AN EVALUATION OF THIRTEEN BRANDS OF FOOTBALL HELMETS ON THE BASIS OF CERTAIN IMPACT MEASURES

by John Francis Alexander

The purposes of this dissertation were to evaluate 13 brands of football helmets on the bases of three measures resultant from impact, and to analyze the data of each measure with an analysis of variance design. Maximum acceleration, maximum deceleration, and rate of acceleration were the measures used.

The methodology was to impact thirty-nine helmets at four positions with a 4.58 pound flat surfaced metal pendulum at four different velocities. The helmets were fitted onto a 12.2 pound wooden head which was suspended from the ceiling by two steel cables.

Effects of impact were detected by two accelerometers placed within the head and at the back of the pendulum. The output from these accelerometers was fed into a dual trace oscilloscope, photographed, projected, analyzed, and calculated in Gs and Gs per second.

The helmets were ranked according to the lower values for each evaluating measure at each velocity and position. Graphs depicted the mean responses of acceleration, deceleration, and rate of acceleration for all velocities

and positions. All helmets were graphically compared at each position and velocity.

It was concluded that, in general, leather and rubber shelled helmets were inferior to the plastic-type helmets. Helmets with pliable plastic type shells and padded suspension liners were superior to hard brittle shells with canvas suspension liners. The worst position for all but two brands was the back. Helmets vary according to positions tested and velocities used. Inconsistencies in reponse to impact were noted within brands of helmets, particularly at the front and back positions, and at the higher velocities. The consistently best ranking helmets were for: acceleration--Mac-0, Spal-1, and Rawl; deceleration--Rid-5, Rid-4, and Spal-2; and rate of acceleration--Ral, Spal-1, and Wil-211.

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CHAPTER I

THE PROBLEM

The insurance of adequate head protection is extremely important in the selection of football helmets. Although concern has been shown for the improvement of protective helmets in recent years by physicians, physiologists, design engineers, and athletic personnel, nevertheless, a limited amount of research has been undertaken in this vital area of head protection.

This problem is not limited to rigorous body contact athletic endeavors and sports car racing, but pervays into the realms of aviation-medicine, military pursuits, and hazardous civilian occupations. The jet pilot, tank driver, steel worker, and sports car enthusiast are equipped with helmets as a deterrent to injuries of the brain and possible death.

There is a wide range of helmet design available on the market today. Helmet shells vary from flexible rubber-like plastic to stiff phenolic bound fiberglass or steel. Older modeled leather shells are yet available. Suspensions, pads, and webbed straps are but a few of the liner types.

With the advent of the oscilliscope, criteria were developed for measuring responses to inflicted blows. These responses can be arbitrarily categorized into four measures, namely, (1) velocity changes, (2) pressure determination localization and time duration, (3) kinetic energy absorbtion and dissipation, and (4) rate of change of acceleration.

The selection of helmets is based upon a compromise between operational suitability and protective qualities. The pertinent characteristics upon which the purchase of these helmets is based includes comfort, shape, fit, durability, visability, and cost.

Statement of the Problem

The purposes of this study are, as the result of impact, to (1) evaluate various brands of helmets regarding maximum acceleration and rates of acceleration of the wooden head, and maximum deceleration of a striking pendulum; and (2) statistically analyze the differences of each of these evaluating criteria with a three-way analysis of variance. The method used was to strike specific locations on all helmets with a free swinging pendulum at different impact velocities.

Justification of the Study

The use of the helmet in sports is not limited to football, but is evidenced in ice hockey, boxing, bicycling, and baseball. The sole purpose in this transcendental use of the helmet is to provide protection for the head, and in particular for the brain. According to Borgeson:

> The ability of the shell and liner system to cope with forces of impact is indicated by the amount of acceleration transmitted to the head, and acceleration and deceleration are extremely important factors in the mechanics of brain injury. (17, p. 3)

If a blow to the head is of sufficient magnitude concussion may result, the severity of which is seemingly related to the force with which the blow is inflicted, to the rate at which the brain is set in motion, and to the pressure distribution over the brain. The function of the football helmet is protection of the head through a minimization of these effects, as well as prevention of skull fracture.

Among the recommendations of the Twenty-Seventh Annual Survey of Football Fatalities, following the 1958 season, are listed:

1. Helmets that will further protect the (a) front and sides of the head, and (b) top and back of the head.
2. Regular inspection of the player's uniform for (a) head suspension that will not allow the head to come in contact with the helmet shell when struck, and (b) placement of pads to properly protect the internal organs. (1, p. 4)

This survey indicates that seventeen facilities were directly associated with football during the fall of 1958. The average yearly fatality incidence from 1931 to 1958 is 17.5 deaths per year.

The causes of direct fatalities are: (1, p. 11)

Causes	Percentage
Head injury	51.39
Spinal injury	20.86
Abdominal injury	24.73
Not specified	3.02

Further divisions of these causes indicate that the back, right side, and left side are the sites of the head most associated with direct fatalities. (1, p.14)

Figure 1 reveals, for the period 1931 to 1958, a decrease in fatalities due to abdominal injuries, in contrast to an increase due to head and spinal injuries.

Head injuries resulting from impact are not limited to athletic contests. Wahl reports that seventy-five per cent of air crash fatalities result from head injuries. He concluded that head injury is the most frequent single cause of fatality in air craft accidents. (10, p. 8) Rawlins claims forty per cent of all Royal Air Force war time injuries were craniofacial, with fourteen per cent of all fatalities due to head injuries. Rawlins further states that fifty per cent of all motorcycle injuries are those of the head. (12, pp. 8-9)

According to Gross,

> Although most protective helmets currently in use provide reasonable protection from scalp laceration and skull fracture, few are designed to provide adequate protection from brain concussion. The reason for this is that the design and evaluation of protective headgear has not yet been placed on a sound scientific basis. (26, p. 1)

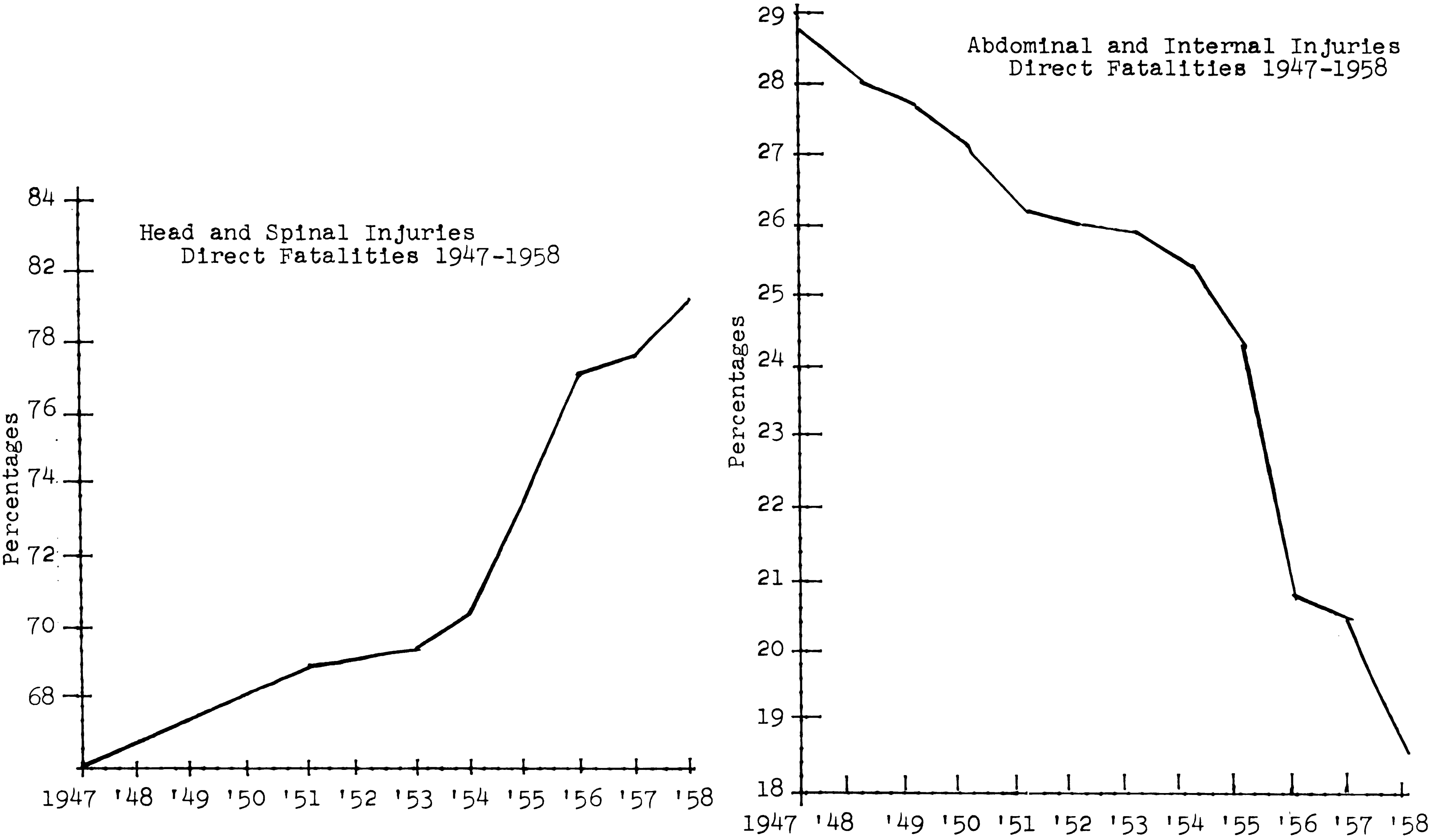

Fig. 1. Yearly Percentage Comparisons of Direct Fatalities from Head and Abdominal Injuries. (Accumulative Averages--based on all fatalities reported yearly since 1931.)

The preponderance of head injuries and football fatalities establishes the urgent need for research to determine the best means of protection for the head.

Limitations of the Study

1. Three criteria were used to evaluate the helmets. Other factors, such as kinetic energy absorbtion and dissipation, pressure development localization, and time duration within the head, merit considerations in relation to concussion.

2. The near solid texture of the wooden head does not closely simulate the human head. Perhaps an aluminum head of standard size and weight, filled with a semi-viscous fluid, would more accurately characterize the responses of the human head to impact.

3. The effects of extreme temperatures on the helmets were not considered in this study.

4. The consistency of the blows, especially those of the higher impact velocities, could not be completely controlled. A very slight motion preceeding or during the release of the pendulum markedly effected the response of the helmet.

5. Angular accelerations were not accounted for in this study.

6. Fatiguing effects of the helmet from a series of impacts were not considered.

7. All blows were inflicted at right angles to the helmet. It is obvious that many other types of impact are subjected to the helmet during a football game. Moreover, the four positions tested are not necessarily those covering the vital areas of the head.

CHAPTER II

REVIEW OF THE LITERATURE

It must be stated initially that there is a paucity of literature directly concerned with the testing of football helmets. With this in mind, considerations must be given to collateral experimental areas of head protection, such as commercial and military research. Since the validity of the three criteria for evaluating helmets is predicated on prior medical experimentation involving concussion, it was deemed best to devote the first part of this chapter to a review of the relation of impact and brain concussion. The second phase is concerned with research related to the testing and design of protective headgear.

Brain Concussion and Impact

Medical literature reveals that contemporary research on head injury began with an analysis of the mechanism by which the skull is fractured. Although, as Wilson indicates, skull fracture per se does not necessarily result in brain concussion, nevertheless it does provide for more clearer understanding of potential brain damage. (33, p. 149)

Gurdjian attempted to determine the amount of energy necessary to produce fracture of the skull in cadaver heads and dried skulls. Firstly, lacquered skulls were dropped a known height onto a slab of known weight, sawed in half and analyzed. The greater cracks were noted along the flatest portions of the skull. Fractures were found to generally initiate on the external surface due to an outbending at a point considerably distant from that of impact. These fracture lines were found to run toward the impact point, and to the opposite direction because of a rebounding action of the skull. Secondly, this dropping technique was used on intact cadaver heads at four positions. The average energies needed for a single line fracture at each position were: frontal midline--571 inch pounds, top midline--710 inch pounds, back midline--517 inch pounds, and sides--615 inch pounds. This is corroborrated by Wahl who, working with the effects of impact on plastic heads filled with liquid, concluded that fracture occurred at approximately 600 inch pounds. (10) Gurdjian concluded that the energy requirement for a single line fracture in cadaver heads was 400 inch pounds in contrast to 40 inch pounds for a dried skull. The authors attribute the difference to the absorbing property of the scalp. It was proposed that a considerable reduction of fatalities would ensue if energy transformation to the human head was kept below 400 inch pounds.

