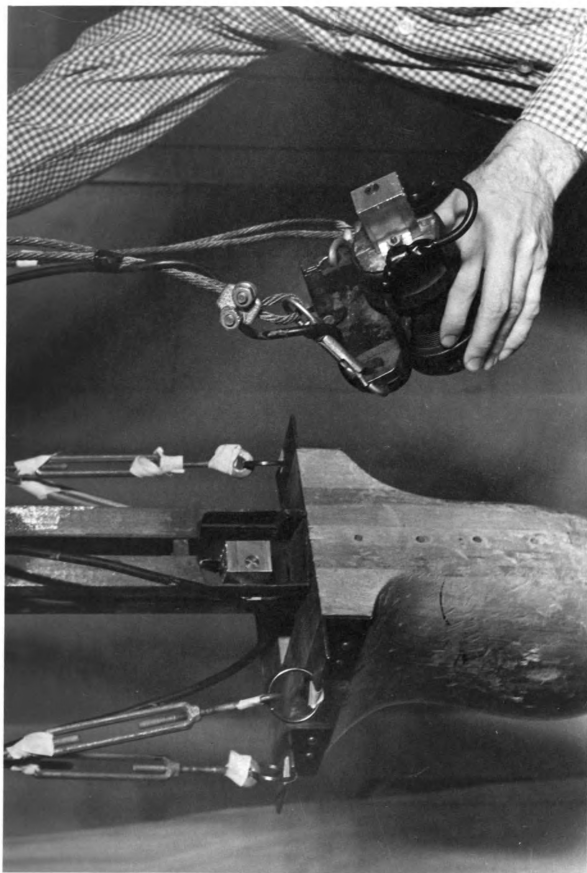


Fig. 3. Accelerometers Mounted on Insert and Pendulum Striker

Camera (Figure 4) was mounted on the face of the oscilloscope to secure a time exposure of the oscilloscope tracings at the time of impact. This photograph provided a record of the time-acceleration curves on both traces (Figure 5) from which the desired measures were later secured. To increase the accuracy of the measurements the photographs were placed in a Beseler Van Lyfe II projector and displayed four times as large on graph paper (20 squares to the inch). The outline of the acceleration-time curves was plotted (Figure 6) and later drawn in completely with a French curve.

A calibration record was taken each test period using the following technique. The accelerometer was first positioned so that its main axis was parallel to the force of gravity. In this position the force of gravity tends to pull the core of the accelerometer toward the null position. It was then swung down through the neutral position to a point where the gravitational force was again directed parallel to the main axis. In this position, the force tended to pull the core away from the null position. A photographic record (time exposure) was taken at the most sensitive setting as each accelerometer was positioned and moved as described. The deflection recorded represented twice the force of gravity, or two G's.

Design of the Experiment

Three replicates of each of thirteen different helmet models were subjected to the impact tests. Impact blows at



Fig. 4. Polaroid Camera, Dual Trace Oscilloscope, and Oscillator

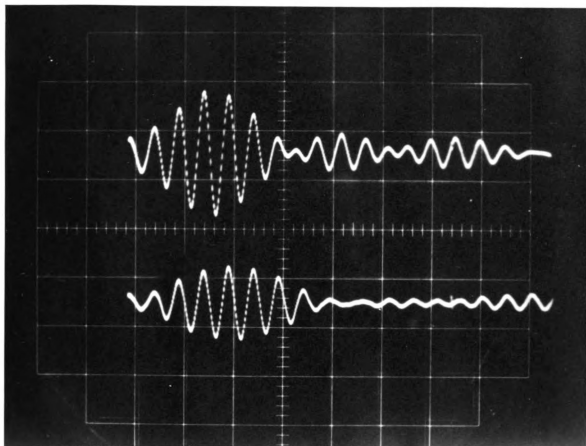


Fig. 5. Photographic Record Showing Acceleration-Time Curves for the Head and Pendulum

(Upper Trace - Acceleration; Lower Trace - Deceleration)

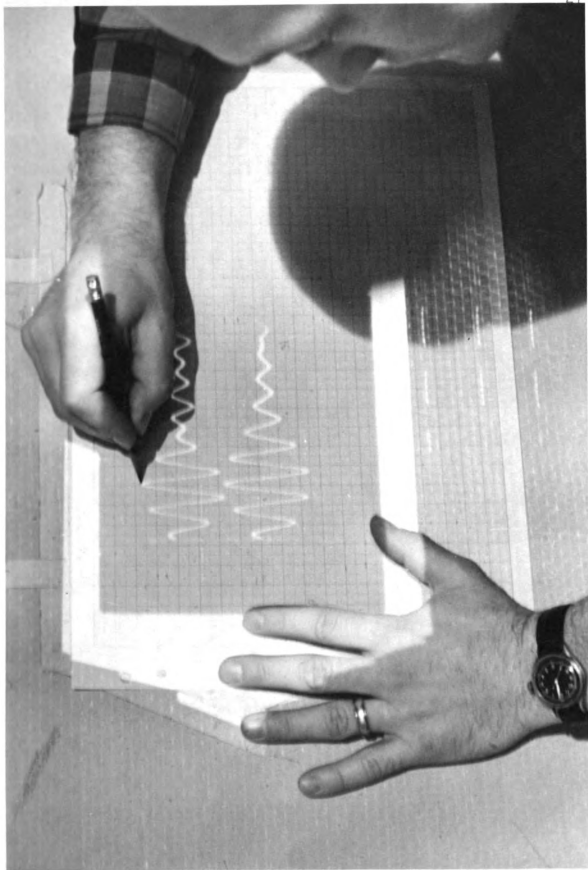


Fig. 6. Plotting of the Projected Photographic Record

four velocities (12, 15, 18, 21 ft./sec.) were inflicted to the front, side, back, and top positions. Each replicate received the blows in the same sequence for a given position. In order to minimize the fatigue effect of repeated impacts, the order of pendulum velocities was randomized for each replicate at each position. The brand names and model numbers as well as the weights of the helmets appear in Appendix A.

Both acceleration of the head and deceleration of the pendulum were recorded simultaneously at impact. The photograph in Figure 5 shows the curves for the head and pendulum. A sample of 104 was drawn from the total 624 blows recorded. For each helmet model at each position two velocities were randomly selected. The records of the three replicates for each velocity chosen were examined and the one displaying the most complete acceleration-time curve was selected for the study.

Measurements and Calculations

Four measures were deemed important to examine in this study. They were: peak acceleration, rate of change of acceleration, time duration of acceleration, and the area under the acceleration-time curve (representing the change in velocity).⁽³⁴⁾ Since the maximum difference in weight of the helmets was only 4% of the head and insert weight, the head and helmet mass was considered to be the same for all helmets. The calculation of kinetic energy is dependent

upon the mass and the square of the velocity. However, since the mass was considered to be constant for all helmets the square of the area under the curve was used for comparative purposes to represent kinetic energy. In the case of acceleration of the head the kinetic energy absorbed was represented in this way while for deceleration the kinetic energy lost. Throughout this dissertation the square of the area under the curve is referred to as kinetic energy.

Peak acceleration was determined by measuring with a sliding vernier caliper the maximum deflection (Distance A in Figure 7), subtracting the baseline width (Distance B) and dividing by two. This value was in turn multiplied by the calibration factor for the given test period and sensitivity setting to obtain the G value.

The average rate of acceleration was computed by dividing the peak acceleration by the time required to reach the peak. The time value was calculated by measuring the time line (Distance D) and multiplying it by a calibration factor for the given sweep time.

The time duration of acceleration was obtained by measuring Distance C (Figure 7) and converting it to time, using the computed factor for the appropriate sweep time.

The area under the curve was secured by the use of an Ott Compensating Polar Planimeter. Five tracings were made around the total area and the mean determined. Next the area of the baseline was subtracted from the total area.

This result was divided by two to give the average area above the baseline. Since the area is dependent upon sweep time and sensitivity all values for area had to be converted to a common sweep time and sensitivity setting. Factors were determined for each combination of the two and multiplied by the value obtained for area from the plot. In addition, slight corrections were made to compensate for variations from day to day in calibration factors. These were all converted to a common calibration value and compensating factors computed. The previously adjusted area values were next corrected for calibration variation by multiplying these values by the appropriate factor. The measures for deceleration were obtained in the same manner.

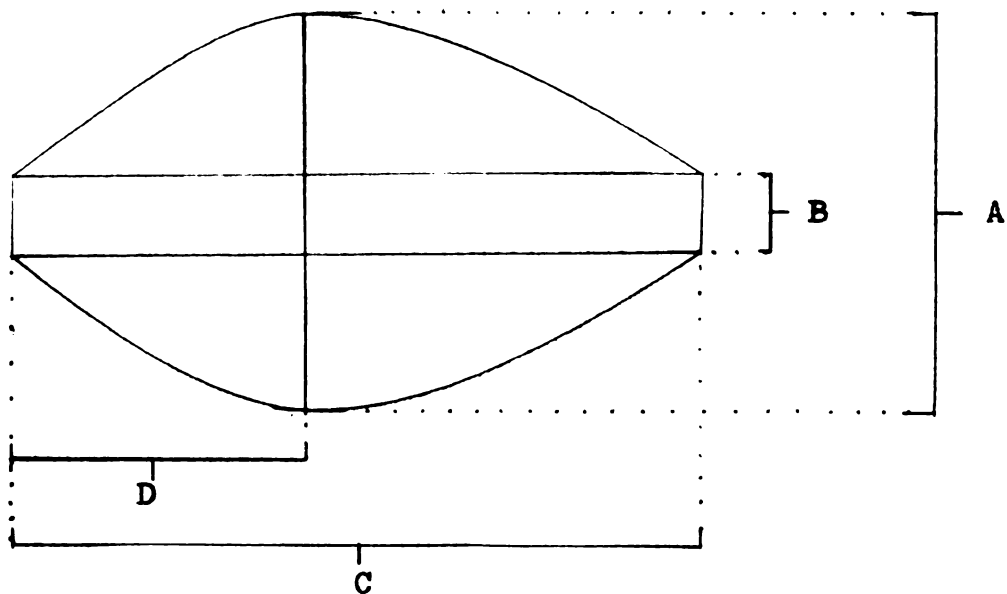


Fig. 7. Sample Acceleration-Time Curve

The data determined for all four measures from the sample selected appear in Appendix B.

CHAPTER IV

RESULTS

The results are presented in two sections. The first considers the relationships of the various measures for acceleration of the head, and the second the relationship of the measures for acceleration and deceleration. Each pair of values has been plotted and presented in graphic form.

These data are based on the use of four impact velocities. Because of this, the calculation of correlation coefficients was deemed unnecessary since they could be erroneously high or low, and, therefore, obscure the true relationship. An example would be the case in which no relationship exists within each impact velocity. If both measures tend to increase, however, as the impact velocity does then combining of the data adds linearity to the relationship. Consequently, the correlation coefficient would indicate a stronger relationship than actually exists. In each of the plots the velocity of the pendulum at impact is identified by its appropriate symbol.

I. Comparison of Measures for Acceleration of the Head

Kinetic Energy vs. Time Duration

Examination of the plots for the front and back

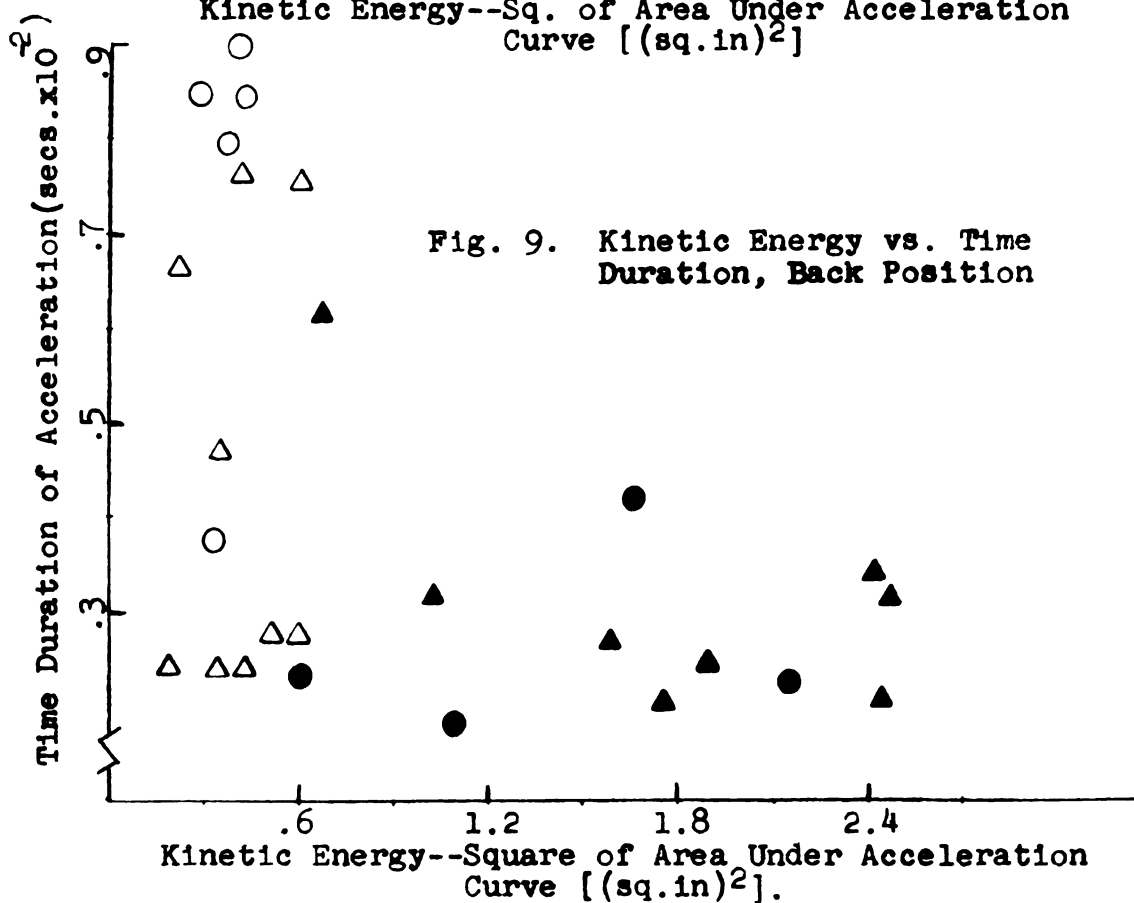
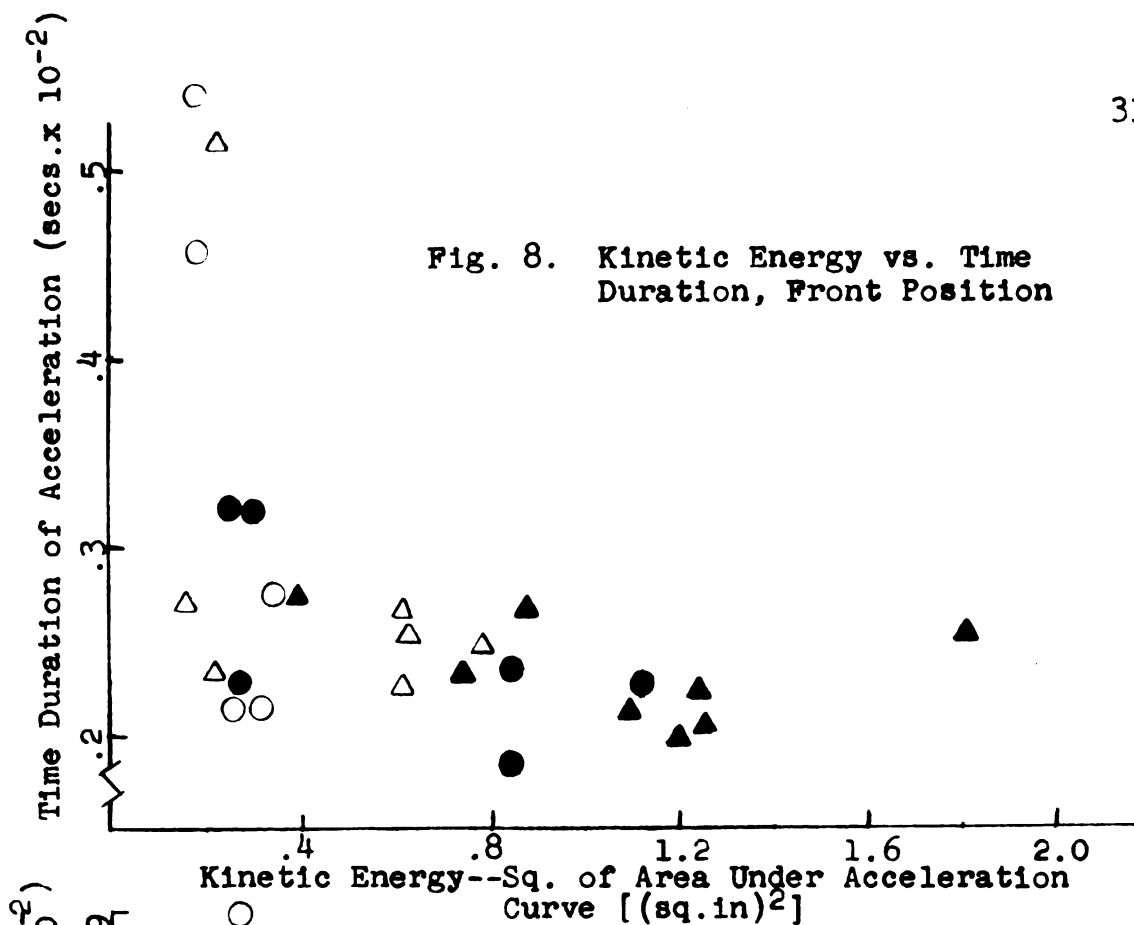
positions indicates that both show a negative relationship. That is, the longer time duration is associated with a lower kinetic energy. It is also apparent that the higher impact velocities have shorter time durations and higher kinetic energy values. This does not hold true for the top and side positions, however. For each impact velocity a strong positive relationship exists. When all velocities are considered together, this dependence is considerably weakened. (Figures 8, 9, 10, and 11)

Kinetic Energy vs. Peak Acceleration

The front and back positions both show a very strong positive association between these two measures. This appears to hold for all four impact velocities. Over-all the top and side positions show little or no dependence. For the two higher impact velocities, a negative tendency is present. (Figures 12, 13, 14, and 15)

Kinetic Energy vs. Rate of Acceleration

The front position plot indicates a strong positive correlation exists which is consistent across all impact velocities. This is not as pronounced for the back position except for the two higher blows. The top and side values suggest no composite relationship but the lower blows reflect a slight negative slope, and the higher blows a more definite one. (Figures 16, 17, 18, and 19)



Code for Impact Velocities (ft./sec.)

12--○	15--△
18--●	21--▲

Fig. 11. Kinetic Energy vs. Time Duration of Acceleration

Top Position

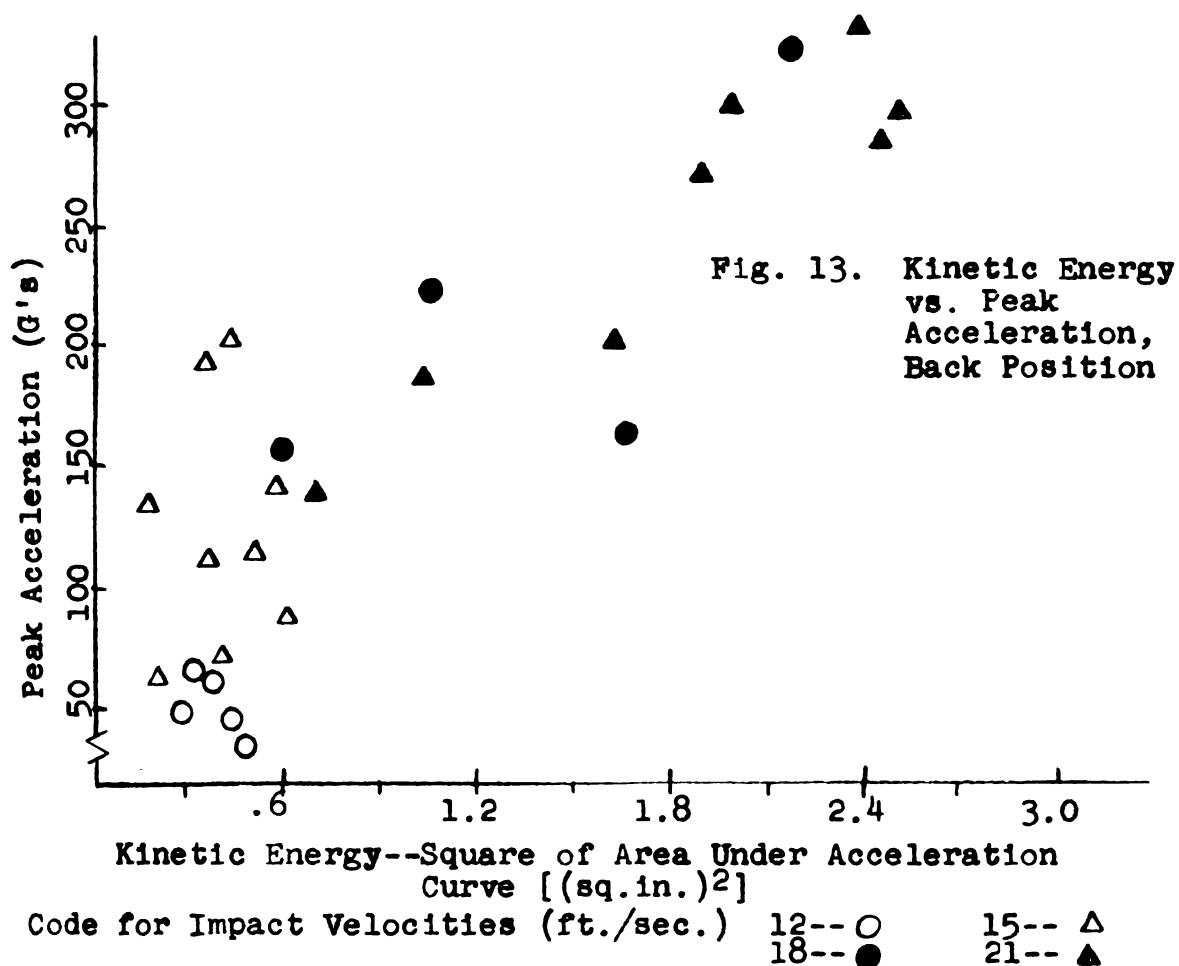
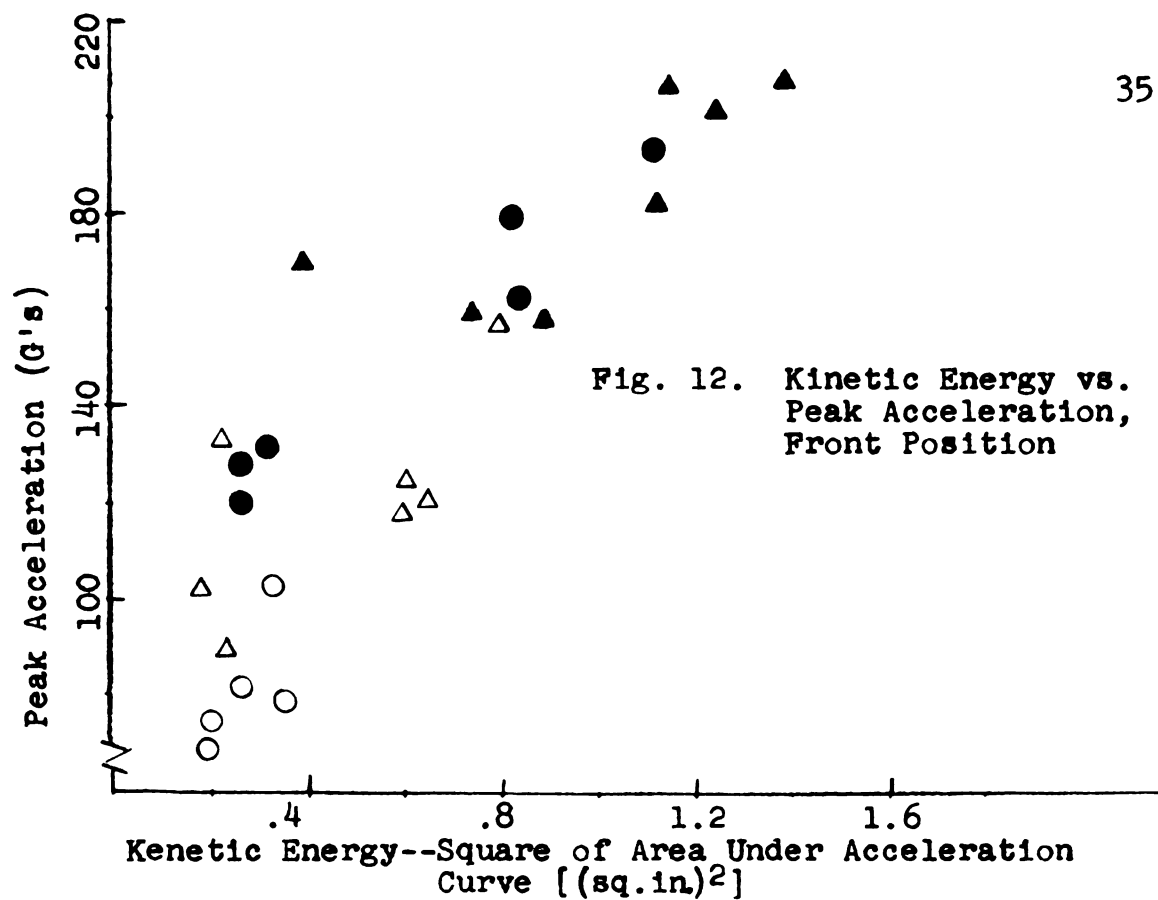
Bottom Position

Time Duration of Acceleration (secs.x10⁻²)

Kinetic Energy--Square of Area Under Acceleration Curve [(sq.in)²]