Gurdjian, Webster, and Lissner, (3) in a similar study involving the extent of fracture resulting from the fall of cadaver heads found no correlation between the energy absorbed and the extent of bony damage to the skull.

Again was noted the energy absorbing quality of the skull.

Based on the difference of energy level required to produce fracture in skulls and in cadaver heads because of the absorbing quality of the scalp, it is reasonable to consider helmets which will arrest this impact energy before it reaches the brain.

The association of acceleration and deceleration with head injury was proposed by Gurdjian and Webster.(5) The application of force to the head is accomplished directly where, as the result of impact, the head is set in motion or accelerated, or indirectly, where having struck another object the head is decelerated. A positive correlation is affirmed between the time duration of the acceleration of the brain and the severity of clinical results. Rise in blood pressure, apnea, and loss of corneal reflex were manifest as the result of concussive blows causing acceleration of 250 to 650 Gs. Pressures from concussive blows range from 20 to 100 pounds per square inch.

Cerebral and other body responses to the infliction of head blows have been studied. Acceleration, intracranial pressure and time durations, as well as blood pressure and respiration rates were studied in dogs following hammer administered head blows. The results showed no apparent correlation between severity of concussion and acceleration of the skull. Time duration of intracranial pressure was concluded to be the governing factor in the production of concussion. The acceleration range for concussion was 250-500 Gs.(6)

The effects of pressure applied to the dural sac for varying periods of time was studied in anesthetized dogs. Air pressure was administered by a spring controlled cylinder with intracranial pressure being recorded by a diaphram strain gauge fed to an oscilloscope. Four degrees of concussion were determined. The results showed no concussion with lower pressures except with those of increased time duration. It was concluded that, (1) the longer the duration of pressure the lower the pressure needed to produce concussion, and (2) the shorter the duration of pressure the higher pressure needed for severe concussion.(7)

Research has been done for the armed services regarding physiological responses to forces acting on the human body. It is asserted that uniform high speeds per se do not harm the body because rectilinear motion does not contain the element of force. Accordingly, change of velocity may have deleterious effects on the human body. Two salient points linking acceleration and injury are the magnitude of the force and its time duration.(8)

The effects of acceleration on the blood flow from the heart to the brain were studied. If the hydrostatic pressure developed, as the result of acceleration, is greater than the blood pressure, the circulation is stopped. According to Lombard, nine Gs can be tolerated for two to three seconds in a sitting position, twelve Gs for ten to thirty seconds in the prone position, and fourteen Gs for ten seconds in the supine position.(8, pp. 27-28)

In order to adequately protect the head for military, civilian, and athletic persuits we must first know how much acceleration the human head can tolerate.

Lombard, *et al.*, tried to determine human tolerance levels to impact of the head. Subjects, wearing various football and airforce crash helmets, were administered varying pendulum type blows with all accelerations being determined. Average human tolerance levels were determined to be:

Position	Acceleration--Gs	Rate of Acceleration G Per Second
Top	23	4,800
Front	22	5,600
Side	20	3,500
Back	18	3,700

It was felt by the authors that the psychological effect of being injured precluded the subject from tolerating blows of greater magnitude. Fifty-seven Gs were suggested as a potential tolerance limit to impact.(9)

The mechanics of concussion have been reviewed by Case (29) and Edwards (38), of Michigan State University, so that further discussion is not warranted. However, a brief resume of the salient features might be in order.

Gurdjian defines concussion as, "accute post traumatic state associated with unconsciousness, pallor, and a shock-like state, and is the result of derangement in the function of the brain stem."(22, p. 690)

Gurdjian believes that anoxia is not necessarily the cause of initial unconsciousness, but rather mechanical forces acting on the intracranial contents.(22) He is in agreement with Denny, Brown, and Russell in that portions of the skull and brain may be damaged without resulting concussion. All three state that brain contusion and lacerations may occur without unconsciousness provided the brain stem is not injured.(37)

Gurdjian proposes the following considerations relevant to concussion as the result of impact:(22)

1. Velocity and kinetic energy of a blow govern the amount of deformation of the skull.
2. Pressure level and its time duration correlate with the severity of clinical effects. Pressure levels of 750-5,000 mm. Hg can cause concussion.
3. Acceleration and deceleration are associated with movements of intracranial contents. Contracoup brain injuries are ascribed to mass movements or to cavitation.
4. Concusion is the result of major damage to the brain as the result of its closed cavity dynamics.

An interesting theory on the dynamics of brain concussion has been advanced by Gross who premises his research on the fact that if certain detectable physical phenomena within the head can be ascribed to concussion it may be possible to determine concussion threshold information from impact research with cadavers. The results of this research would then be used as criteria for the testing and evaluation of helmets. (26, p. 1)

Gross's explanation of concussion is based on the assumption of potential traumatic effects due to the violent collapsing of cavities within the brain due to impact (27, p. 21) In a simple hydrodynamic experiment involving impact upon a closed test tube partially filled with liquid, it was discovered that the fluid was accelerated in the opposite direction of the blow by the tensile force of the fluid itself. Should the tensile force, resultant from impact, be greater than the tensile strength of the liquid itself, the fluid will tear apart into gaseous cavities. The appelation given this tearing apart action is "cavitation." The tensile stress developed is greatest as the point opposite the impacted end.(27, p. 3)

In a subsequent experiment involving impactment of a sealed test tube completely filled with fluid, it was concluded that the fluid was accelerated by both pressure from the impacted end and tension from the opposite end of the tube. This contralateral effect is called "contracoup cavitation." It is assumed by the author that the same principles of coup and contracoup cavitation can be applied to the human head following impact.

A limitation to this theory is that brain damage, as the result of coup and contracoup cavitation, is of a focal nature near the surface of the brain. It does not explain contusions found elsewhere in the brain.

A third form is "resonance cavitation." In response to impact of sufficient magnitude to a sealed fluid medium, radial oscillations were initiated as the result of the violent collapsing of coup cavities. The result was cavitation of a dispersed nature.(27, pp. 13-16)

The importance of Gross's research lies in the possibility of determining concussion thresholds applicable as criteria for the future testing of football helmets. A second feature was his practical experimental set-up, which simulated responses of the human head. A third value was a generous chronological listing of literature related to the mechanism of brain concussion and brain injury.

Protective Materials

Research from the fields of aviation medicine and commercial endeavors are herein presented to fully discuss the topic of protective headgear.

Protective head padding may generally be categorized into resilient or non-resilient materials. Resilient or energy storing material have rapid recovery from deformation following impact. Examples are spring steel and rubber. Non-resilient substances are energy dissipating or absorbing materials and, following deformation, are slow to recover. Examples of these materials are polystyrene foam and cellulose acetate foam. The cushioning effect observed by the crushing of a lump of sugar by a hammer blow serves to illustrate an energy dissipation process.

Lombard, *et al.*, considered various approaches toward maximizing energy absorbtion and minimizing acceleration, resultant from impact to the head. Accordingly, the disadvantage of resilient material is that following deflection, as a result of energy storing, it rebounds with considerable force. In contrast it was asserted that non-resilient materials dissipate energy with no subsequent rebound. Foamed or cellular plastic products are listed as satisfactorily tested non-resilient products. Of these latter, cellular cellulose acetate was found to be superior to foamed or cellular plastic because of its deformation resistance to blows of great magnitude.(13) Borgeson, however, points out that the optimal thickness of non-resilient type liners varies according to the material used. Such a variable might pose problems regarding fit, size, comfort, and visibility in designing football helmets. He also states that this type is crushed with heavy impact blows.(17)

Dye lists four essential considerations, in the determination of materials, designed to give head protection against impact:(16, pp. 8-11)

1. Materials of low density such as polystyrene foam, cellulose acetate foam, and sponge rubber.
2. Energy absorbing features as exemplified by ensolite.
3. Resistance to deformation.
4. Enough padding to allow satisfactory distribution of pressure before bottoming.

To evaluate helmets Hendler advocates: (1) high impact velocity, and (2) measurement of the pressure distribution over the head. It is suggested that, by proper helmet design, force can be strategically distributed over the head. Two consideration for determining force distribution are offered: (1) helmets which distribute force to a low uniform pressure, and (2) helmets which distribute force to stronger areas of the skull.(18, pp. 64-70)

Rawlins, of England, lists seven essentials in the design of aviation and commercial crash helmets: (1) protection against penetration, (2) protection against skull deformation, (3) reduction of rotational acceleration of the head, (4) reduction of average linear acceleration of the head, (5) reduction of peak acceleration, (6) absorbtion of kinetic energy, and (7) distribution of impact forces. To accomodate these critera, helmets should be "tough, rigid, smooth surfaced, without projections and with the ability to dissipate the force of impact over the head."(12, p. 721) He advocates that the shell be made of Resin-bonded continuous-filiment nylon as designed by the Royal Aircraft-Establishment for the Royal Air Force. The lining should be made from nylon tape for best impact distribution. Regarding padding within the helmet, polyvinyl chloride is superior to foam polysterene or natural cork for peak force distribution.(12)

The effects of impact on two types of protective helmets were studied by Strand in a technical report for the United States Air Force. The Protection, Incorporated, Toplex Helmet, a stiff shelled helmet with cellular cellulose acetate lining, and the USAF--P1 Helmet, a similarly stiff shelled helmet with webbed suspension, were impacted at two velocities on four positions. Accelerations and decelerations were determined for all velocities and positions. In terms of lower acceleration at both velocities, the P1 helmet was found to react best to blows from the back and worst to blows from the side. The best position of the Toptex was its top with the worst being at the back. Among the recommendations for further study, Strand lists the inclusion of the rate of change of acceleration.(15)

Head injury has been a perplexing problem to sports car enthusiasts. Research has been done by Snively of the Snell Study Plan. Evaluating crash helmets on the basis of one severe impact he concluded that the above mentioned Toptex Helmet with fiberglass shell and non-resilient liner provided the best protection because of its small transmission of impact force to the head. Snively estimates 500 foot pounds as the upper tolerance limit to impact to the head. Accordingly, this is equivalent to the helmet striking a fixed surface at a speed of 34 miles per hour.(11)

It should be understood that Snively's preference for this helmet is based on the helmet giving best protection against a single high energy impact as experienced by the racing driver in a crash. Football helmets, in contrast, are subjected to blows of lower magnitude, but of a repeated nature.

In terms of survivable high energy impact levels, Lombard recommends that, using a one quarter slug pendulum mass with contact velocity of 20 feet per second, the head not exceed accelerations of 250-300 Gs, and the rate of acceleration not exceed 100,000 Gs per second.(Personal correspondance--Lombard)

Dye suggests limits of 60 Gs for acceleration of the head, 20,000 Gs per second for the rate of acceleration, and 400 pounds per square inch as the intensity of pressure sustained in line with the blow. His figures are based on a twenty pound pendulum impacting the helmet at a velocity of 17 feet per second.(34, p. 4)

Edward R. Dye, formerly of the Cornell Aeronautical Laboratory, Incorporated, experimented with the design of football helmets. Believing that helmets offer inadequate protection around the "equator," and are only 1/300th as stiff as the human skull, he proposed to: (1) lessen the kinetic energy transmitted to the wearer by padding, and (2) distribute the force of the blow. Sixteen experimental models were designed and tested by "static" and "dynamic" tests. The general constructional patterns were hard shells of phenolic canvas and fiberglass cloth, beam pads of ensolite, muslin foam, cushion rubber, plastifoam, and suspension liners of webbed belt or "geodetic" cotton. The "beam pad" was a circular disk laterally placed between the shell and suspension liner. The "static" test was administered by the pressure of a hydraulic press on the helmet the results of which were recorded in terms of deformation on an "injury meter." The "dynamic" test was accomplished by the infliction of blows onto the unsupported helmet by a twelve pound striker. Results were determined from fractures to a liquid filled ten pound head within the helmet. Although Dye's work is the first step forward in the testing and design of protective football helmets, nevertheless his computational methods are somewhat unorthodox.(21)

Lombard devides blows to the head received in football into: (1) low energy, and (2) high energy impacts. It is stated that current football helmets provide protection against low energy impacts. He states,

> To improve the protective value of football helmets it follows that protection against the high energy impacts must be provided. To accomplish these two tasks in one helmet is possible by requiring that the helmets have (1) a resilient energy attenuating property for repeated low order energy impacts and (2) an energy absorbing property with the ability to handle high order of energy impact.(36)

Recently football helmet research has been undertaken at Michigan State University.

Case (29) measured peak deceleration of an impacting pendulum on nine different football helmets. Blows were inflicted at six velocities and at four positions on each helmet with the average of five blows at each velocity being considered. Characteristics of the blows were photographed from an oscilloscope by a hand cranked 16 millimeter camera. Among his conclusions were the superiority of plastic to leather shelled helmets, and the optimal combination of a hard plastic shell with a snugly fit canvas suspension in describing an ideal helmet.