**Fig. 11. Kinetic Energy
vs. Time Duration,
Top Position**

Code for Impact Velocities (ft./sec.) 12-- ○ 15-- △
18-- ● 21-- ▲



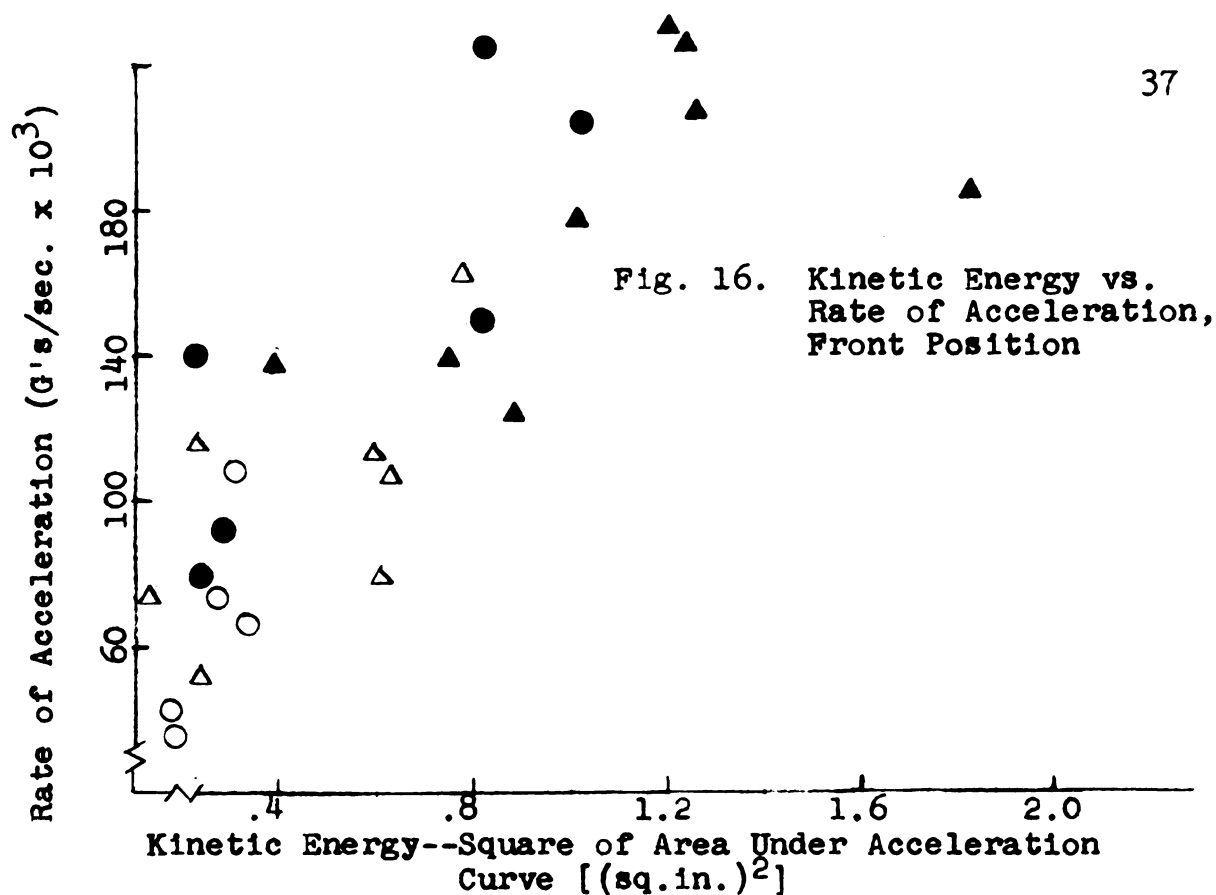


Fig. 18. Kinetic Energy vs.
Rate of Acceleration,
Side Position

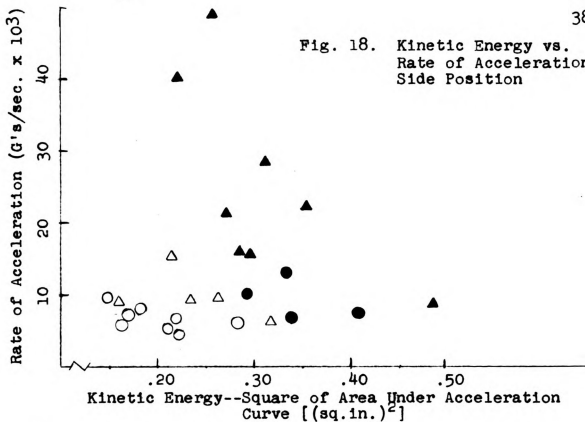
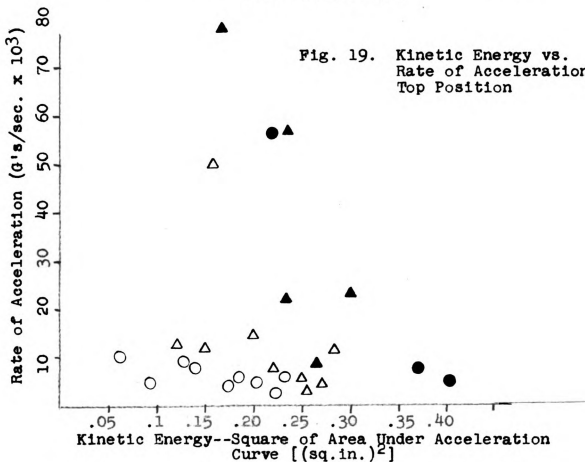


Fig. 19. Kinetic Energy vs.
Rate of Acceleration,
Top Position



Code for Impact Velocities (ft./sec.) 12--○ 15--△
18--● 21--▲

Peak Acceleration vs. Time Duration

All four positions show a marked negative correlation which is apparent at each pendulum velocity. With the exception of the side position, the slopes are slightly curvilinear. In all positions the higher impact velocity results in a higher peak acceleration and a lower time duration. (Figures 20, 21, 22, and 23)

Peak Acceleration vs. Rate of Acceleration

A very strong positive relationship is apparent especially for the back and front positions. In this case, the higher blows are associated with high peak acceleration and also high rate of acceleration. (Figures 24, 25, 26, and 27)

Time Duration vs. Rate of Acceleration

All four plots denote a definite curvilinear negative association. The slopes for back and front depict a "break-off" point at approximately 75G per second for rate, and .0035 seconds time duration. This is also present in the plots for side and back but it occurs at a lower rate and longer time duration point. (Figures 28, 29, 30, and 31)

These results suggest that two basic acceleration-time curves exist under the present test situation. The one is characterized by a high rate of acceleration (high peak, also) and relatively short time duration. The second basic curve has a low peak and rate of acceleration but a

Fig. 20. Peak Acceleration vs.
Time Duration,
Front Position

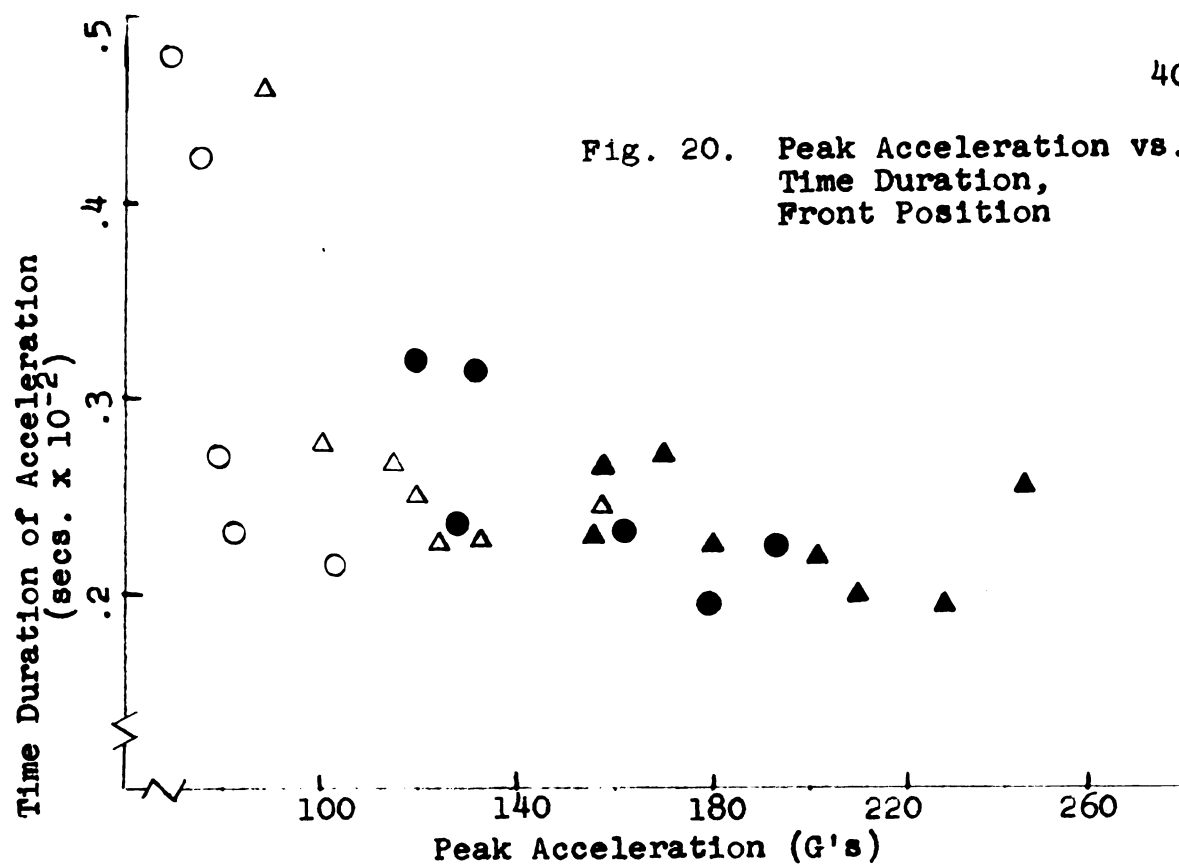
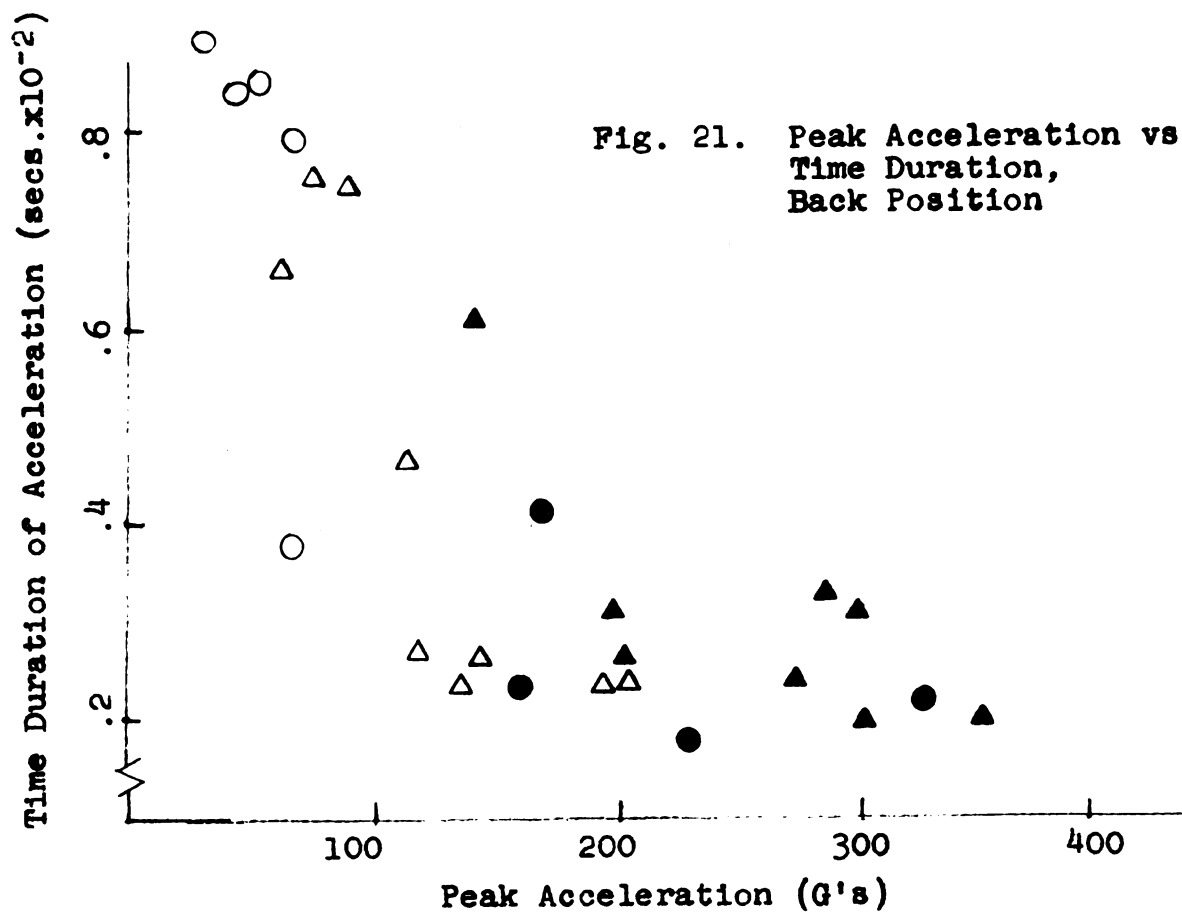
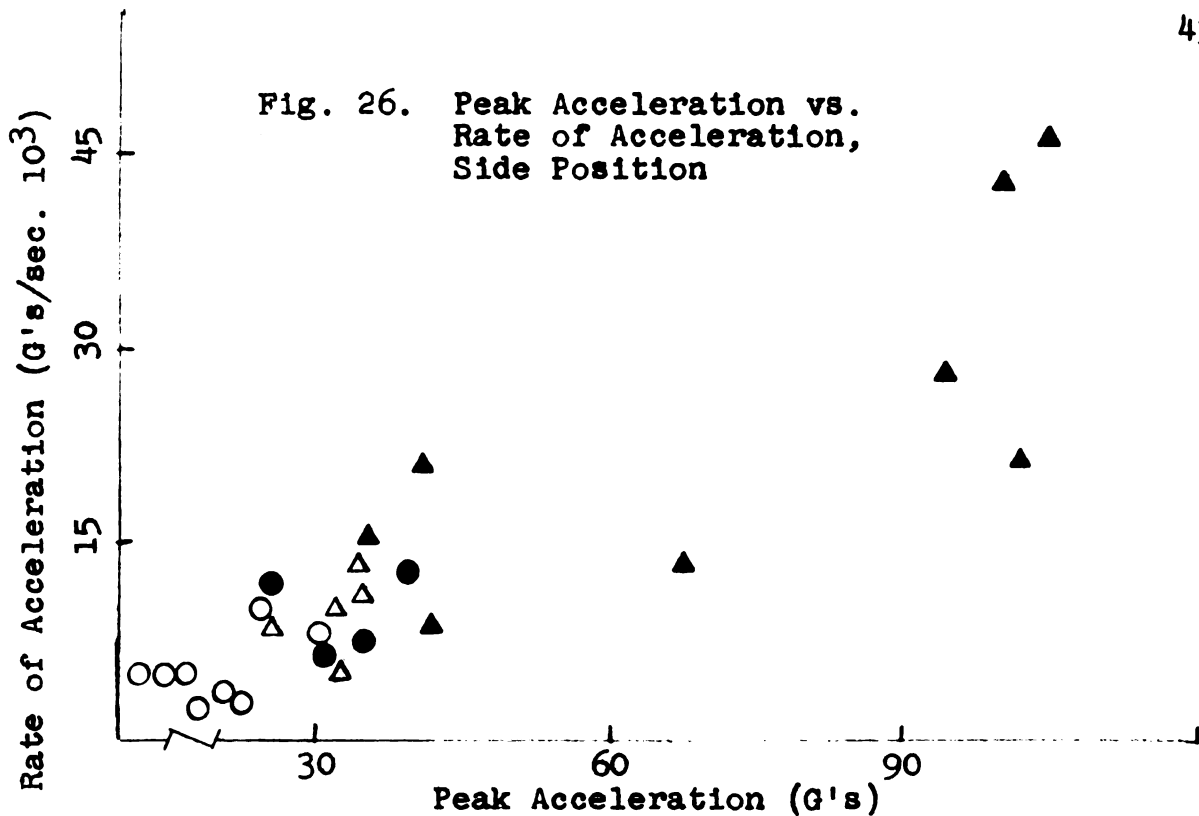


Fig. 21. Peak Acceleration vs.
Time Duration,
Back Position

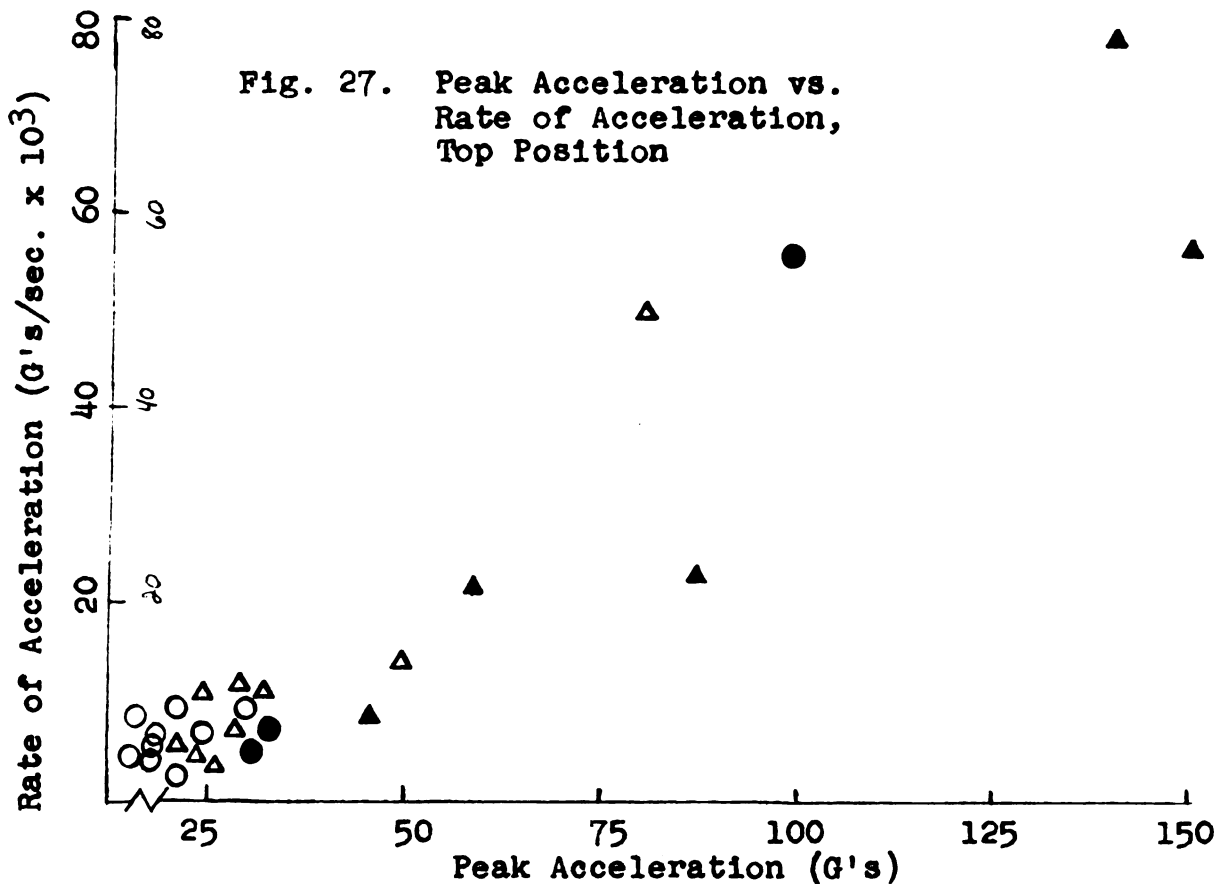


Code for Impact Velocities (ft./sec.) 12--○ 15--△
18--● 21--▲

**Fig. 26. Peak Acceleration vs.
Rate of Acceleration,
Side Position**

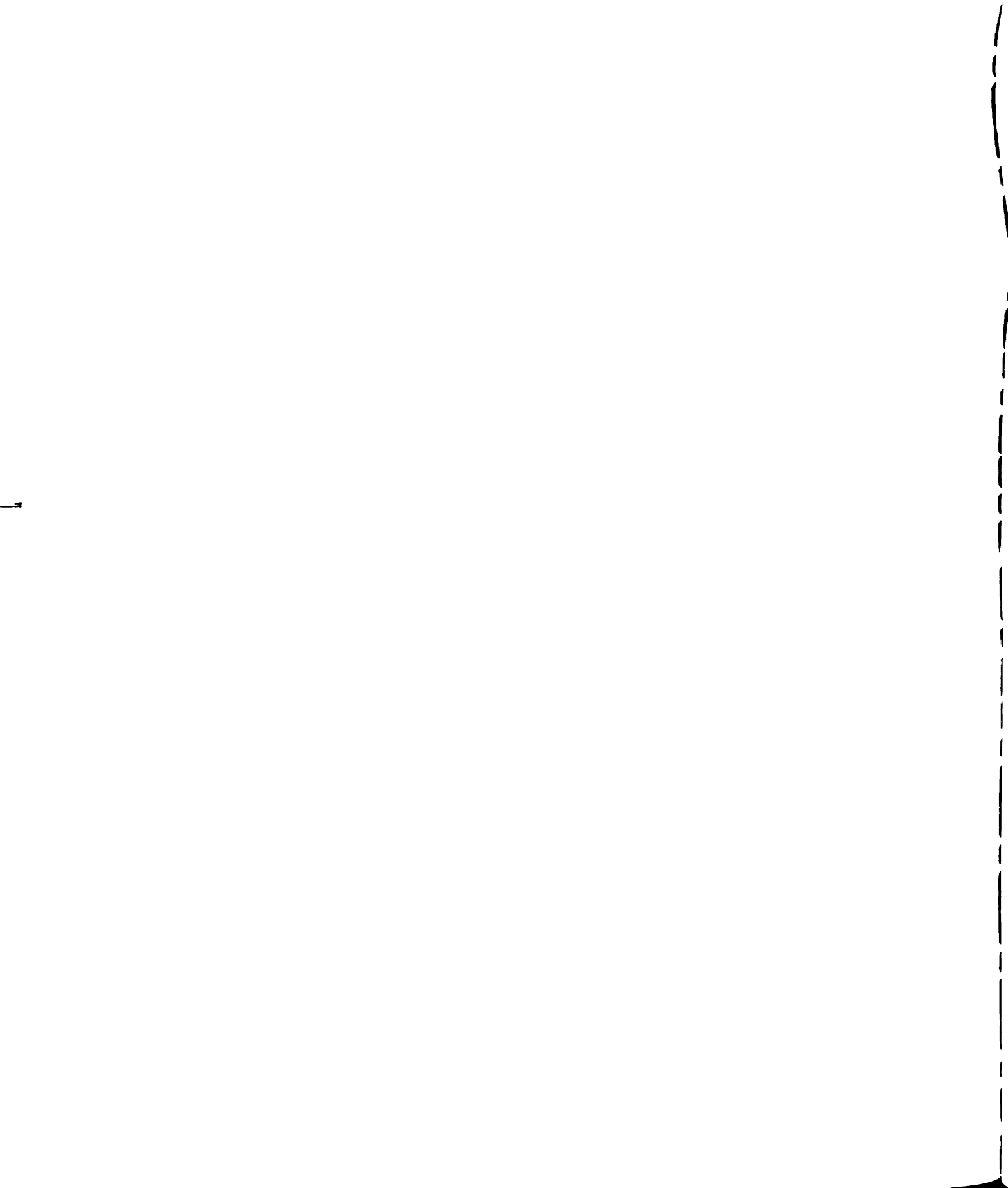


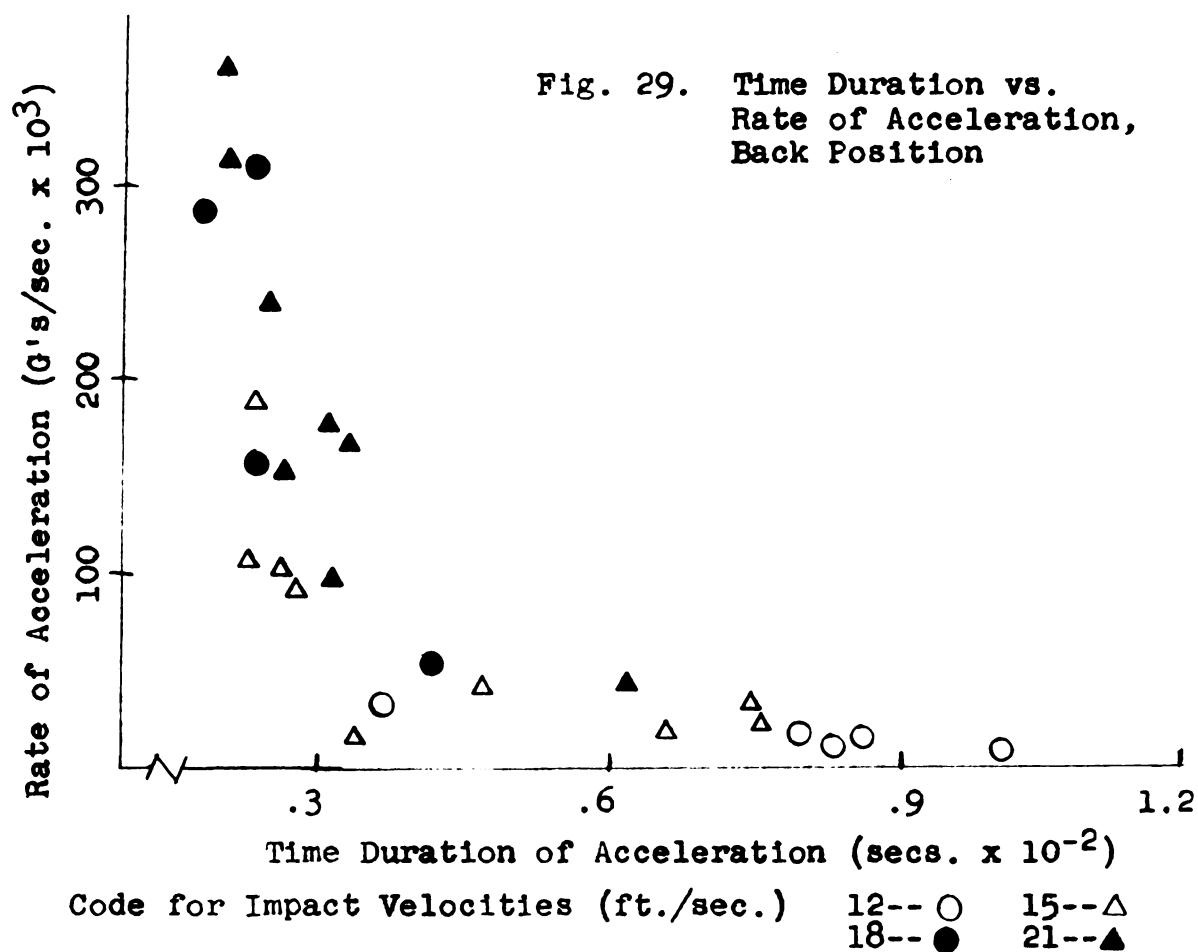
**Fig. 27. Peak Acceleration vs.
Rate of Acceleration,
Top Position**