Edwards(28) subsequently evaluated nine individual football helmets on the basis of acceleration of the head and deceleration of the pendulum. The experimental design was similar to that of Case with the exceptions of five impacting velocities being used, and oscilloscopic photographs being made by a polaroid camera attachment. The results of his study supported those of Case. Although measurement of acceleration was included, it must be mentioned that two limitations persist, namely, (1) inability to measure both deceleration and acceleration simultaneously because of the single channel osciolliscope, and (2) use of only one helmet of each type.

CHAPTER III

METHODS OF PROCEDURE

Experimental Equipment

The impacting device was a metal pendulum bob weighing 4.58 pounds (.143 slug mass). This was selected to approximate the weight of the knee. The striking surface was flat to provide for uniformity of blows (Fig. 64). The pendulum was suspended from the ceiling by two steel cables which were attached to either side of the bob in order to preserve a constant position throughout its descent. An accelerometer was permanently attached to the back of the pendulum. A protruding core atop the pendulum was inserted into a solenoid switchbox to which was attached a chain which could be hoisted to any height corresponding to a desired impact velocity. The release of the pendulum was controlled by an electro-switch adjacent to the oscilloscope.

The head was made of laminated wood, weighed 12.2 pounds, and was designed to accommodate a size seven and a quarter football helmet. An iron insert, measuring two and one-half by two and one-half by ten inches long and bearing a second accelerometer, was inserted into the center of the head so that the proper axis of the accelerometer was in line with the direction of the blow. The accelerometer could be rotated to respond to blows on any position of the helmet. The combined weight of the wooden head plus the insert and accelerometer was 15.1 pounds.

The head was suspended from the ceiling by two steel cables, each of which could be raised or lowered by turn buckles fastened to the four extremities of the head (Fig. 66). In this manner the precisely desired height and degree of levelness could be had. It was possible to detach and turn the head to accommodate any desired striking position on the helmet. Masking tape was applied to the extremities of the turn buckles to minimize angular motion of the head.

Two Schaevitz, type VG-250, linear variable differential transformers were the accelerometers used (Fig. 64). The opperation of these accelerometers was based on the principle of displacement of the spring supported core, so that voltage differences between the two coils could be portrayed as visual signals on the oscilloscope. The line was operated on 3,000 cycles per second and was controlled by a model 200 CD wide range oscillator which fed into the primary coil of the transformer.

A Hewlitt Packard oscilloscope (Fig. 65) model 150A with dual trace amplifier was used to display the signals from the accelerometers. This oscilloscope can be operated on 115 or 230 volts A.C., and can be used as single trace high grain amplifier or dual trace amplifier. The advantage of the latter is the simultaneous portrayal of signals from both accelerometers making possible the determination of both acceleration and deceleration. Any signal up to a frequency of 10 M.C. per second can be displayed on the oscilloscope. Sweep time can be varied between .1 MSEC and 5 seconds per centimeter. Independently controlled vertical sensitivities are variable from .05 volts to 2 volts per centimeter.

To photograph the signal traces the oscilloscope was set to trigger internally, upon activation of the input signal, so that one sweep per impact was displayed across the grid. The sensitivities and sweep times were set according to the expected deflection as a result of the magnitude of the impact velocity. The complete envelope, depicting maximum deflections and time duration, could, therefore, be studied. Photographs of the deflections on the grid were made by a Beattie-Varitron Polaroid Camera. This was attached over the grid surface, and was equipped with a mirror system enabling the operator to view the face of the oscilloscope prior to and during impact; 400-ASA Polaroid Film was used in the camera. Calibration was accomplished by photographing the signals displayed as a result of the difference in position of the linear variable differential transformer turning from the null position to one where its axis was maximally effected by the forces of gravity, and back through the null position to the opposite axis. This difference is equivalent to two Gs. Sweep time and vertical sensitivity for this callibration were set at 5 seconds per centimeter and .05 volts per centimeter, respectively. The equivalence to one G in millimeters was determined for each sensitivity setting for both deceleration and acceleration. Calibration was done prior to each testing session.

For optimal operational efficiency two technicians were required. The operation of the oscilloscope, camera, and pendulum release switch were controlled by the first technician. Manipulation of the helmets and change of intended impact velocities were done by the second.

All photographs were individually projected on a flat surface by a Beseler Van Lyfe II projector. This projector was meticulously placed four feet from, and at right angles to, the projection surface. It had been determined that this position produced the clearest image, with an absolute minimum of optical distortion. The exact position of the projected picture was marked on the projection surface with masking tape, as were the positions of the legs of the projector on the floor. This permanent tape on the wall, framing the projected picture, insured that all photographs were in the exact same centermost position in the projector. These projected figures were traced onto graphing paper (twenty squares to oneinch). Measurements of the figures were made in millimeters with sliding Vernier calipers.

Calculations

Determination of the G level was done by measuring the highest deflection on either side of the base line, subtracting out the base line, and dividing by two. This residual, representing the increase in voltage due to the impact, when divided by the appropriately calibrated sensitivity factor, resulted in Gs.

A smooth curve was drawn through the extremities of all deflections on the graph paper. Rate of acceleration was calculated from the point of initial rise from the base line to the peak of the curve. Knowing the indicated sweep time and the distance from the initial rise to the peak it was possible to determine the time elapsing between these two points. Maximum acceleration divided by the time required to reach the maximum was construed to be the rate of acceleration.

Observance of the projected tracings indicated that a few of the envelopes were blank at the side corresponding to the beginning of the sweep on the oscilloscope. In these cases the most uniform portion of the slope was considered. This condition prevailed irregularly at the lowest impact velocity of twelve feet per second.

Experimental Design

Thirteen brands of football helmets were struck by a free swinging pendulum at impact velocities of 12, 15, 18, and 21 feet per second (Fig. 67). These represent the football helmets most currently in use by high school, college, and professional teams. There were three helmets of each brand which were labeled one through three for identification purposes. Each helmet was tested at four positions: front, side, back, and top. The infliction of blows was at right angles to the position being tested. Each position on all 39 helmets was struck once at each of the four impact velocities. Oscilloscopic responses of the head and pendulum to impact were analyzed according to the previously discussed method.

The shells ranged from stiff, rigid, non-penetrating surfaces, through pliable materials, to leather (Fig. 2). Cotton suspensions, padded suspensions, webbed straps, and geodetic suspensions represent the liners used in this study. Liner materials were composed of resilient and non-resilient materials. Ancillary information concerning the helmets was secured from a questionnaire sheet forwarded to the manufacturers (Appendix A). All but one manufacturer responded to this questionnaire.

A three-way layout design was set up to include thirteen brands of helmets, three replicates of each brand, four impacting velocities, and four helmet positions. This design was applied individually to the measures of acceleration, deceleration, and rates of acceleration. A three-way analysis of variance was performed on each impact measure. The variances due to the three main effects of brands, positions, and velocities were statistically analyzed with F ratios, as were the interactions of brand and position, brand and velocity, position and velocity, and the triple interaction of brand and position and velocity.

Helmet	Code	Shell Composition	Shell Thickness in Inches	Liner Type	Liner Material	Wt.	Attachment Mat. of Liner to Shell
Riddel RK-4*	Rid-4	Kralite	.136	Suspension	Web	1.83#	Stitching & metal rivets
Wilson F2104	Wil-210	Etholite	.146	Pad	Ensolite Latex foam	2.03#	Cotton stitching, metal snaps
Riddell TK5*	Rid-5	Kralite	.136	Suspension	Web	1.73#	Stitching & metal rivets
MacGregor E700	Mac-0	Duralite	.188	Pad-Geodetic	Bedford Vinyl	1.75#	Nylon Stitch. metal rivets
Wilson F2110	Wil-211	Etholite	.140	Suspension	Cotton	1.91#	Metal rivets
MacGregor E705	Mac-5	Duralite	.188	Pad-suspen. geodetic	Bedford Vinyl	1.68#	Nylon stitch. metal rivets
Spalding 3122	Spal-2	Cycoloc	.161	Suspension	Web	1.93#	Metal snaps & screws
Nokona	NoK	Vulcanized Rubber Leather	.090	Web strap Pad	Vinyl-aire	1.82#	Cotton stitch. metal rivets
Reach-SMBR	Rea	Sponge Rubber Leather	.370	Suspension	Vinyl sheep skin	1.91#	Cotton stitch

Figure 2. Supplementary Information on Helmet Brands

Figure 2--Continued

Helmet	Code	Shell Composition	Shell Thickness in Inches	Liner Type	Liner Material	Wt.	Attachment Mat. of Liner to Shell
MacGregor H612	MAC-2	Leather Fiber	.200	Pad	Bedford Vinyl	2.25#	Nylon stitch. metal rivets
Wilson F2010**	WIL-201	Rubber & Plastic	.120	Pad	Ensolite Latex foam	1.94#	Cotton stitch. metal snaps
Spalding 3131	Spal-1	Cycoloc	.145	Pad Suspension	Ensolite	2.14#	Linen stitch. snaps-rivets
Rawling HCR	Rawl	Cycoloc	.145	Pad	Ensolite air foam	2.48#	Metal snaps metal screws

Notes: *Data furnished by author.
**Manufacture discontinued.

Any bias from fatiguing effects of the helmets was minimized by randomizing the striking order of the velocities across helmet brands and positions.

The order of impact, by positions, was (1) front, (2) side, (3) back, and (4) top. The striking order for helmet brands was the same across positions, so that a particular replicate number was hit at four randomized velocities across all brands for a position. The procedure was to test a given replicate of all brands at all velocities for a given position in one testing session.

The helmets were ranked in order of efficiency as determined by the lowest value of the evaluating measure in question. For purpose of rating a brand of helmet, the mean of its three replicates was considered for a given position and velocity. This was done at each velocity and position for all three evaluating measures.

Graphs were plotted to show: (1) the average deceleration, acceleration, and rate of acceleration compositively for all velocities and positions; and (2) the individual responses of the three replicates of all brands at each position and velocity for all three evaluating measures.

CHAPTER IV

RESULTS

Based on thirteen brands, four positions, four velocities, three replicates, and 624 determinations, the allocation of degrees of freedom were: Total--623, Brands--12, Positions--3, Velocities--3, Brand x Velocity--36, Brand x Position--36, Position x Velocity--9, Brand x Position x Velocity--108, Within Position--8, and Error--408. Because an attempt was made to keep the calibration effect constant throughout each replicate involving a given position and all brands and velocities, two degrees of freedom were apportioned for each position, or eight for all positions for the within position variance.

The variance due to replication was found significant at the one per cent level for all three evaluating measures (Acceleration, $F = 15.17$, Deceleration $F = 35.29$, Rate of Acceleration $F = 5.93$). Analysis of the contribution, by position, to this variance for the three measures showed that, for deceleration the front position contributed more than all other positions combined (Table 7, Appendix B), and for acceleration (Table 8, Appendix B), and rates of acceleration (Table 9, Appendix B), the back position contributed more than all other positions combined.

Results of the three way analysis of variance are shown for each measure in Tables 1, 2, and 3. With 408 degrees of freedom in the error term a very low F ratio was required for significance. F ratios for all sources were significant for the three impact measures.

TABLE 1

ANALYSIS OF VARIANCE OF DATA FOR MAXIMUM ACCELERATION

Source of Variation	D.F.	Sums of Squares	Mean Square	F	F.95	F.99
Total	623	3,333,576.81				
Brands	12	227,620.25	18,968.35	49.57	1.78	2.23
Position	3	1,417,485.11	472,495.03	1234.76	2.62	3.83
Velocity	3	882,191.79	294,063.93	768.47	2.62	3.83
Brand x • Velocity	36	90,710.69	2,519.74	6.58	1.45	1.69
Brand x Position	36	116,364.86	3,232.36	8.45	1.45	1.69
Position x Velocity	9	202,748.57	22,527.62	58.87	1.90	2.46
Brand x Position x Velocity	108	193,883.29	1,795.22	4.69	1.28	1.42
Within Position	8	46,448.38	5,806.05	15.17	1.96	2.54
Error	408	156,123.87	382.66			

TABLE 2

ANALYSIS OF VARIANCE OF DATA FOR MAXIMUM DECELERATION

Source of Variation	D.F.	Sums of Squares	Mean Square	F	F.95	F.99
Total	623	18,788,713.30				
Brands	12	1,443,538.42	120,294.87	50.23	1.78	2.23
Position	3	7,222,281.72	2,407,427.24	1005.30	2.62	3.83
Velocity	3	4,531,996.21	1,510,665.40	630.83	2.62	3.83
Brand x Velocity	36	513,408.86	14,261.36	5.96	1.45	1.69
Brand x Position	36	1,523,729.71	42,325.83	17.67	1.45	1.69
Position x Velocity	9	721,569.90	80,174.43	33.48	1.90	2.46
Brand x Position x Velocity	108	1,179,033.06	10,916.97	4.56	1.28	1.42
Within Position	8	676,104.59	84,513.07	35.29	1.96	2.54
Error	408	977,050.83	2,394.73			

TABLE 3

ANALYSIS OF VARIANCE OF DATA FOR RATE OF ACCELERATION

Source of Variation	D.F.	Sums of Squares	Mean Square	F	F.95	F.99
Brands	623	382,588,179				
Types	12	31,297,468	2,608,122.33	31.04	1.78	2.23
Position	3	131,002,960	43,667,653.00	519.62	2.62	3.83
Velocity	3	84,192,425	28,064,141.60	333.95	2.62	3.83
Brand x Velocity	36	13,970,519	388,069.97	4.62	1.45	1.69
Brand x Position	36	41,299,050	1,147,195.83	13.65	1.45	1.69
Position x Velocity	9	30,324,942	3,369,438.00	40.09	1.90	2.46
Brand x Position x Velocity	108	12,229,847	113,239.32	1.35	1.28	1.42
Within Position	8	3,983,749	497,968.62	5.93	1.96	2.54
Error	408	34,287,219	84,037.30			

Note: Data coded with division of each determination by one hundred.

It was felt that part of the within variance could have been attributed to experimental fluctuations. An adjustment was, therefore, made on the values within each position based on a percentage above and below the mid replicate total for each position (Tables 7, 8, and 9, Appendix B). All graphical representation were made on the basis of these adjustments. These adjustments were not applied to the values used in the three analyses of variance.

Figures 3 through 15 are graphs comparing the means of the three evaluating measurements across all velocities and positions.

The similarity of response between acceleration and rate of acceleration was evident throughout most helmet brands. Decelerations were consistently higher than the accelerations. This is reasonable because of the greater mass of the head compared to that of the pendulum.

The front and back positions appear to be inferior to the side and top positions for all three measurements. The wider distance between the shell and liner at the side and tops in most of the helmets may partially explain this difference. For all three measures at 21 feet per second the back is the worst position for all brands except for helmets Mac-0 and Mac-5. The front is the worst position at all velocities for all three measures of evaluation with helmets Mac-0 and Mac-5.

It was of interest to note the lower deceleration values at impact velocity of twenty-one feet per second, compared to those at eighteen feet per second. Observed in the front and back positions, this was noted in helmets

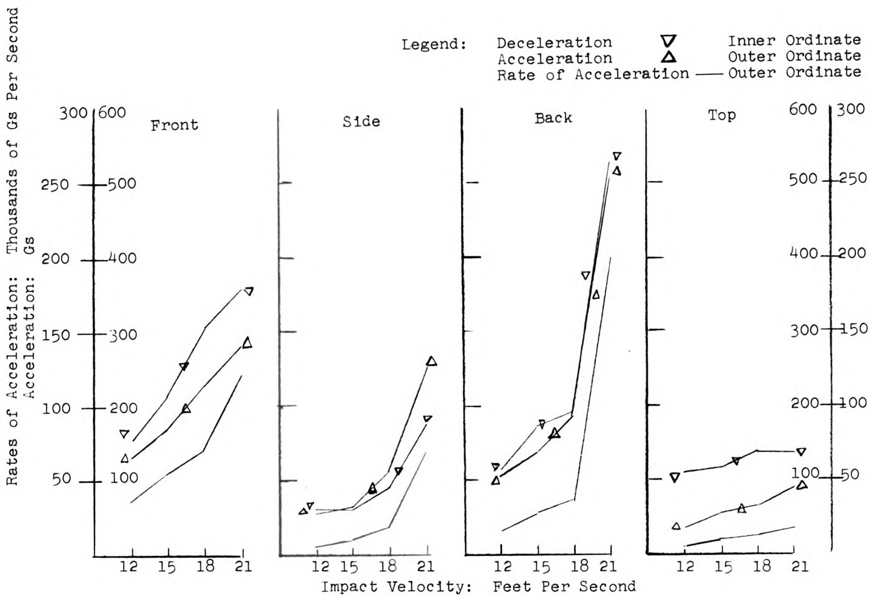

Fig. 3. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Rid-4.

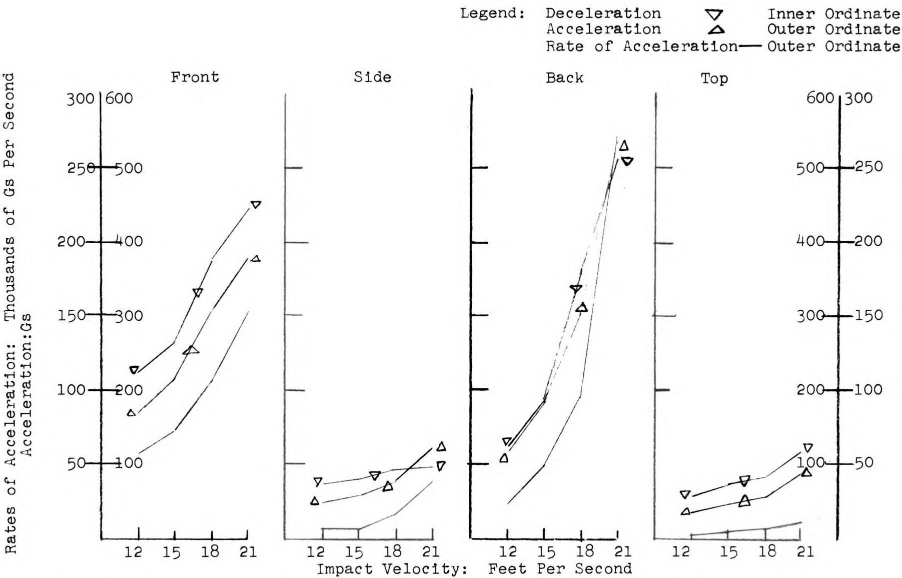

Fig. 4. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet W11-210.

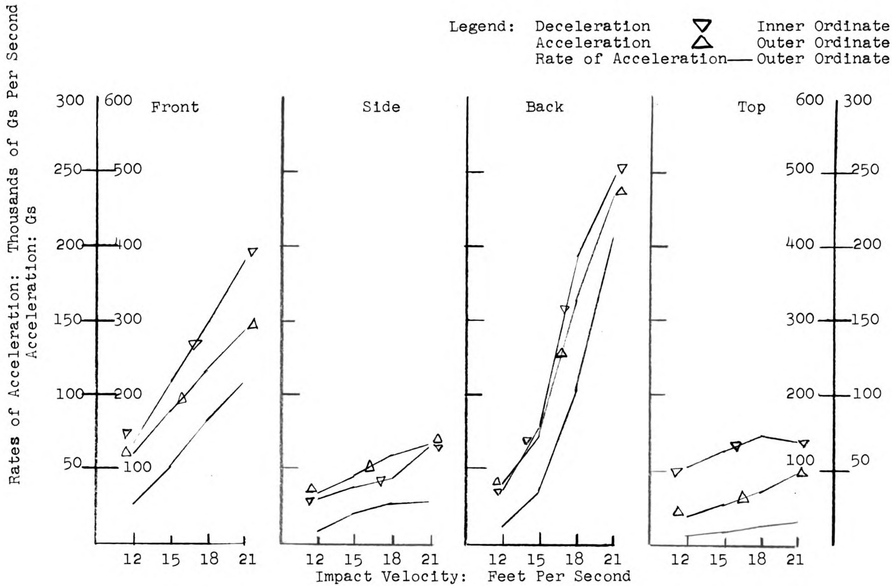

Fig. 5. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Rid-5.

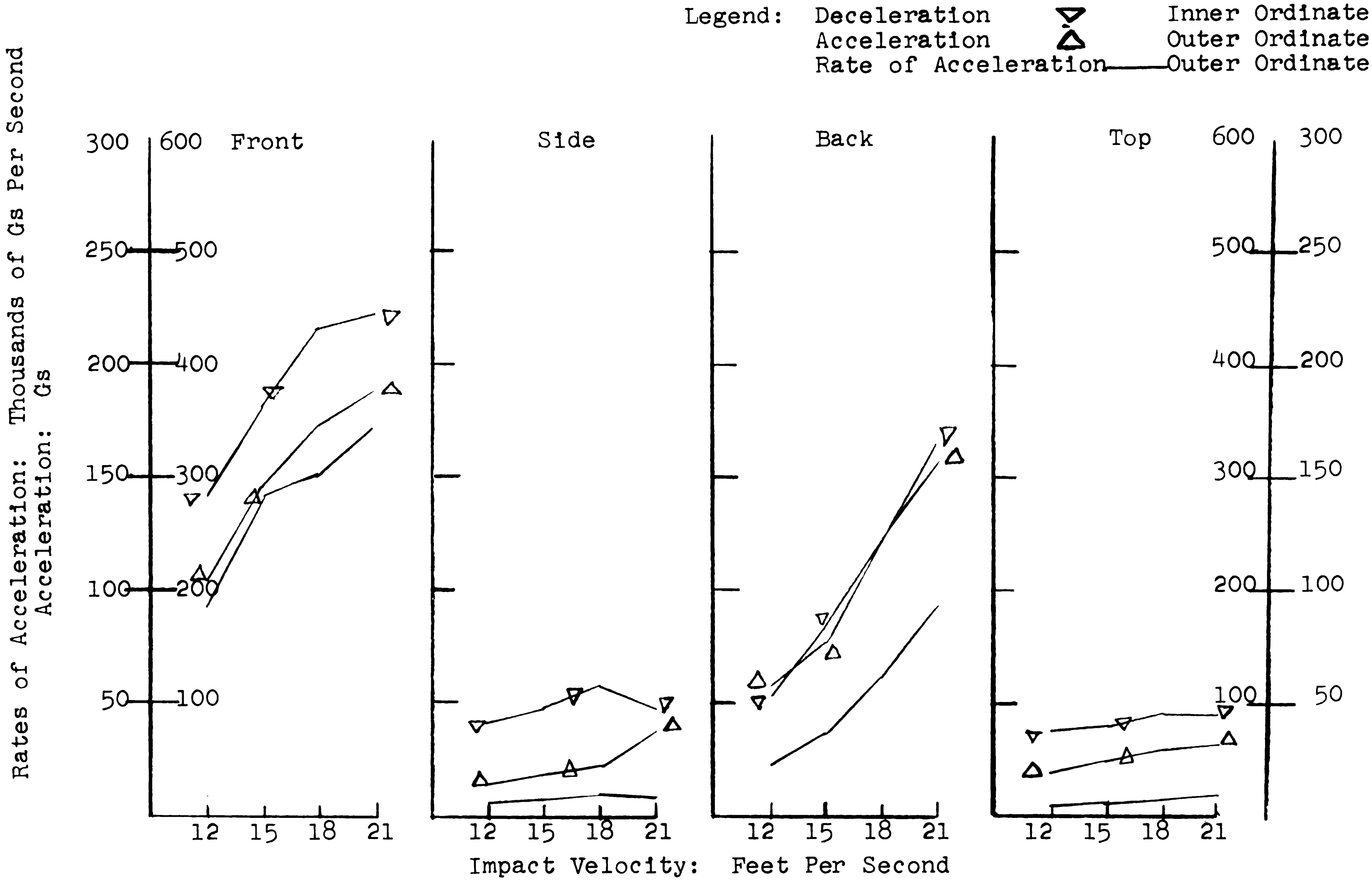

Fig. 6. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Mac-O.

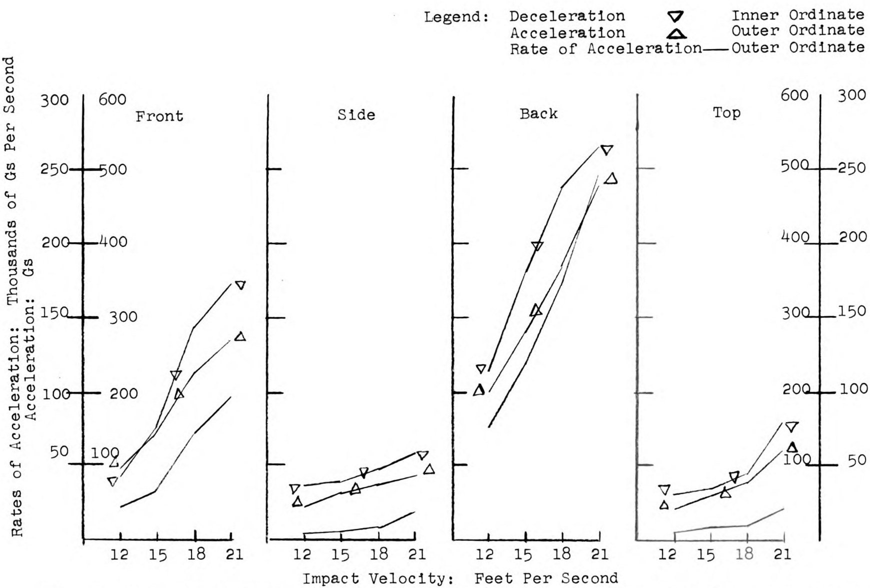

Fig. 7. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet W11-211.