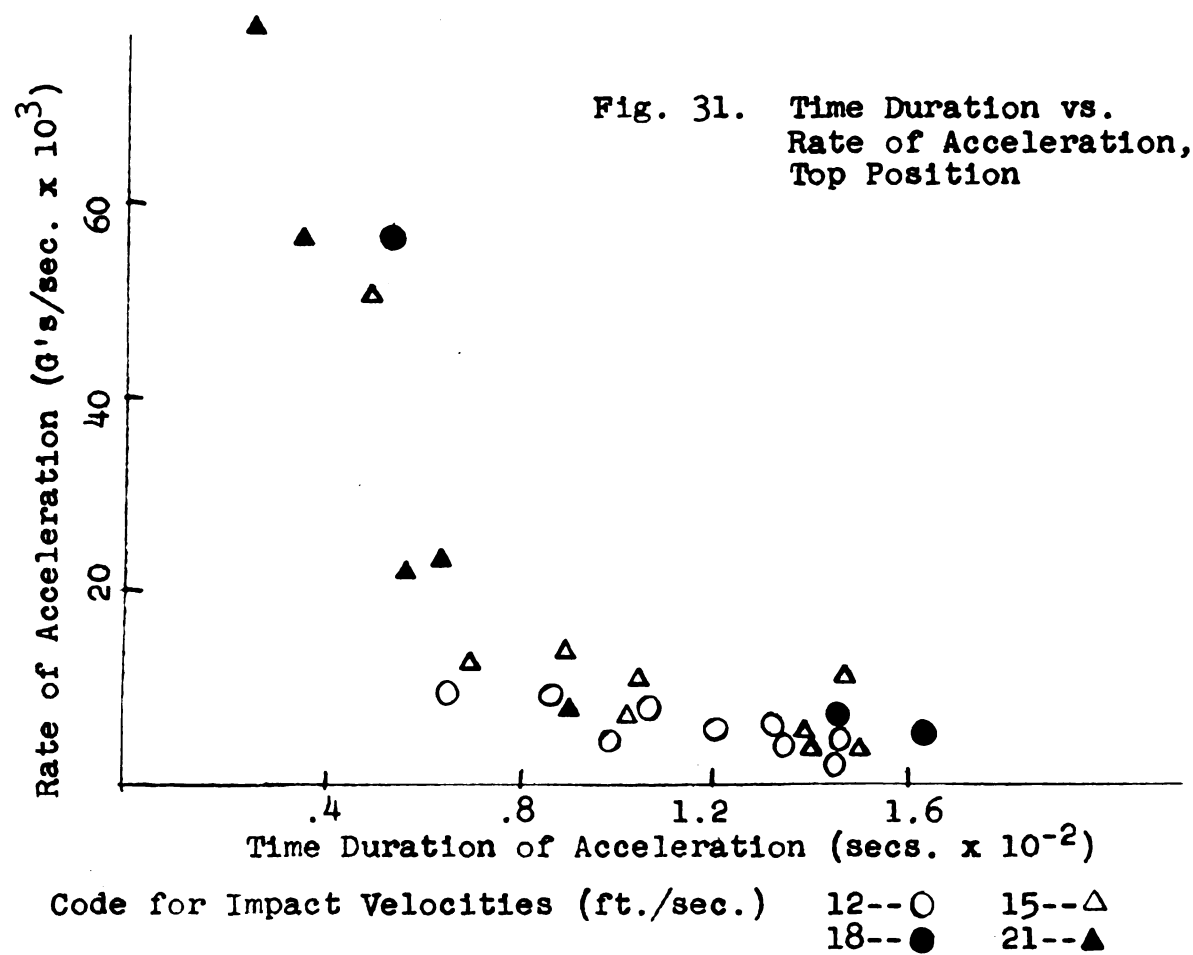
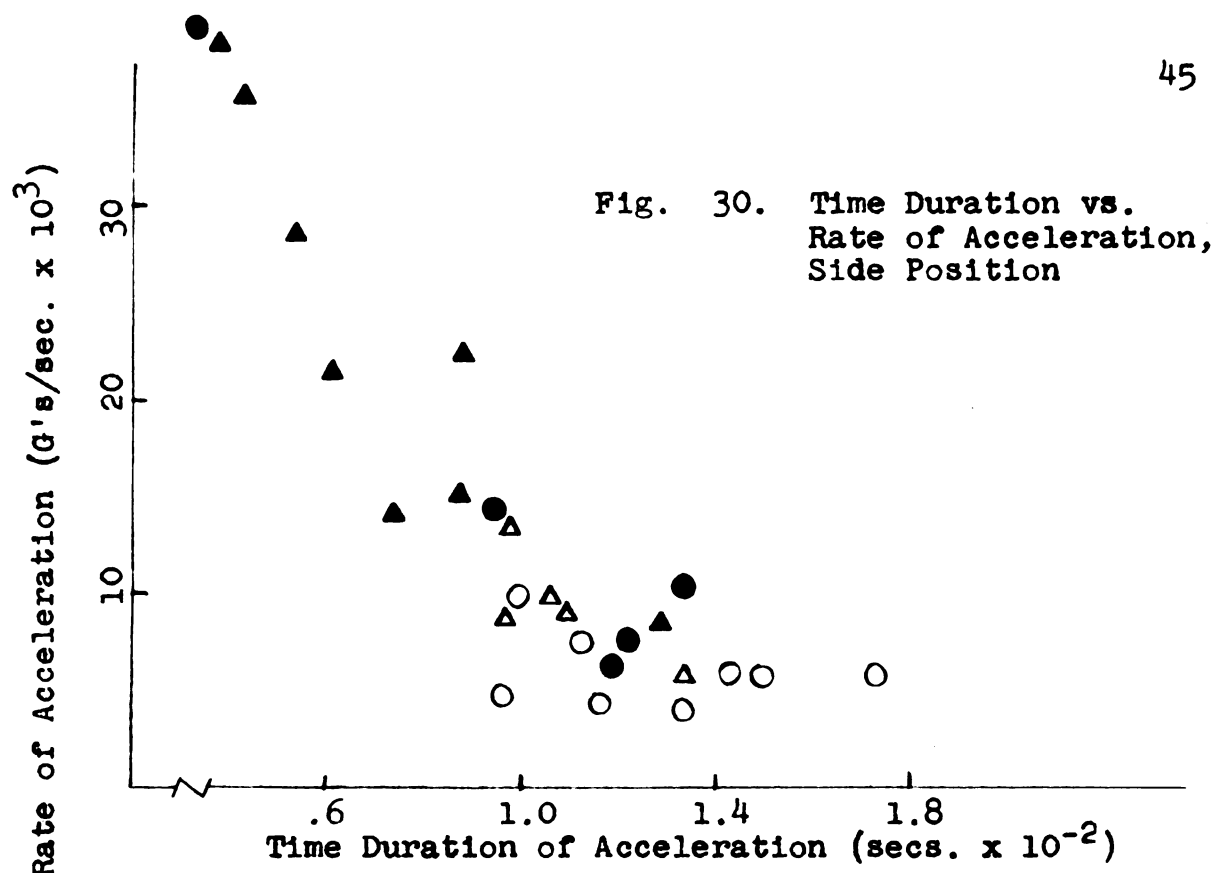


Code for Impact Velocities (ft./sec.)

12-- ○	15-- △
18-- ●	21-- ▲







relatively long time duration. The first is more triangular in shape while the latter tends to be flat and spread out along the time axis. This contention was substantiated by a re-examination of the basic photographic records.

Summary

The results presented in this section may be summarized:

1. The front and back respond similarly. This was also true for the side and top.
2. The strongest positive relationship considering all four positions was peak acceleration vs. rate of acceleration.
3. The strongest negative correlations for all blows occurred with peak acceleration vs. time duration and rate of acceleration vs. time duration.
4. The back and front positions showed a strong correlation between kinetic energy and rate of acceleration and also kinetic energy vs. peak acceleration.
5. The back and front positions showed no clear relationship between kinetic energy and time duration.
6. The top and side showed a strong positive association for each impact velocity for kinetic energy vs. time duration but no clear connection between

kinetic energy and peak acceleration or kinetic energy and rate of acceleration.

7. Peak acceleration, rate of acceleration and kinetic energy all increased with an increase in pendulum velocity.
8. Time duration decreased with an increase in impact velocity.

II. Acceleration vs. Deceleration

Peak

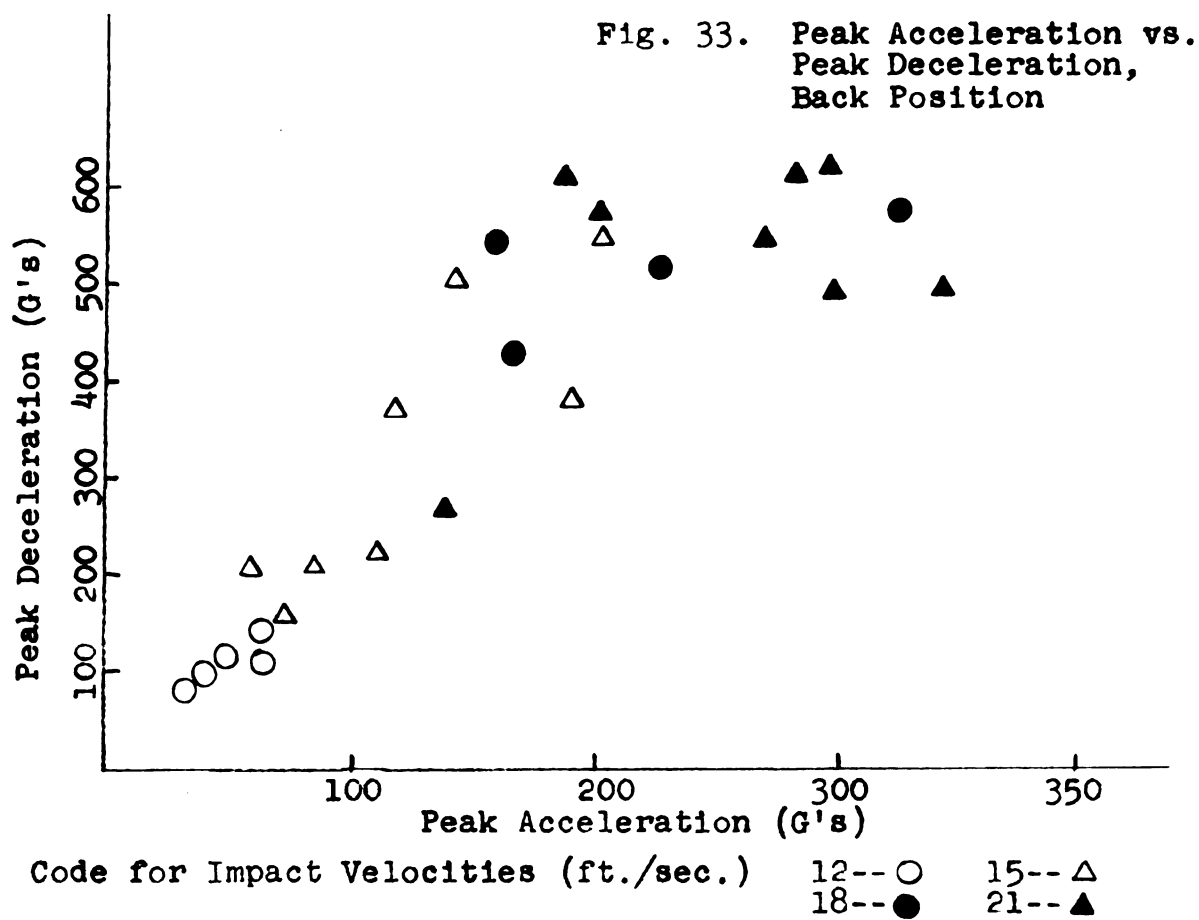
A strong positive relationship was apparent for all positions and at all impact speeds especially for the back and front. The highest impact velocity for the top and side was the most variable. (Figures 32, 33, 34, and 35)

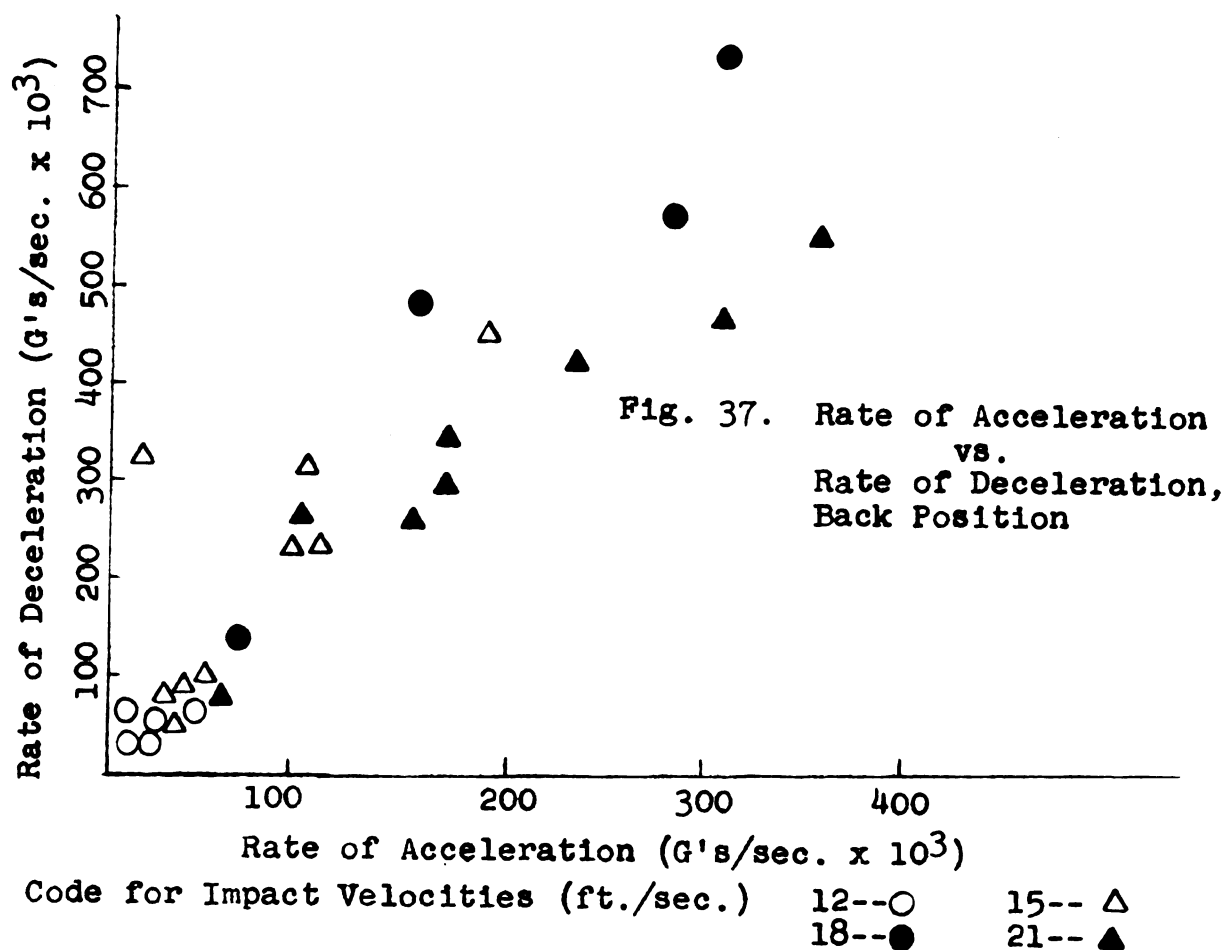
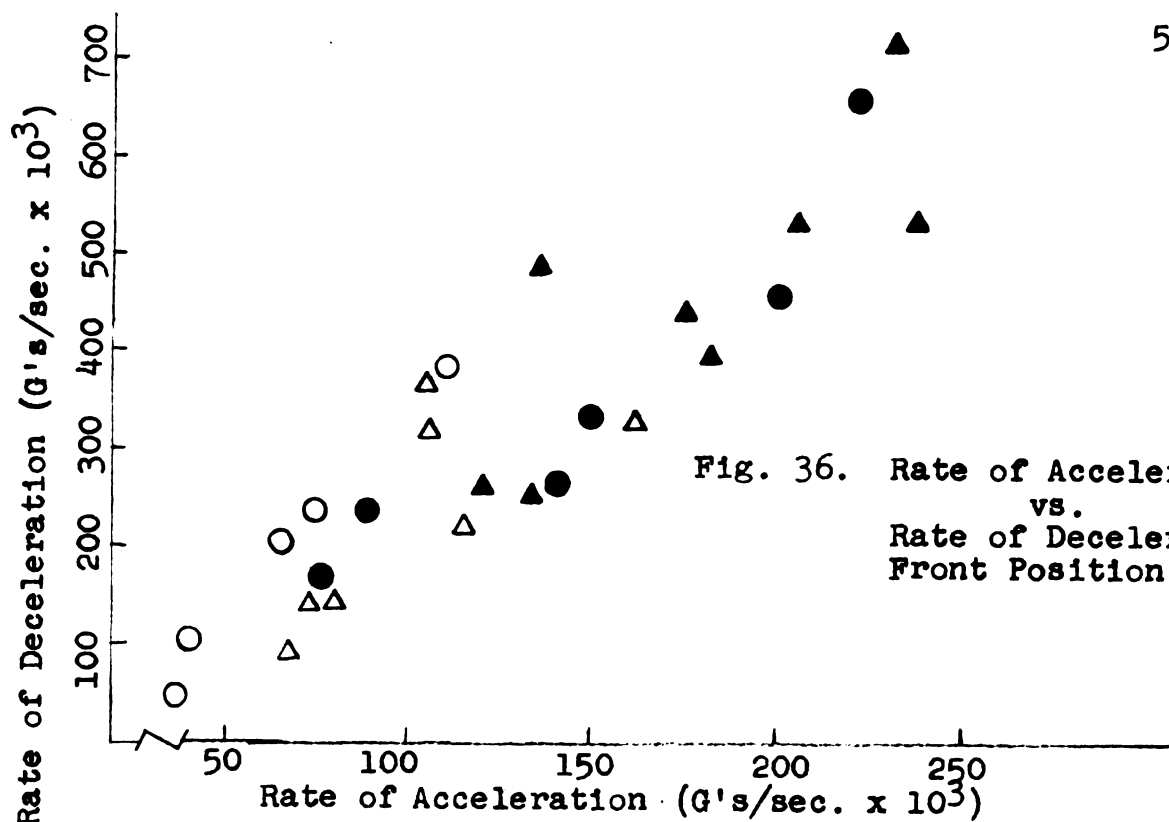
Rate