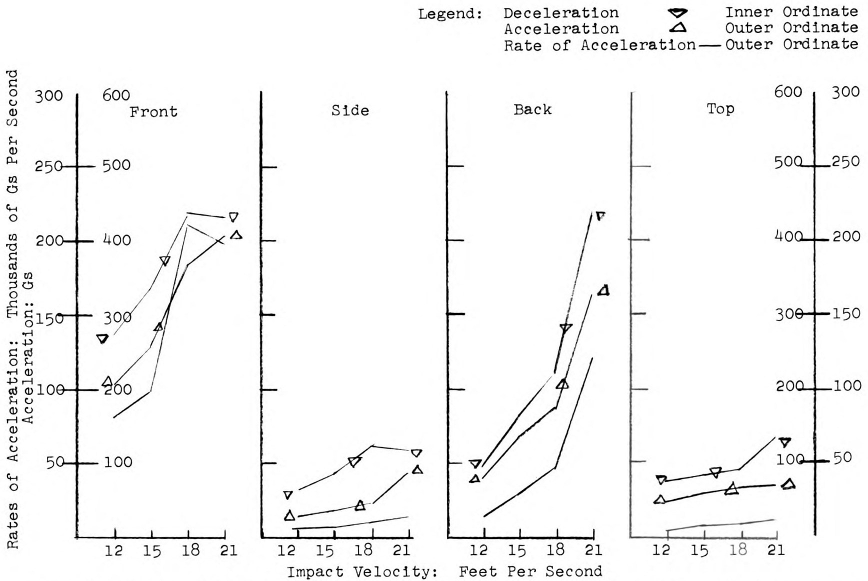

Fig. 8. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Mac-5.

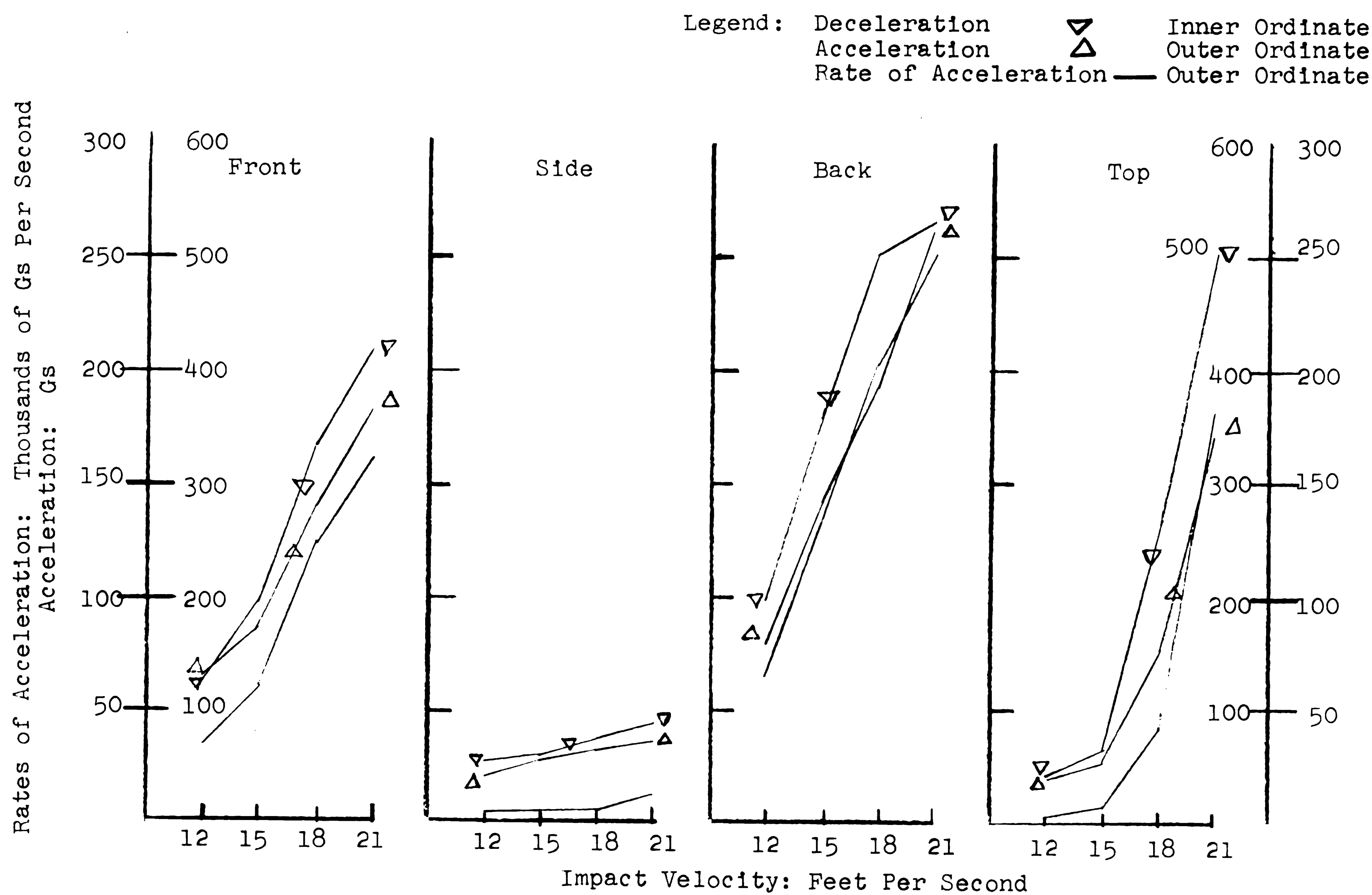

Fig. 9. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Spal-2.

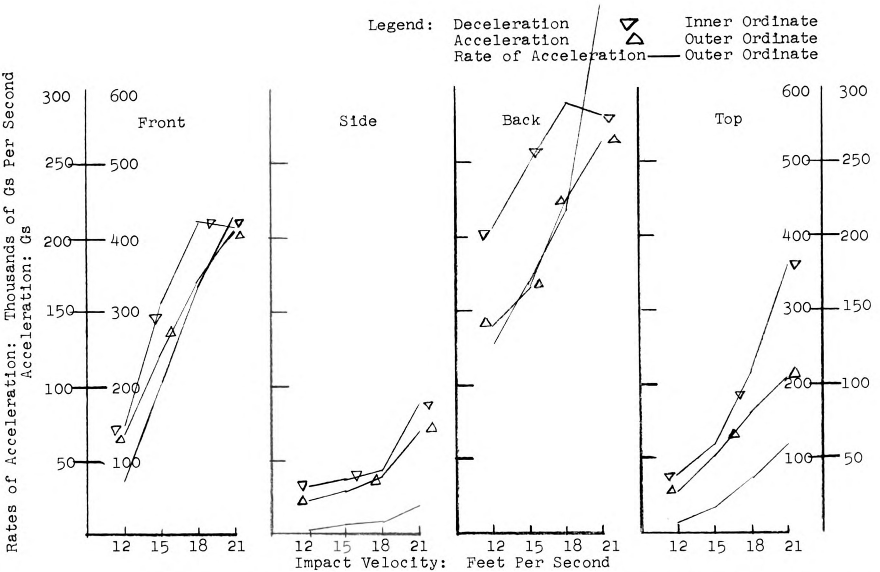

Fig. 10. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Nok.

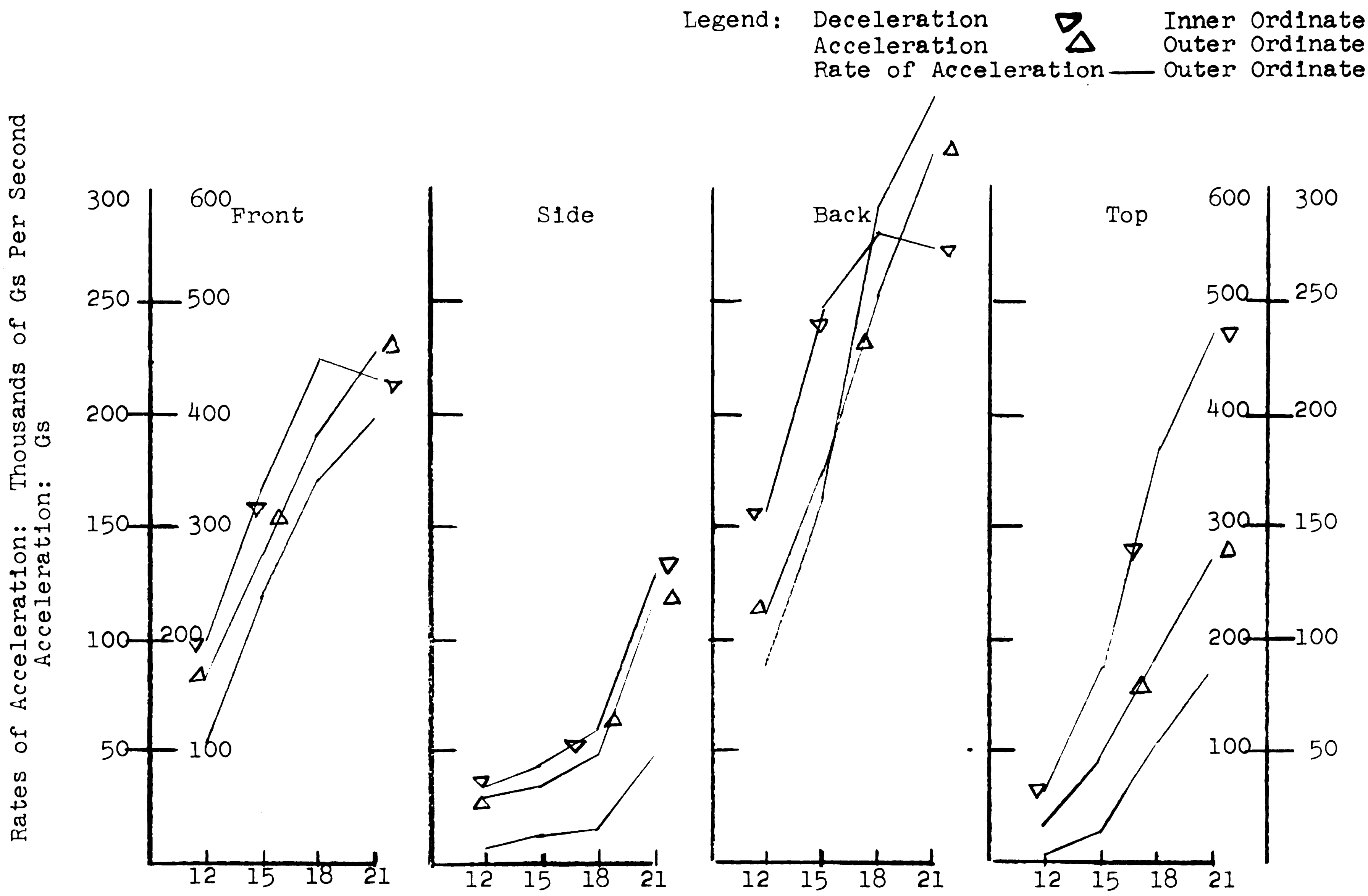

Fig. 11. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Rea.

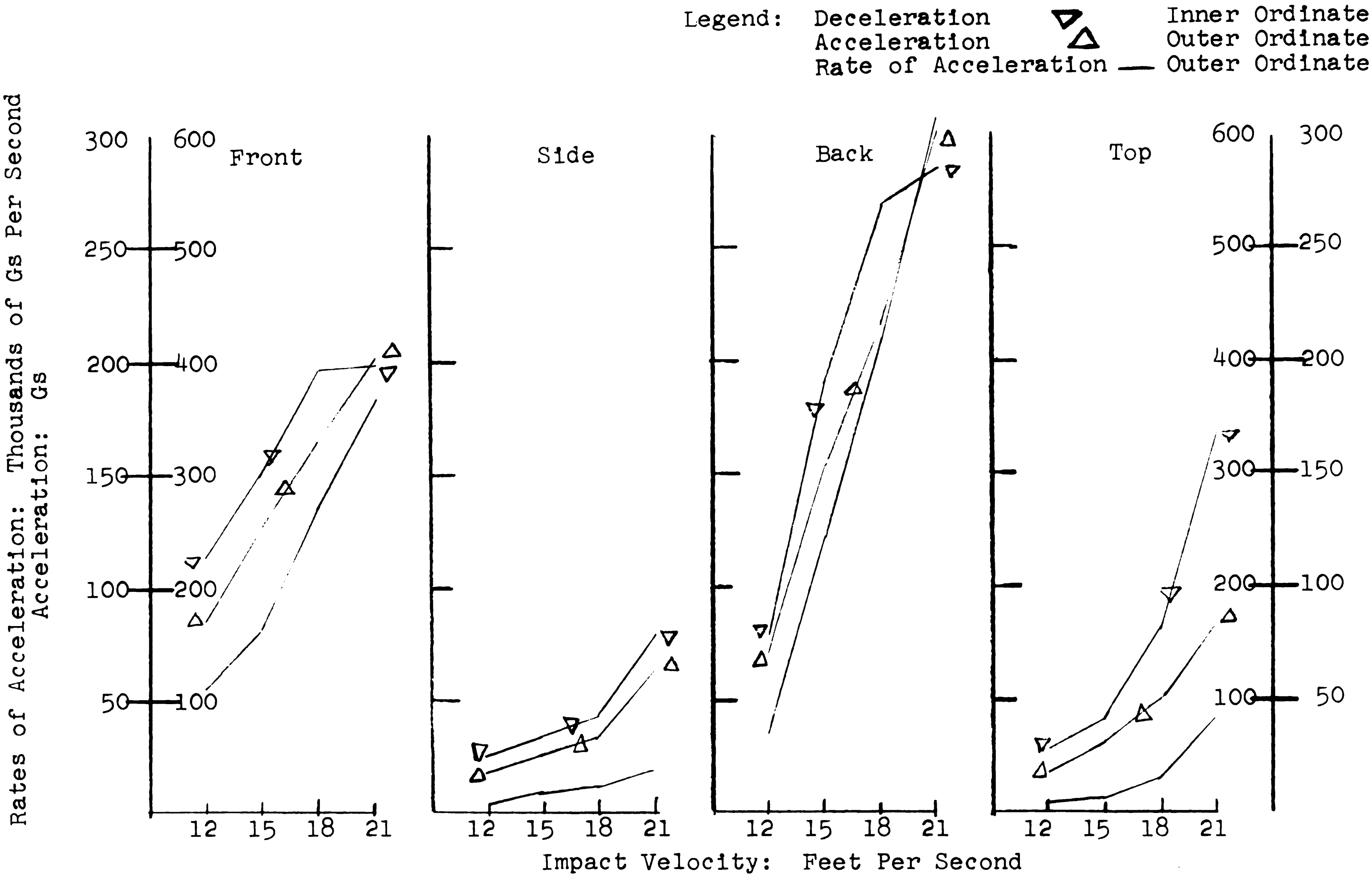

Fig. 12. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Mac-2.

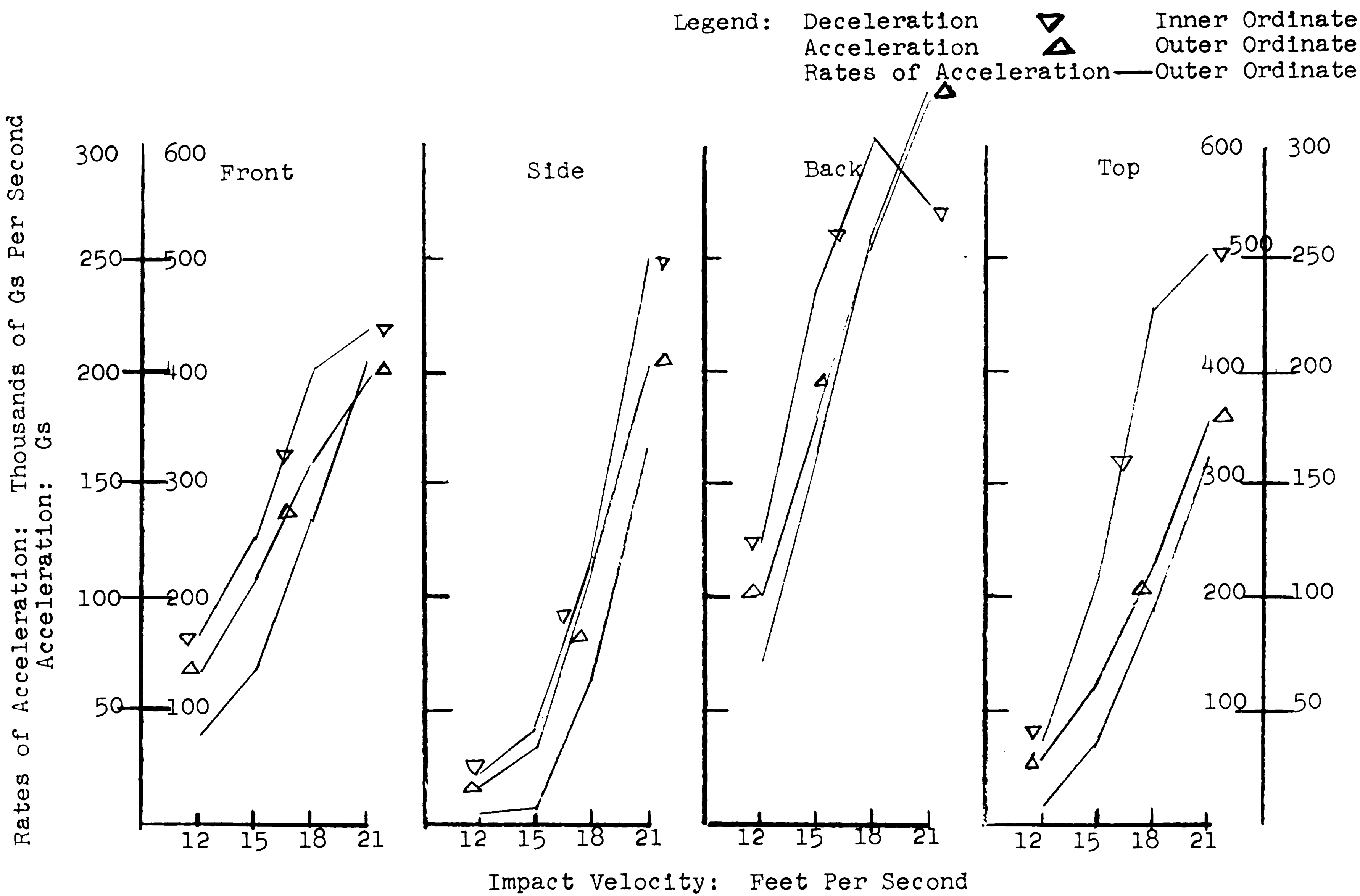

Fig. 13. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Wil-201.

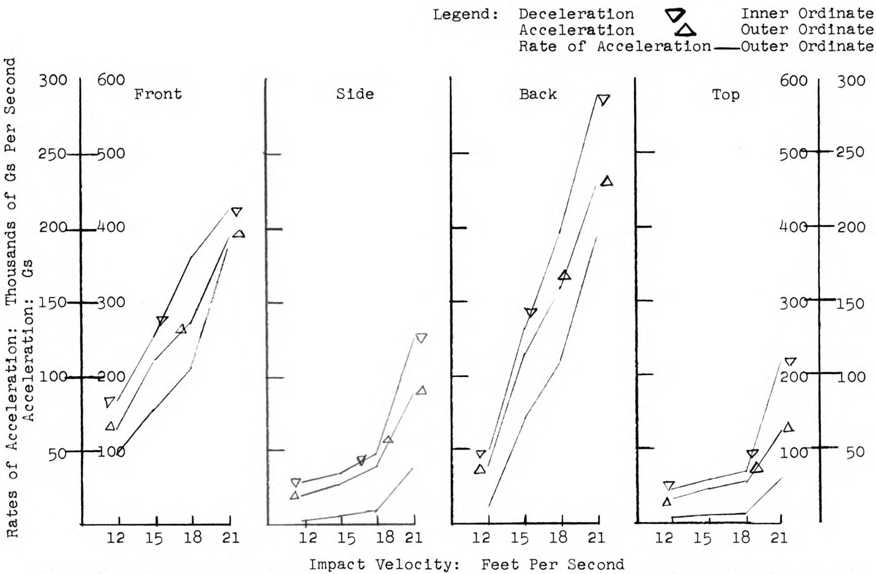

Fig. 14. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Spal-1.

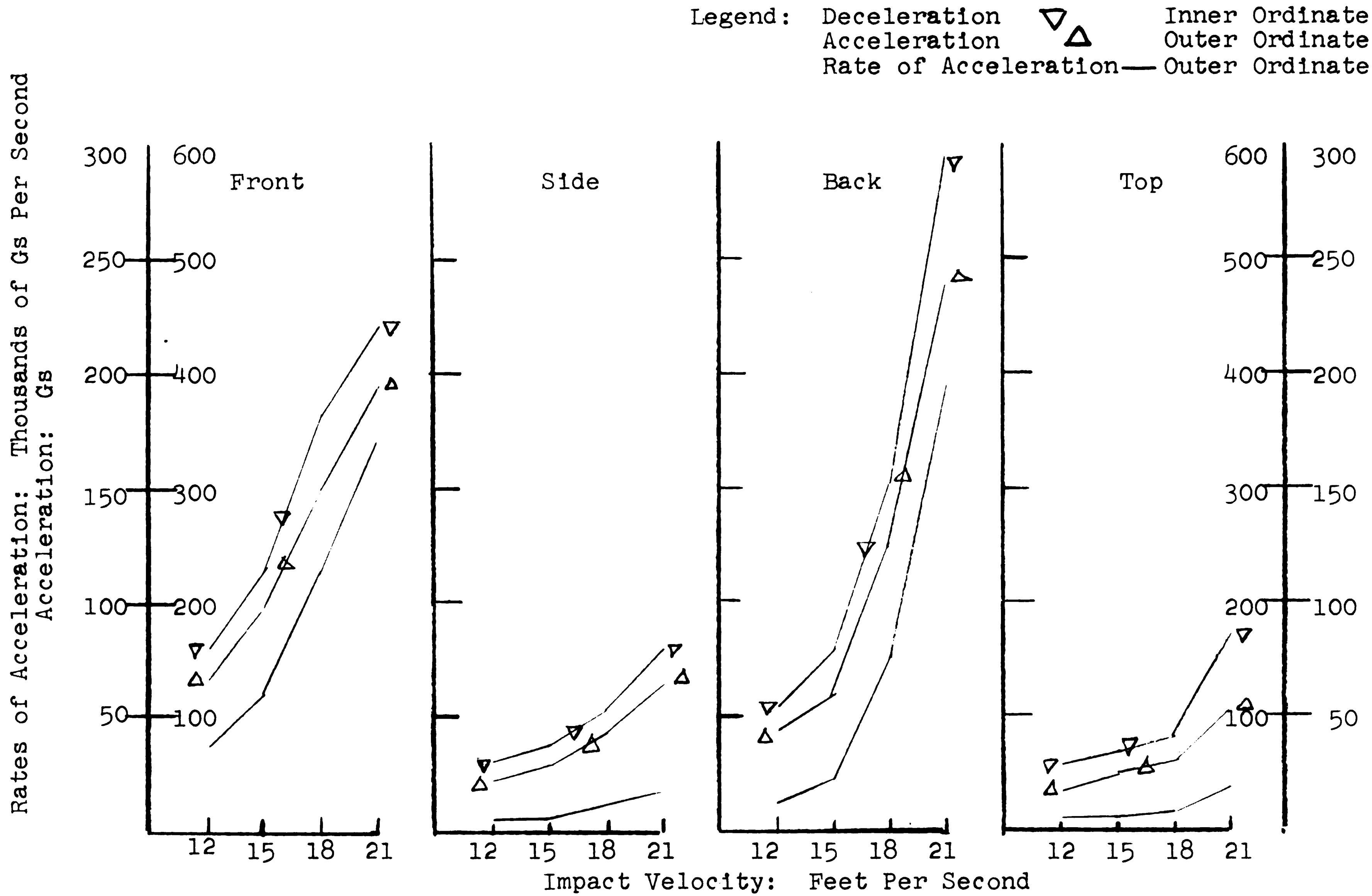

Fig. 15. Mean Deceleration of Pendulum, Acceleration, and Rate of Acceleration of Head Following Four Impact Velocities at Four Positions with Helmet Rawl.

Rea (Fig. 11), Nok (Fig. 10), and Wil-201 (Fig. 13), all of which rated poorly for these positions. It was thought that the softer shells of these helmets may have sufficiently given with the blow without bottoming so that the pendulum decelerated more slowly.