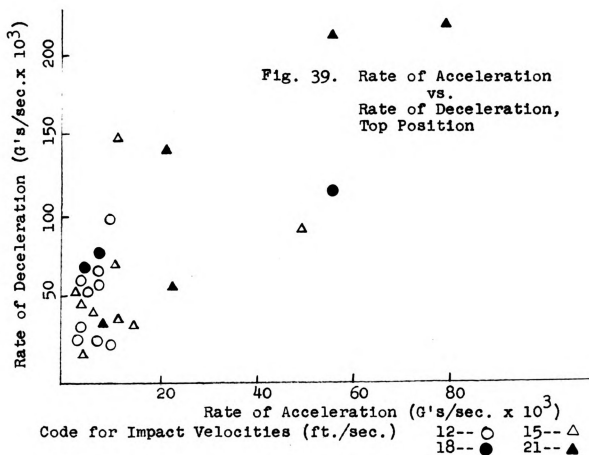
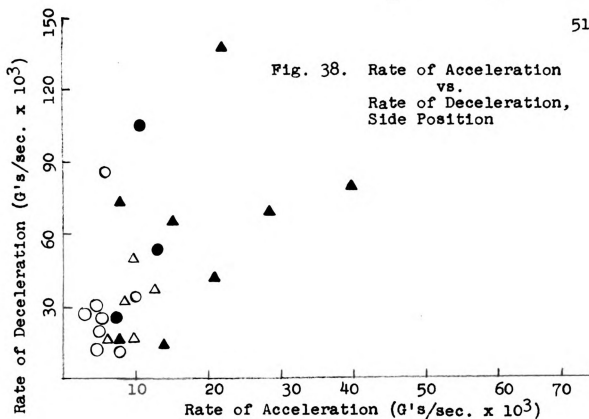
The response for rate of acceleration was similar to that for peak acceleration. The top and side position plots indicate an even less strong association when each impact speed is considered separately. (Figures 36, 37, 38, and 39)

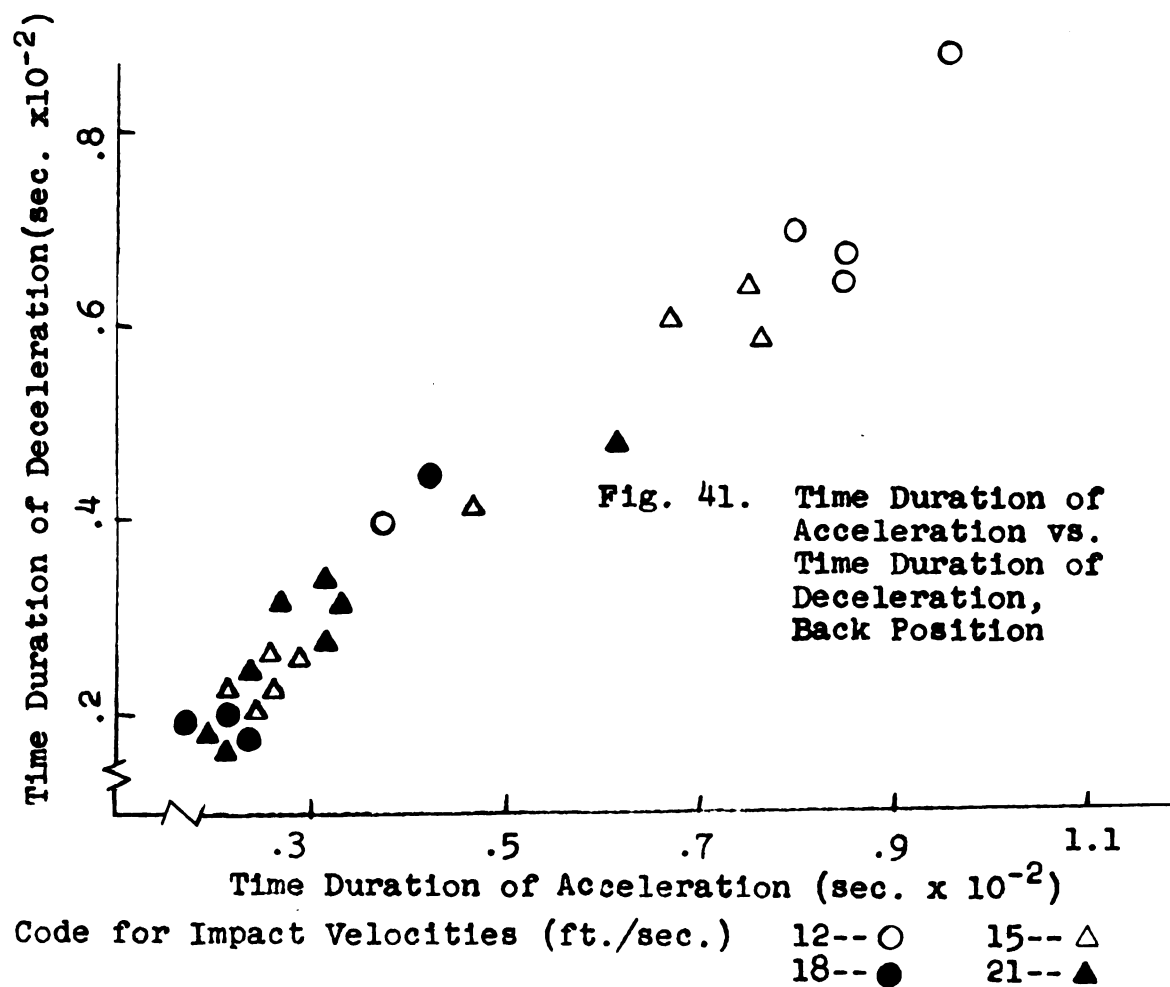
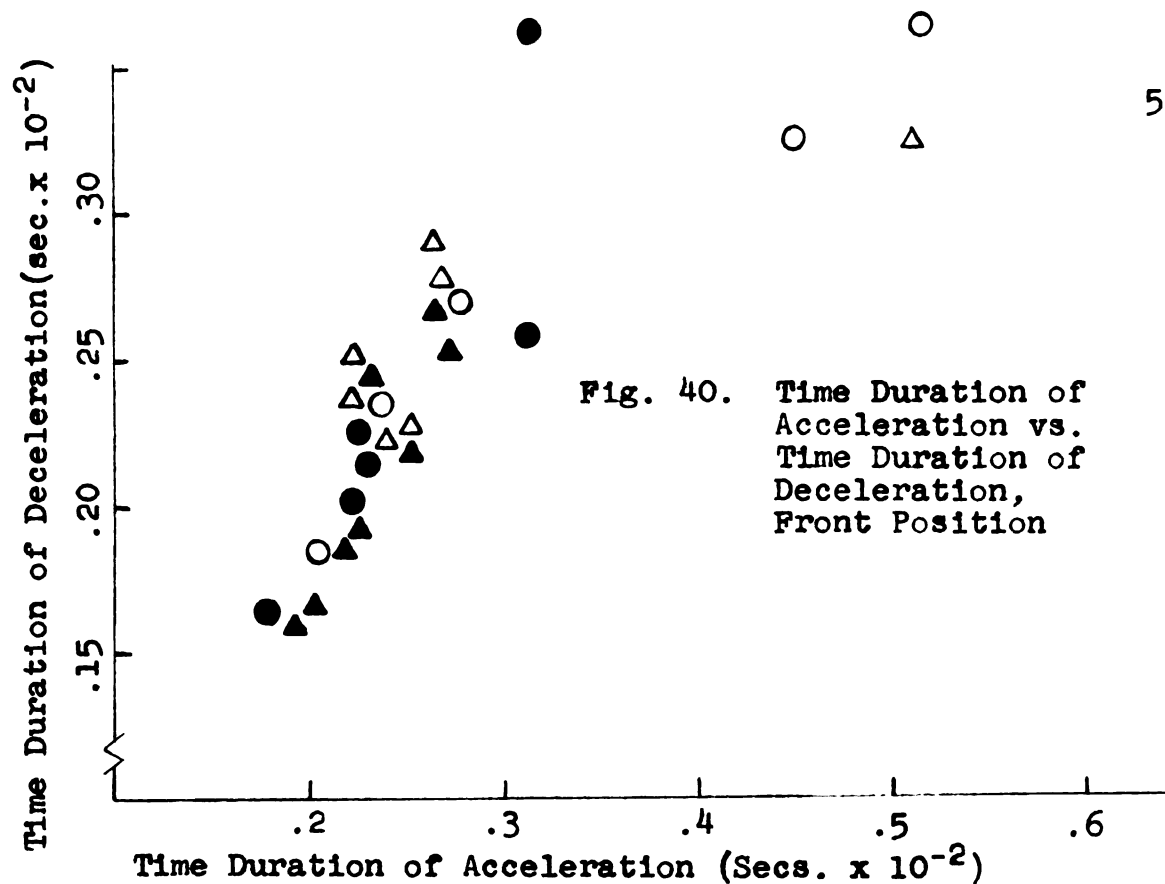
Time Duration

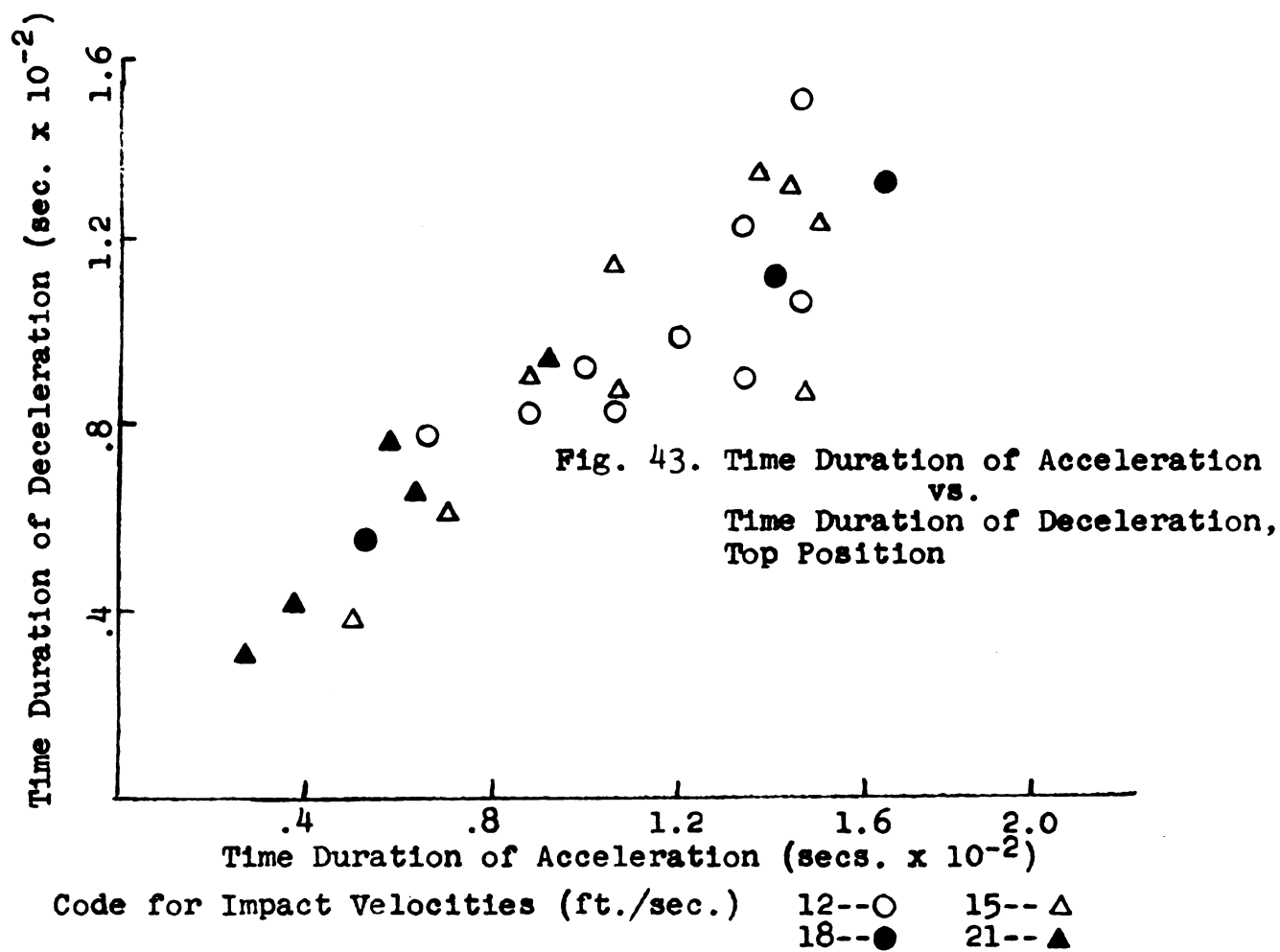
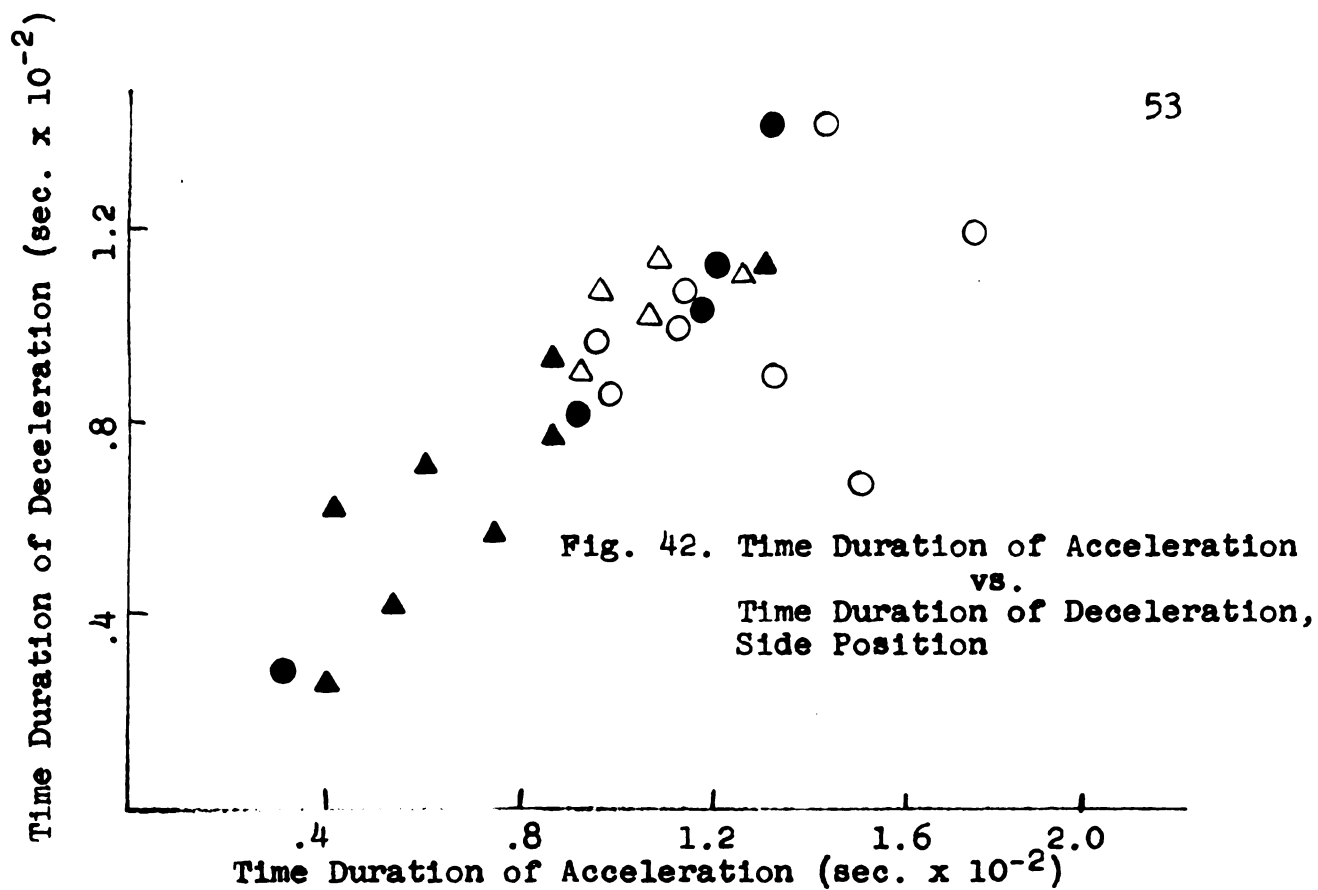
The comparison of time duration of acceleration and deceleration reveals that a strong positive correlation exists. This was true for all positions and pendulum impacts. (Figures 40, 41, 42, and 43)