The worst position for all three evaluating criteria was the back. This was most noticeable in helmet Nok. This newly designed helmet had a shell of vulcanized rubber and leather, and a web suspension type liner. The Rea and Mac-2, both leather helmets, also responded poorly in the back position at the higher velocities. Values at this position often exceeded 250 Gs, the limit as recommended by Lombard.(38)

Tables 4 through 6 are the rankings of all brands of helmets of all three evaluating measures for each position and velocity. These rankings are supplemented with a breakdown of helmet brands into the individual responses of their constituent replicates in Figures 16 through 63.

The best helmet in regard to maximum acceleration of the head at all velocities in the front position was Wil-211 (Table 4). The shell of this helmet is a flexible plastic (Etholite) and the liner is a double suspension cotton type. The average response of this helmet to impact at twenty-one feet per second was 135 Gs. Second and third in the front position at this velocity were Rid-4 and Rid-5 with average values of 140 and 143 Gs, respectively. All liners of these three helmets were very similar but with the shells of the Rid-4 and Rid-5 being noticeably more rigid than

TABLE 4

HELMET RANKINGS BY POSITION AND VELOCITY FOR MAXIMUM ACCELERATION OF THE HEAD

Position	Front					Side					Back					Top					
Velocity / Helmets	21	18	15	12	Total	21	18	15	12	Total	21	18	15	12	Total	21	18	15	12	Total	Composite
Rid-4	2	2	2	3	2	12	11	9	12	12	7	2	2	5	4	3	5	5	2	3	4
Wil-210	6	7	6	11	7	5	7	8	10	8	9	5	6	7	7	4	3	3	5	3	8
Rid-5	3	3	4	2	3	8	12	13	13	13	4	7	4	3	6	5	7	6	7	6	7
Mac-0	5	11	13	13	11	2	1	2	2	1	1	3	5	6	3	1	2	2	6	1	1
Wil-211	1	1	1	1	1	4	5	10	8	6	6	8	8	10	8	7	8	8	10	8	6
Mac-5	11	12	11	12	12	3	2	1	1	1	2	1	3	2	1	2	6	9	11	7	5
Spal-2	4	5	3	4	4	1	3	6	6	3	8	9	9	9	9	12	10	7	9	10	9
Nok	12	10	9	8	9	9	7	7	9	9	10	11	11	13	11	10	11	12	13	12	11
Rea	13	13	12	9	13	11	10	11	11	11	12	12	12	12	12	11	12	11	4	10	13
Mac-2	10	9	10	10	9	7	4	3	4	4	11	10	10	8	10	9	9	10	8	9	10
Wil-201	9	8	7	6	7	13	13	12	3	10	13	13	13	11	13	13	13	13	12	13	12
Spal-1	8	4	8	4	5	10	6	4	5	5	3	6	7	1	5	8	1	1	1	1	2
Rawl	7	6	5	7	6	6	9	5	7	6	5	4	1	4	2	6	4	4	3	5	3

Ranks determined from mean of three replicates; position and composite rankings determined from total of ranks for four and sixteen velocities, respectively.

TABLE 5

HELMET RANKINGS BY POSITION AND VELOCITY FOR MAXIMUM DECELERATION OF THE PENDULUM

Position	Front					Side					Back					Top					
Velocity / Helmets	21	18	15	12	Total	21	18	15	12	Total	21	18	15	12	Total	21	18	15	12	Total	Composite
Rid-4	2	3	3	5	3	9	5	2	5	3	5	1	5	6	4	3	7	9	13	9	2
Wil-210	12	7	8	11	10	3	6	9	12	8	4	7	6	7	6	2	3	5	5	3	7
Rid-5	3	2	4	3	2	6	4	7	7	4	3	5	1	1	1	5	8	11	12	10	1
Mac-0	13	12	13	13	13	2	10	13	13	12	1	3	4	5	3	1	5	6	9	5	10
Wil-211	1	1	1	1	1	4	7	8	11	8	6	8	9	10	8	6	4	3	6	4	4
Mac-5	8	11	12	12	12	5	12	12	8	10	2	2	3	3	1	4	6	7	10	6	9
Spal-2	6	4	2	2	4	1	1	1	3	1	7	9	8	9	8	13	11	4	2	7	2
Nok	5	10	10	4	7	10	2	6	9	5	10	12	13	13	13	10	10	10	10	11	11
Rea	8	13	11	9	11	12	11	11	10	13	9	11	12	12	12	11	12	12	7	12	13
Mac-2	4	8	9	10	8	7	3	3	2	2	11	10	10	8	10	9	9	8	4	7	8
Wil-201	10	9	6	7	9	13	13	10	1	10	8	13	11	11	11	12	13	13	8	13	12
Spal-1	7	5	7	8	5	11	8	4	4	5	12	6	7	2	7	8	1	1	1	1	5
Rawl	11	6	5	6	6	8	9	5	6	7	13	4	2	4	5	7	2	2	3	2	6

Ranks determined from mean of three replicates; position and composite rankings determined from total of ranks for four and sixteen velocities, respectively.

TABLE 6

HELMET RANKINGS BY POSITION AND VELOCITY FOR RATES OF ACCELERATION OF THE HEAD

Position	Front					Side					Back					Top					
Velocity Helmets	21	18	15	12	Total	21	18	15	12	Total	21	18	15	12	Total	21	18	15	12	Total	Composite
Rid-4	3	1	3	4	3	12	11	10	8	11	6	1	2	5	3	5	7	10	8	8	4
Wil-210	4	5	7	11	6	10	10	6	12	10	9	5	6	6	7	3	3	4	5	3	8
Rid-5	2	3	2	2	2	8	12	13	13	13	5	6	4	1	4	4	8	8	10	8	7
Mac-0	7	10	13	13	11	1	5	9	10	6	1	3	5	7	4	1	4	3	7	3	5
Wil-211	1	2	1	1	1	6	2	4	7	4	7	8	8	11	8	7	5	6	9	5	3
Mac-5	11	13	10	12	13	3	7	7	9	7	2	2	3	4	1	2	6	9	12	7	9
Spal-2	5	7	4	3	4	2	1	2	3	1	8	9	10	9	9	13	11	7	6	11	5
Nok	13	11	11	6	10	7	4	5	6	5	12	11	13	13	12	10	10	12	11	12	11
Rea	10	12	12	9	11	11	9	12	11	12	13	13	11	12	12	11	12	11	2	10	13
Mac-2	8	9	9	10	9	5	8	11	5	8	10	10	9	8	10	9	9	5	4	5	10
Wil-201	12	8	6	7	8	13	13	8	2	9	11	12	12	10	11	12	13	13	13	13	12
Spal-1	9	4	8	8	7	9	3	3	1	3	3	7	7	2	6	8	1	1	3	2	2
Rawl	6	6	5	5	5	4	6	1	4	2	4	4	1	3	2	6	2	2	1	1	1

Ranks determined from mean of three replicates; position and composite rankings determined from total of ranks for four and sixteen velocities, respectively.

that of the Wil-211 (Fig. 2). Helmets Mac-5,Nok, and Rea ranked eleventh, twelfth, and thirteenth, at twenty-one feet per second with maximum Gs of 203, 206, and 227, respectively. Mac-5 had a plastic type shell (duralite), and a combination pad-suspension liner. Nok and Rea are soft shelled helmets.

Intra-helmet variations were noted at the highest impact velocity among helmets Rid-4, Mac-5, and Spal-2 (Fig. 16). At the velocity of twelve feet per second Spal-1, Nok, and Rea had the widest replicate variation (Fig. 19).

Helmets Spal-2, Mac-0, Mac-5, and Wil-211 were ranked the best four at the side position at twenty-one feet per second. At this velocity Wil-201 had the highest acceleration at 198 Gs. The consistency of Spal-2 and Wil-211 at the front and side positions was in direct contrast to that of Mac-0 and Mac-5 for these two positions. Intra-helmet variations were noted among helmets Rea and Rid-4 at twenty-one feet per second to a lesser extent (Fig. 20). Rid-5 was ranked thirteenth at both impact velocities of fifteen and twelve feet per second. For the side position at twenty-one feet per second the values ranges from 31 to 198 Gs.

At twenty-one feet per second in the back position the three best helmets were Mac-0, Mac-5, and Spal-1. The acceleration of the best helmet Mac-0 was 156 Gs as compared to 324 Gs for the worst, Wil-201. The range of replicate values of Wil-210 at this velocity is 164 Gs.

The definite superiority of Mac-0 at the top position (twenty-one feet per second), with an average of 30 Gs was in direct contrast to that of Wil-201 with an average of 177 Gs (Fig. 28). The manufacture of this brand of football helmet (Wil-201) has been discontinued. Most helmets in this position show little replicate variation.

The most consistently low ranking helmet for all velocities and positions in regard to acceleration of the head was Mac-O. The characteristics of this helmet are a firm pliable plactic-type shell (Duralite) and a geodetic padded liner (Bedford Vinyl).

Regarding maximum deceleration of the pendulum at all velocities in the front position it was found that Wil-211 consistently ranked first (Fig. 6). Mac-O was ranked thirteenth at all velocities for this position except at eighteen feet per second, where it was rated twelfth.

The most consistently low ranking helmet across all velocities for the side position was Spal-2. The worst at the side position was Rea.

Best over-all protection from the back was afforded by Rid-5 while the least protection, in terms of deceleration of a striking pendulum, was given by Nok.

Rid-4, Rid-5, and Spal-2 are the persistently lowest ranked helmets for the measure of deceleration across all positions. Intra-helmet variation was more noticeable, particularly in the front position for deceleration as compared to acceleration. This was more pronounced at the highest impact velocity (Fig. 32). It was observed that factors such as whipping motions of the descending pendulum cables, projections at the ear level, and rims along the axis of the helmets, often resulted in inconsistent blows. These were mostly produced at the higher impact velocities.

The rankings of helmets by rates of accelerations (Table 6) were markedly similar to those by maximum acceleration.

At twenty-one feet per second in the front position Wil-211 was ranked first with an average rate of 96,772 Gs per second (Fig. 48). In spite of it being impacted with the highest velocity possible in this experiment, it was yet within the limit of 100,000 Gs per second as advocated for football helmets by Lombard.(38)

Mac-O was ranked first at twenty-one feet per second in the side (8,872 Gs per second), back (93,818 Gs per second), and top (7,200 Gs per second) positions. However, it ranked seventh at twenty-one feet per second in its poorest position the front with 172,688 Gs per second. At the back positions the ratings of Mac-O, for acceleration and rates of acceleration, are nearly identical.

The two lowest cumulative rankings for all positions are, in order, those of Rawl and Spal-1. The shells of these two helmets are almost identically constructed (Cycoloc), with the liners being made of non-resilient ensolite. Their resemblance to the liners of the Mac-O was noted.

The results of this chapter may be summarized:

1. Except for the side position of Mac-2, leather helmets are inferior to plastic shelled helmets.

2. While somewhat alike at the low impact velocities, the responses of helmets are considerably more variable as the result of blows of greater magnitude.
3. Helmet types differed significantly according to position. The back was generally the worst position. The within variance was significant for all three evaluating measures. Intra-helmet variation was found least at the top position.
4. Firm pliable plastic like shells with suspension padded liners are seemingly superior to rigid shells with canvas suspension liners.
5. F ratios of all sources of variance are significant.
6. The best helmet for all three measures at the front position Wil-211. Its shell was of a firm pliable plastic material (Etholite) with the liner being a cotton suspension type.
7. The consistently best three ranking helmets were for:

   Acceleration--Mac-0, Spal-1, and Rawl,

   Deceleration--Rid-5, Rid-4, and Spal-2, and

   Rates of Acceleration--Rawl, Spal-1, and Wil-211.