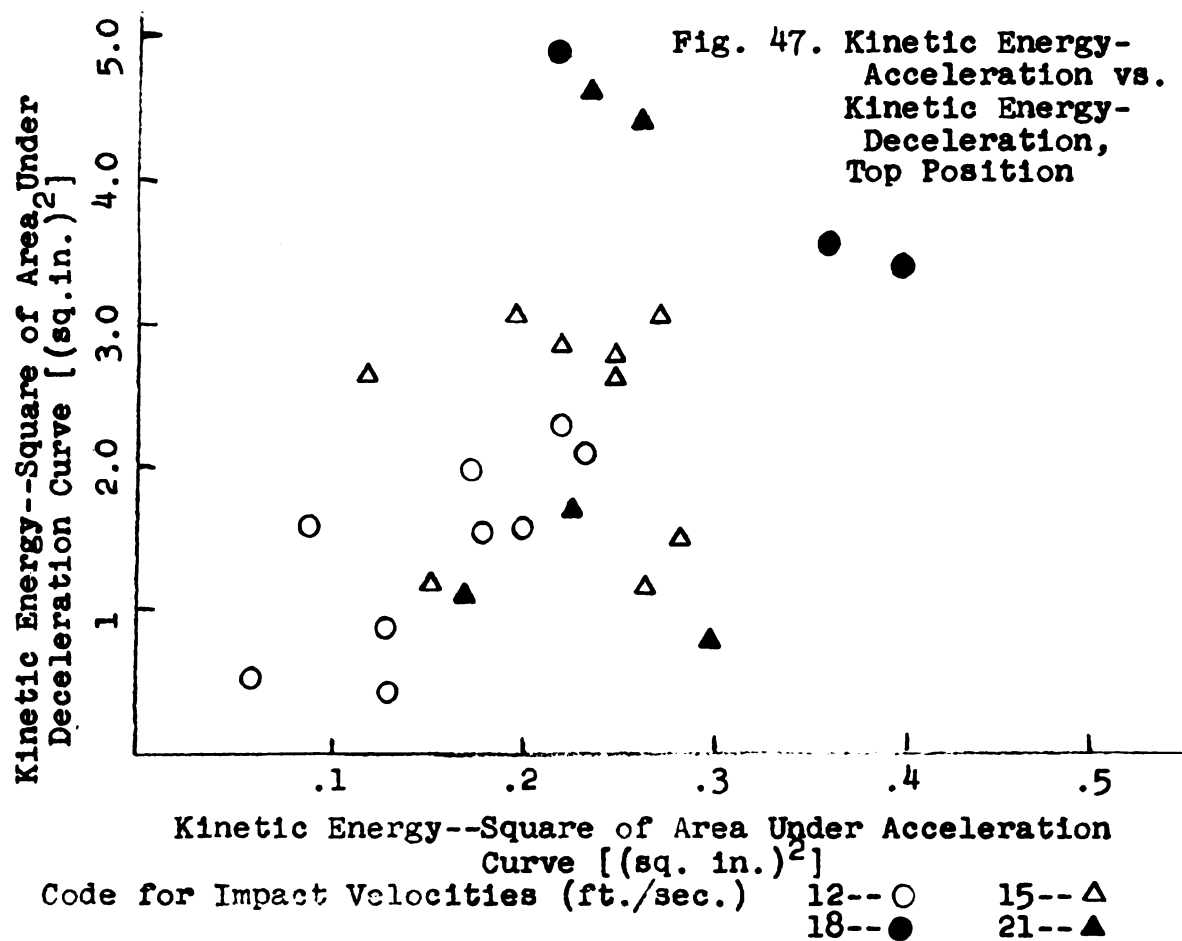
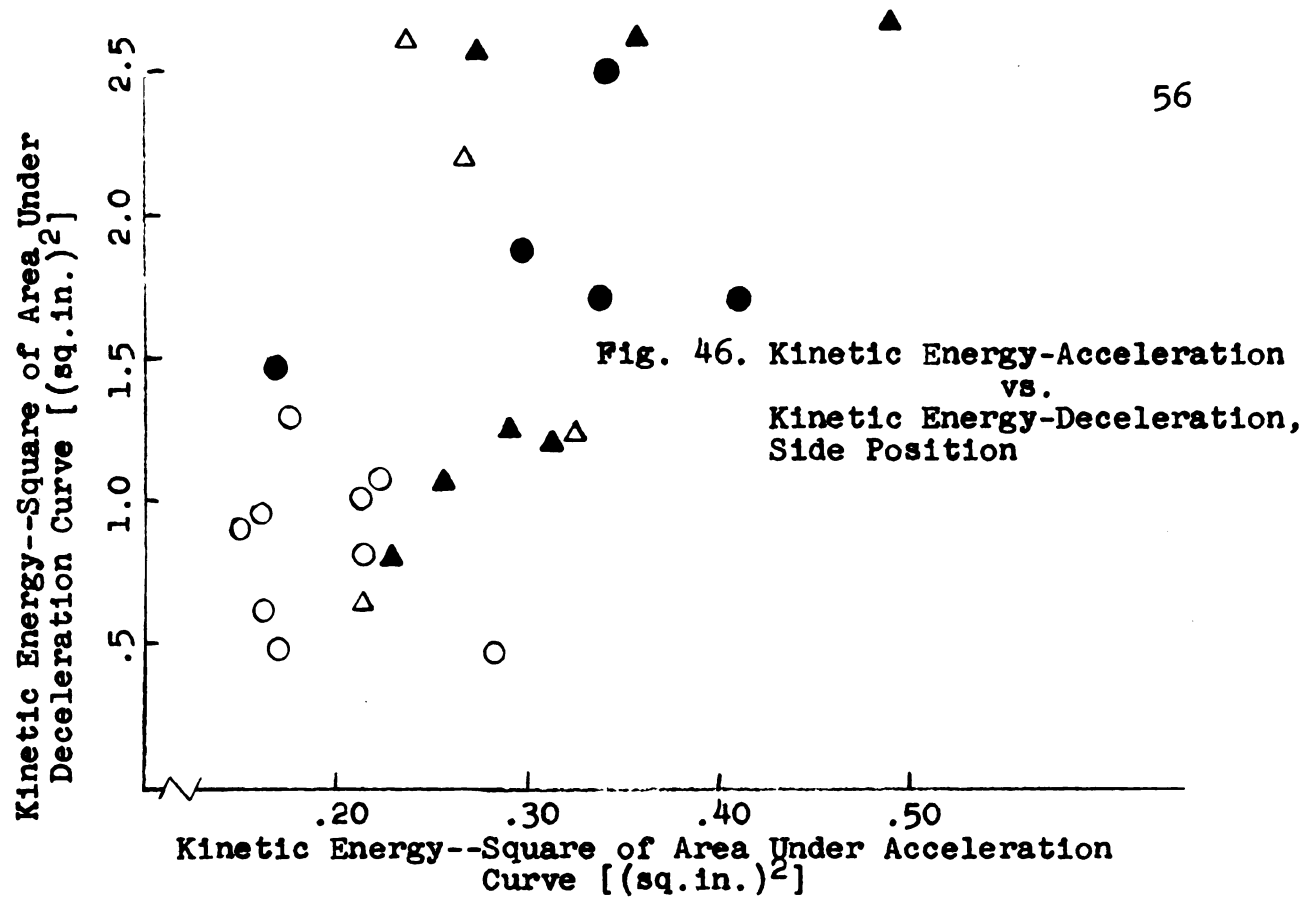
Kinetic Energy

Although the two lowest velocities for all positions showed a slight association, the values for the two highest pendulum speeds were completely dispersed. (Figures 44, 45, 46, and 47)

In his study comparing peak acceleration vs. peak deceleration at 21 feet per second, Edwards (13) found a strong relationship for top and side positions but none for the other two positions. The results of this study show that for the back and front the 21 feet per second values are widely dispersed while for the top and side a strong dependence is present. This essentially agrees with this previous work. It is apparent, though, that rank order correlation coefficients for the back and front on the lower velocities would be considerably higher than that which was reported at 21 feet per second.

Summary of Acceleration vs. Deceleration

1. The strongest positive relationship was for time duration followed by peak acceleration and then rate of acceleration.
2. Kinetic energy showed very low dependence.
3. Since the masses were different, it was not surprising that the peak deceleration, rate of deceleration, and kinetic energy values would be greater than those for acceleration of the head.



4. It was apparent from the data that the deceleration values were more variable than those for acceleration.
5. The over-all results indicate a strong relationship exists between acceleration and deceleration measures.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The objective of this study has been to evaluate and compare certain measures used in the evaluation of football helmets. This has been done by reviewing the existing literature on brain injury and relating these findings to the information secured from the impact testing data.

Thirty-nine football helmets were impacted by a pendulum striker at four velocities (12, 15, 18, and 21 feet/sec.). The helmets, mounted on a wooden head, were struck at four positions; front, back, side, and top. Two accelerometers, one placed on the back of the pendulum and the other inside the wooden head were employed. The output from the accelerometer circuits was fed into a dual trace oscilloscope. A Polaroid camera, mounted on the face of the instrument, was used to record the acceleration-time curves for both acceleration of the head and deceleration of the pendulum striker.

A sample of 104 from the total of 624 blows was chosen. The photographs were projected and plotted on graph paper. Four measures were determined for both acceleration and deceleration: (1) peak or maximum acceleration, (2) rate of change of acceleration, (3) time duration of

acceleration, and (4) kinetic energy.

The interrelationship of these four measures for acceleration of the head was determined from the plots of the six combinations or pairs of measures. The acceleration values were plotted against those for deceleration to determine to what degree they are related.

Conclusions

1. The front and back positions responded similarly. This was also true for the top and side positions. This is probably due to the similarity in construction of the helmets at these positions.
2. Three measures; peak acceleration, rate of acceleration and kinetic energy, increased as the severity of the blow increased. The fourth measure, time duration, decreased.
3. In general, a positive relationship was indicated between acceleration, rate of acceleration, and kinetic energy. These three measures were negatively correlated with time duration of acceleration.
4. Because these relationships exist it is concluded that under these test conditions the measurement of peak acceleration alone is sufficient.
5. The acceleration values were for the most part directly related to the deceleration values.

This was especially true of time duration, peak acceleration, and rate.

6. On the basis of these findings, and the fact that greater importance is usually attached to measurements of the head rather than the pendulum, it is concluded that observing the phenomenon of deceleration of the striker at impact is no longer necessary for this type of helmet testing.

Recommendations

1. Experimental work relating to the magnitude of the acceleration of the head incurred in football games is of primary importance.
2. The evidence indicates that along with acceleration, pressure changes within the head at impact are related to brain injury. An attempt should be made to measure pressure changes and acceleration simultaneously under laboratory conditions to determine to what extent they are related. This necessarily would involve the use of a head form filled with a gelatinous substance to simulate the human brain at impact. Strain gauges could be used to record the pressure at the points desired.
3. The response obtained for acceleration of the head with low velocity impacts should be compared with data on human subjects. This could be done by

securing the accelometer on the subject's head within the helmet to record acceleration at impact.

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APPENDIX A

HELMETS

LETTER CODE, BRAND NAMES, AND WEIGHTS OF HELMETS

Letter Code	Brand Name	Model	Replicate Weights (Grams)		
			1	2	3
A	Riddell	RK-4	829.5	828.8	832.6
B	Wilson	F2104	933.0	911.5	921.4
C	Riddell	TK-5	780.7	783.5	782.8
D	MacGregor	E-700	795.3	793.6	786.7
E	Wilson	F2110	858.5	869.6	865.4
F	MacGregor	E-705	771.1	748.5	761.2
G	Spalding	3122	880.2	870.0	878.9
H	Nokona	WAR	825.8	812.0	826.3
I	Reach	SMBR	845.5	868.2	871.5
J	MacGregor	H612	1004.8	1023.9	1057.7
K	Wilson	F2010	881.2	882.6	852.5
L	Spalding	3131	979.4	971.6	941.7
M	Rawlings	BMR	1117.7	1115.4	1113.9

APPENDIX B

HELMET TEST MEASURES FOR ACCELERATION AND DECELERATION

HELMET TEST MEASURES--BACK POSITION

Helmet Model	Replicate	Impact Velocity	Photo No.	Acceleration			Rate of Accel. G's/sec.
				[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Accel. in G's	
B	1		[327	.325	.376	66.46	33,032
D	1		[335	.274	.851	48.77	14,833
A	2	12	[376	.366	.799	64.00	17,684
L	2		[420	.411	.845	42.54	11,072
C	3		[433	.460	1.005	33.82	9,516
F	1		[341	.396	.760	69.23	23,508
G	1		[345	.178	.232	136.92	104,122
A	2		[374	.335	.469	112.19	38,660
E	2		[390	.341	.237	192.76	15,036
H	2	15	[402	.404	.238	204.73	188,344
D	3		[439	.591	.750	86.55	29,171
J	3		[463	.490	.274	117.24	93,867
K	3		[467	.562	.268	142.76	100,535
M	3		[475	.196	.664	60.97	17,838
C	1		[330	1.646	.420	166.15	53,493
H	1	18	[350	1.069	.180	227.70	284,270
I	2		[407	2.134	.224	325.46	311,445
G	3		[450	.582	.231	159.31	154,370
I	1		[356	1.943	.201	300.78	311,366
K	1		[364	2.434	.205	344.77	360,638
M	1		[372	1.896	.246	271.43	236,437
F	2	21	[395	.667	.615	140.95	42,738
J	2		[409	2.484	.317	297.28	172,436
B	3		[432	2.430	.331	284.55	168,472
E	3		[444	1.595	.270	202.07	152,161
L	3		[472	1.011	.315	188.27	97,802

HELMET TEST MEASURES--BACK POSITION--Continued

Helmet Model	Replicate	Impact Velocity	Photo No.	Deceleration			Rate of Decel. G's/sec.
				[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Decel. in G's	
B	1		327	2.503	.398	149.69	57,862
D	1		335	1.254	.666	114.33	29,758
A	2	12	376	1.132	.697	110.66	35,731
L	2		420	1.732	.656	100.00	52,882
C	3		433	2.011	.967	80.00	27,266
F	1		341	3.893	.588	152.27	46,311
G	1		345	1.210	.231	336.15	239,765
A	2		374	1.572	.413	224.01	79,436
E	2		390	1.406	.216	380.02	325,360
H	2		402	2.853	.220	558.58	452,658
D	3	15	439	2.945	.640	209.29	65,281
J	3		463	4.831	.264	370.72	232,572
K	3		467	6.901	.255	506.44	317,318
M	3		475	2.654	.605	209.29	56,641
C	1		330	8.655	.447	431.64	125,769
H	1		350	5.013	.179	518.70	575,694
I	2	18	407	4.893	.173	575.73	739,063
G	3		450	7.134	.221	545.73	482,094
I	1		356	3.415	.178	491.60	470,431
K	1		364	4.121	.177	495.99	553,560
M	1		372	7.453	.239	547.99	421,531
F	2	21	395	2.839	.478	264.68	75,753
J	2		409	8.550	.276	620.01	341,415
B	3		432	12.489	.317	612.87	297,365
E	3		444	7.918	.316	570.00	261,828
L	3		472	12.731	.332	607.15	267,232

HELMET TEST MEASURES--SIDE POSITION

Helmet Model	Replicate	Impact Velocity	Photo No.	Acceleration			Rate of Accel. G's/sec.
				[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Accel. in G's	
E	1		177	.212	1.162	22.55	4,387
F	1		181	.218	1.427	14.69	5,752
J	1		197	.283	1.735	15.72	5,673
M	1	12	209	.162	.968	20.41	4,916
D	2		228	.169	1.499	13.21	5,988
I	2		252	.150	.986	24.42	9,943
L	2		264	.219	1.338	19.33	3,988
A	3		270	.174	1.120	31.80	7,371
H	1		192	.319	1.274	31.45	5,942
I	1		196	.215	.931	34.07	13,514
B	2	15	219	.236	1.092	25.21	8,921
C	2		223	.265	1.077	35.64	9,560
K	2		259	.162	.978	32.48	8,764
G	1		186	.408	1.220	35.03	7,148
M	1		210	.335	.933	39.72	13,664
H	2	18	245	.339	1.185	31.88	6,533
F	3		292	.292	1.336	25.07	10,117
K	3		312	.167	.321	119.73	67,990
C	1		171	.221	.432	99.86	40,040
G	1		187	.289	.875	34.48	15,788
J	1		199	.314	.543	93.24	28,601
L	1	21	207	.254	.409	104.83	46,488
B	2		218	.296	.748	67.76	14,332
E	2		230	.355	.875	41.75	22,207
A	3		271	.270	.604	102.93	21,236
D	3		283	.487	1.303	41.99	8,238

HELMET TEST MEASURES--SIDE POSITION--Continued

Deceleration						
Helmet Model	Replicate	Impact Velocity	Photo No.	[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Decel. in G's
E	1		[177	1.002	1.068	64.00
F	1		[181	.810	1.413	54.74
J	1		[197	.456	1.189	38.52
M	1	12	[209	.619	.962	57.90
D	2		[228	.482	.669	93.24
I	2		[252	.910	.856	73.10
L	2		[264	1.065	.894	59.86
A	3		[270	1.397	.998	60.85
H	1		[192	1.234	1.117	64.00
I	1		[196	.645	.901	76.84
B	2	15	[219	2.799	1.129	89.38
C	2		[223	2.316	1.020	79.99
K	2		[359	.945	1.077	92.69
G	1		[186	1.728	1.107	65.26
M	1		[210	1.716	.817	96.63
H	2	18	[245	2.637	1.056	94.07
F	3		[292	1.888	1.417	129.70
K	3		[312	1.496	.289	316.38
C	1		[171	.814	.622	171.05
G	1		[187	1.259	.931	64.73
J	1		[199	1.214	.418	203.68
L	1	21	[207	1.090	.262	261.07
B	2		[218	.162	.562	66.76
E	2		[230	2.965	.775	127.59
A	3		[271	2.667	.712	253.34
D	3		[283	2.934	1.108	95.16
						29,892
						26,092
						19,164
						13,286
						86,654
						34,843
						27,271
						14,174
						14,225
						37,013
						17,028
						50,056
						32,557
						15,013
						54,717
						25,019
						105,619
						180,274
						80,494
						66,526
						69,921
						160,658
						14,522
						138,987
						42,076
						74,228

HELMET TEST MEASURES--FRONT POSITION

Helmet Model	Replicate	Impact Velocity	Photo No.	Acceleration			Rate of Accel. G's/sec.
				[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Accel. in G's	
B	1		9	.343	.273	79.64	66,812
I	1		39	.316	.212	103.65	110,619
K	1	12	47	.256	.233	82.09	75,799
E	1		75	.187	.540	68.55	36,041
J	3		146	.196	.451	74.40	38,932
F	1		25	.637	.253	120.00	107,334
L	1		50	.608	.225	125.22	116,810
E	2		74	.230	.514	89.27	49,788
G	2	15	82	.166	.271	101.45	77,443
M	2		106	.608	.267	117.21	79,830
D	3		121	.781	.246	158.00	162,551
H	3		137	.231	.228	132.00	116,197
C	1		15	.252	.320	120.35	76,901
J	1		44	.083	.182	180.00	225,564
G	1	18	81	.223	.230	130.91	140,915
H	2		85	.828	.233	162.73	149,157
A	3		112	.281	.319	131.20	89,434
K	3		152	1.109	.225	194.00	201,245
D	1		16	.397	.272	170.91	137,387
A	2		60	.755	.233	158.18	138,754
F	2		80	1.221	.197	228.18	240,696
M	2	21	108	1.119	.226	181.82	177,558
B	3		115	1.250	.220	202.00	207,179
C	3		119	.887	.268	159.00	122,026
I	3		143	1.828	.256	244.00	184,569
L	3		155	1.250	.200	210.00	233,074

HELMET TEST MEASURES--FRONT POSITION--Continued

Deceleration

Helmet Model	Replicate	Impact Velocity	Photo No.	[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Decel. in G's	Rate of Decel. G's/sec.
B	1		9	4.198	.272	310.48	206,025
I	1		39	3.356	.184	370.45	389,947
K	1	12	47	2.979	.236	292.19	233,006
E	2		75	.399	.385	120.97	48,719
J	3		146	2.650	.328	199.28	106,681
F	1		25	6.205	.226	478.10	379,444
L	1		50	5.448	.236	439.15	320,314
E	2		74	.726	.322	190.32	92,165
G	2	15	82	.755	.277	226.68	143,832
M	2		106	2.654	.288	257.59	148,467
D	3		121	4.217	.222	381.51	328,322
H	3		137	1.447	.250	338.55	222,438
C	1		15	3.893	.388	448.58	168,133
J	1		44	4.028	.163	532.20	664,419
G	1	18	81	.889	.228	288.50	264,194
H	2		85	3.802	.216	380.63	333,010
A	3		112	1.915	.261	360.77	234,571
K	3		152	5.604	.204	463.75	455,511
D	2		16	4.158	.256	611.44	493,495
A	2		60	4.137	.244	357.60	267,264
F	2		80	2.059	.160	339.39	531,959
M	2	21	108	3.056	.193	373.33	439,212
B	3		115	4.884	.190	475.56	535,541
C	3		119	6.452	.272	408.18	265,569
I	3		143	4.951	.223	469.63	396,647
L	3		155	3.686	.162	477.04	714,132

HELMET TEST MEASURES--TOP POSITION

Helmet Model	Replicate	Impact Velocity	Photo No.	Acceleration			Rate of Accel. G's/sec.
				[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Accel. in G's	
M	1		526	.174	1.378	16.79	4,164
C	2		538	.179	1.202	20.07	5,863
D	2		542	.204	1.450	19.52	4,286
G	2		554	.223	1.457	20.69	3,770
J	2	12	566	.092	.999	19.24	4,759
A	3		581	.060	.654	22.16	9,805
E	3		597	.230	1.338	24.57	5,798
H	3		609	.130	.874	30.40	9,053
L	3		625	.131	1.050	18.66	8,022
D	1		491	.268	1.510	20.29	4,158
H	1		507	.197	.901	48.99	14,685
J	1		515	.221	1.059	30.57	7,230
B	2	15	536	.248	1.439	23.17	4,536
G	2		556	.264	1.473	24.69	11,592
M	2		580	.248	1.363	24.00	4,434
A	3		584	.119	.709	29.33	12,702
F	3		604	.283	1.061	34.33	11,282
K	3		624	.155	.491	83.67	50,495
I	1		512	.221	.525	97.43	56,580
E	2	18	545	.402	1.634	32.83	5,776
F	2		549	.368	1.406	34.76	7,726
B	1		481	.262	.901	45.43	8,539
K	1		517	.235	.376	152.86	56,952
I	2	21	563	.168	.268	138.21	80,730
C	3		590	.232	.570	58.33	22,086
L	3		626	.300	.628	87.67	23,901

HELMET TEST MEASURES---TOP POSITION---Continued

Helmet Model	Replicate	Impact Velocity	Photo No.	Deceleration			Rate of Decel. G's/sec.
				[Area(sq.in.)] ²	Time Duration (x10 ⁻² sec.)	Peak Decel. in G's	
M	1		526	1.991	1.237	57.72	22,132
C	2		538	1.615	.975	94.59	53,081
D	2		542	1.615	1.070	78.59	51,299
G	2		554	2.402	1.515	44.94	16,806
J	2	12	566	1.656	.923	60.24	48,620
A	3		581	.543	.782	105.14	92,147
E	3		597	.221	.907	60.80	49,072
H	3		609	.897	.839	74.06	14,750
L	3		625	.393	.825	32.69	16,619
D	1		491	3.045	1.242	83.14	47,508
H	1		507	3.084	.923	137.15	27,674
J	1		515	2.914	1.145	93.43	32,944
B	2	15	536	2.631	1.328	69.18	38,583
G	2		556	1.067	.869	70.35	28,516
M	2		580	2.749	1.353	60.94	12,714
A	3		584	2.704	.615	111.09	142,059
F	3		604	1.445	.883	78.86	64,218
K	3		624	1.339	.385	261.03	85,165
I	1		512	5.755	.559	493.58	107,441
E	2	18	545	3.445	1.332	79.53	53,412
F	2		549	3.553	1.136	96.00	69,015
B	1		481	4.402	.932	165.15	26,131
K	1		517	4.752	.407	597.15	205,418
I	2	21	563	1.252	.301	464.17	213,510
C	3		590	1.756	.769	138.74	134,438
L	3		626	2.816	.648	267.89	48,956

~~NOV 9 1961~~

~~NOV 29 1961~~

~~JUN 6 1962~~

~~SEP 27 1962~~

~~OCT 1 1962~~

~~AUG 7 1963~~

~~AUG 15 1963~~

~~MAY 23 1964~~

~~JUL 29 1966~~