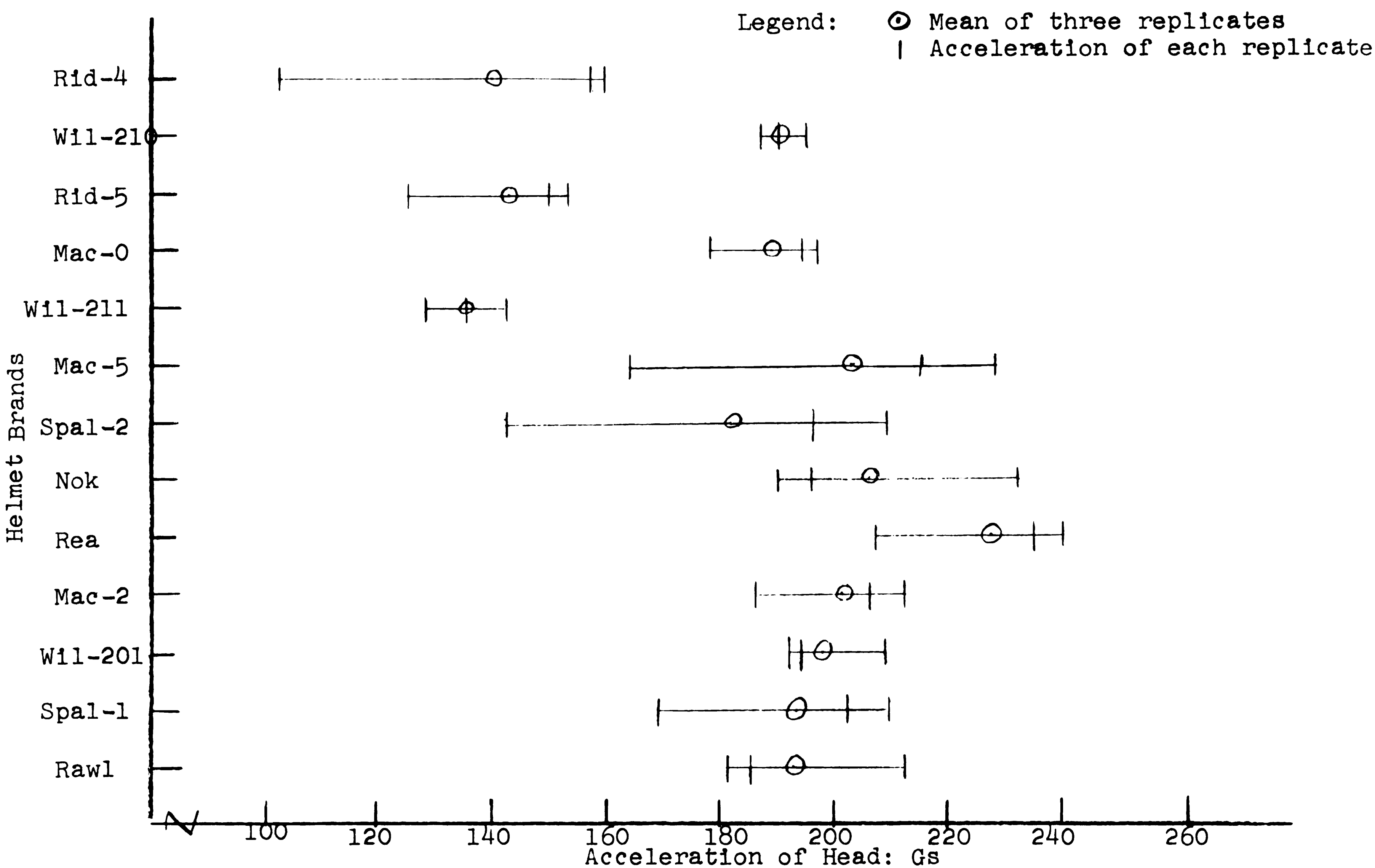

Fig. 16. Maximum Accelerations of All Helmets Following Impact in the Front Position at Twenty-one Feet Per Second.

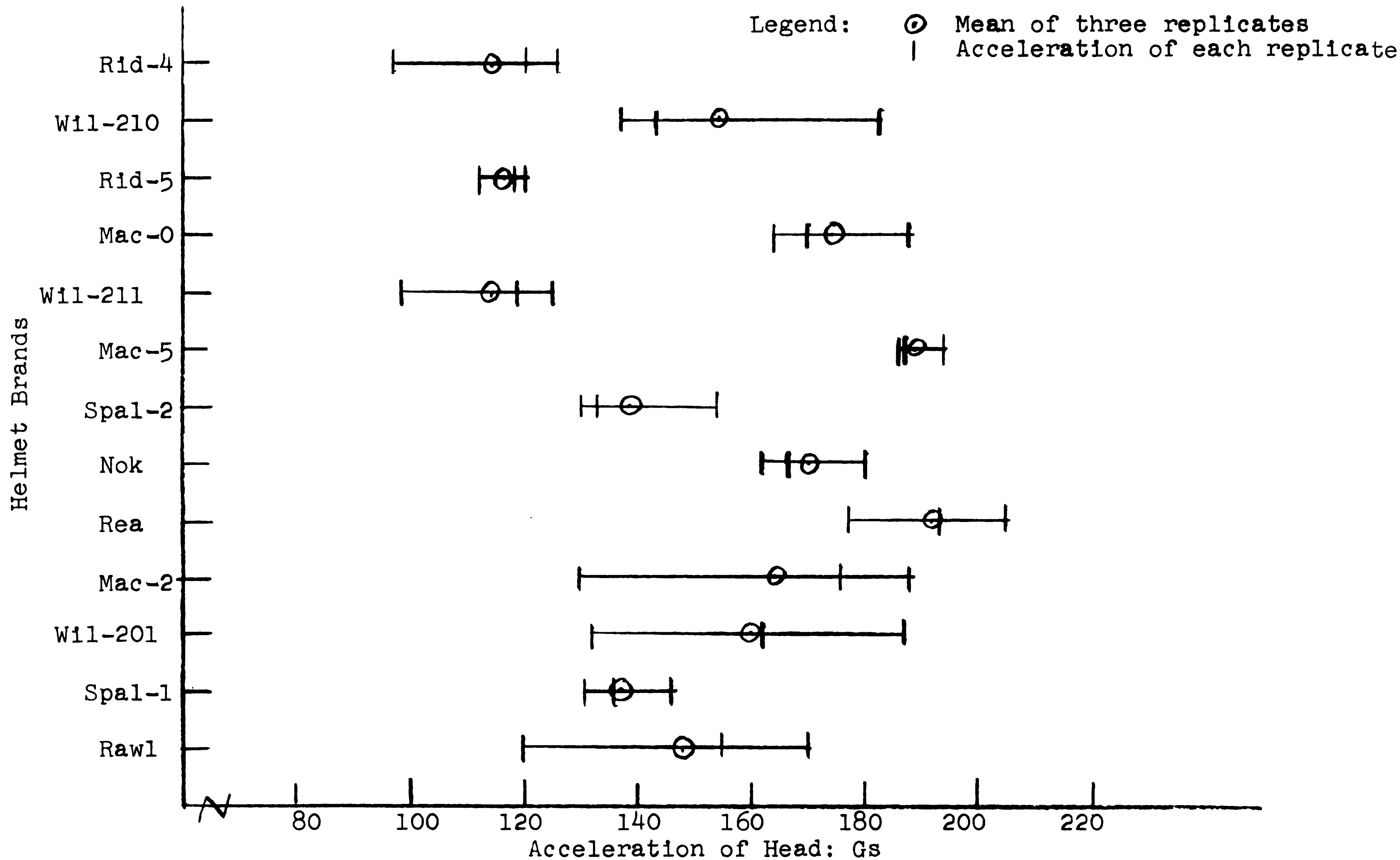

Fig. 17. Maximum Accelerations of All Helmets Following Impact in the Front Position at Eighteen Feet Per Second.

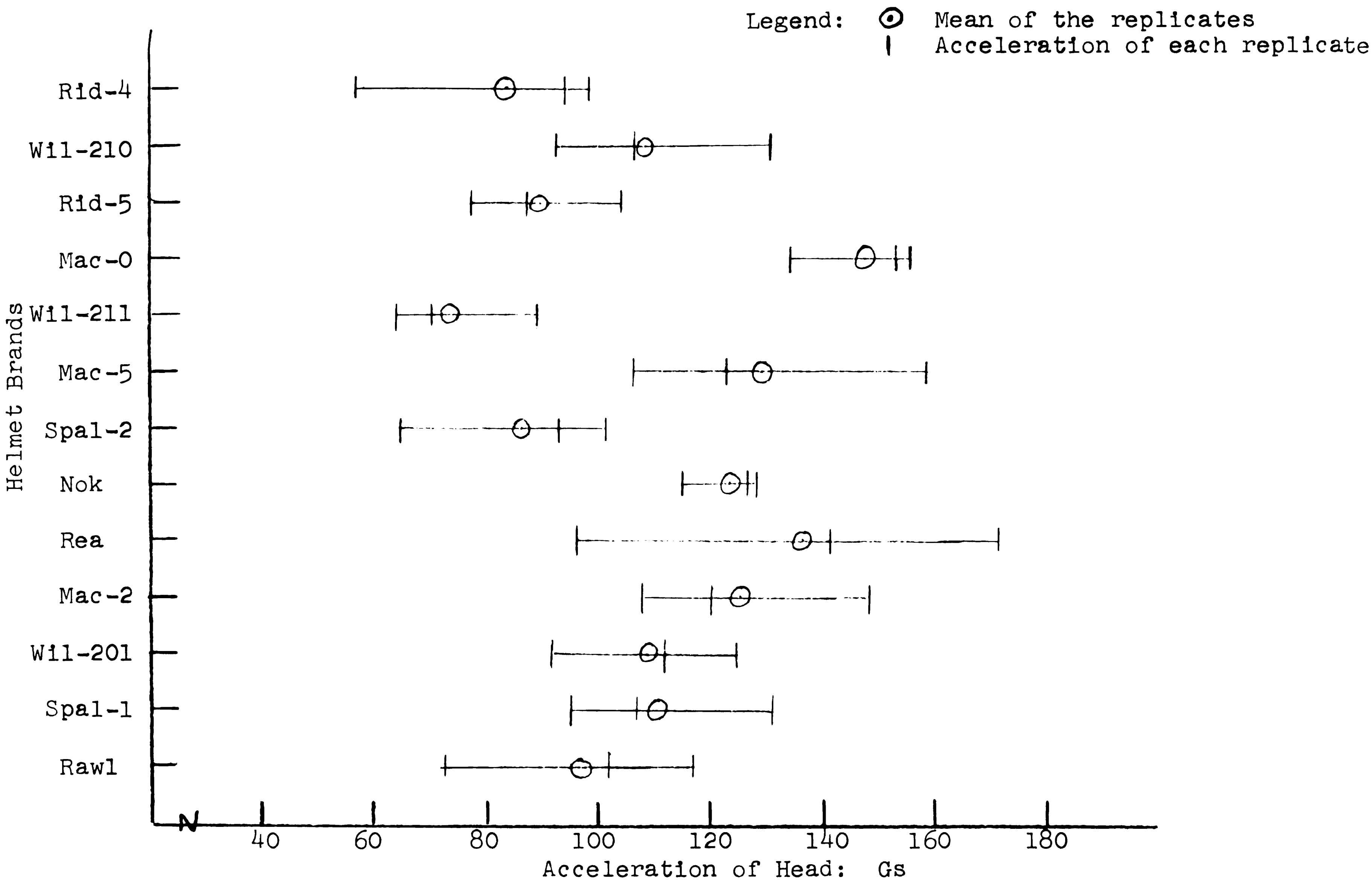

Fig. 18 Maximum Accelerations of All Helmets Following Impact in the Front Position at Fifteen Feet Per Second.

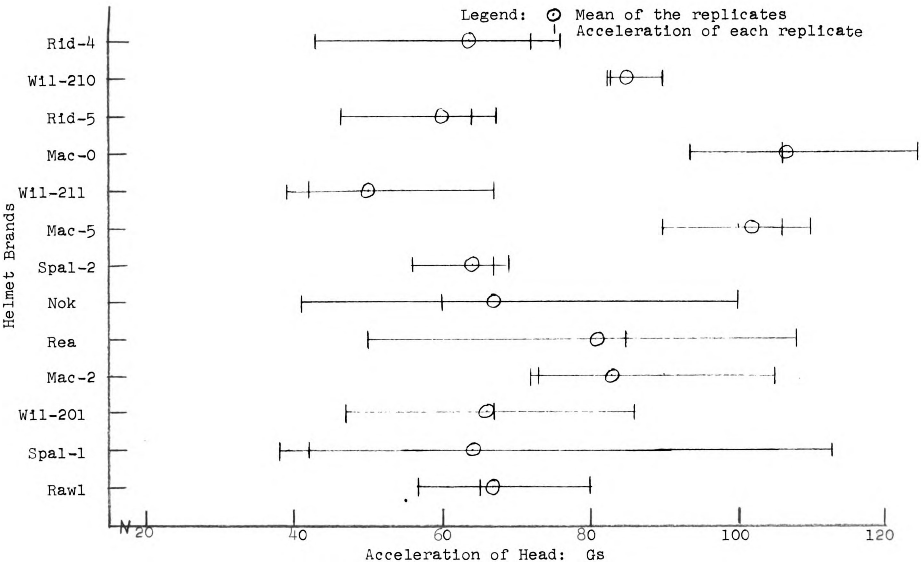

Fig. 19. Maximum Accelerations of All Helmets Following Impact in the Front Position at Twelve Feet Per Second.

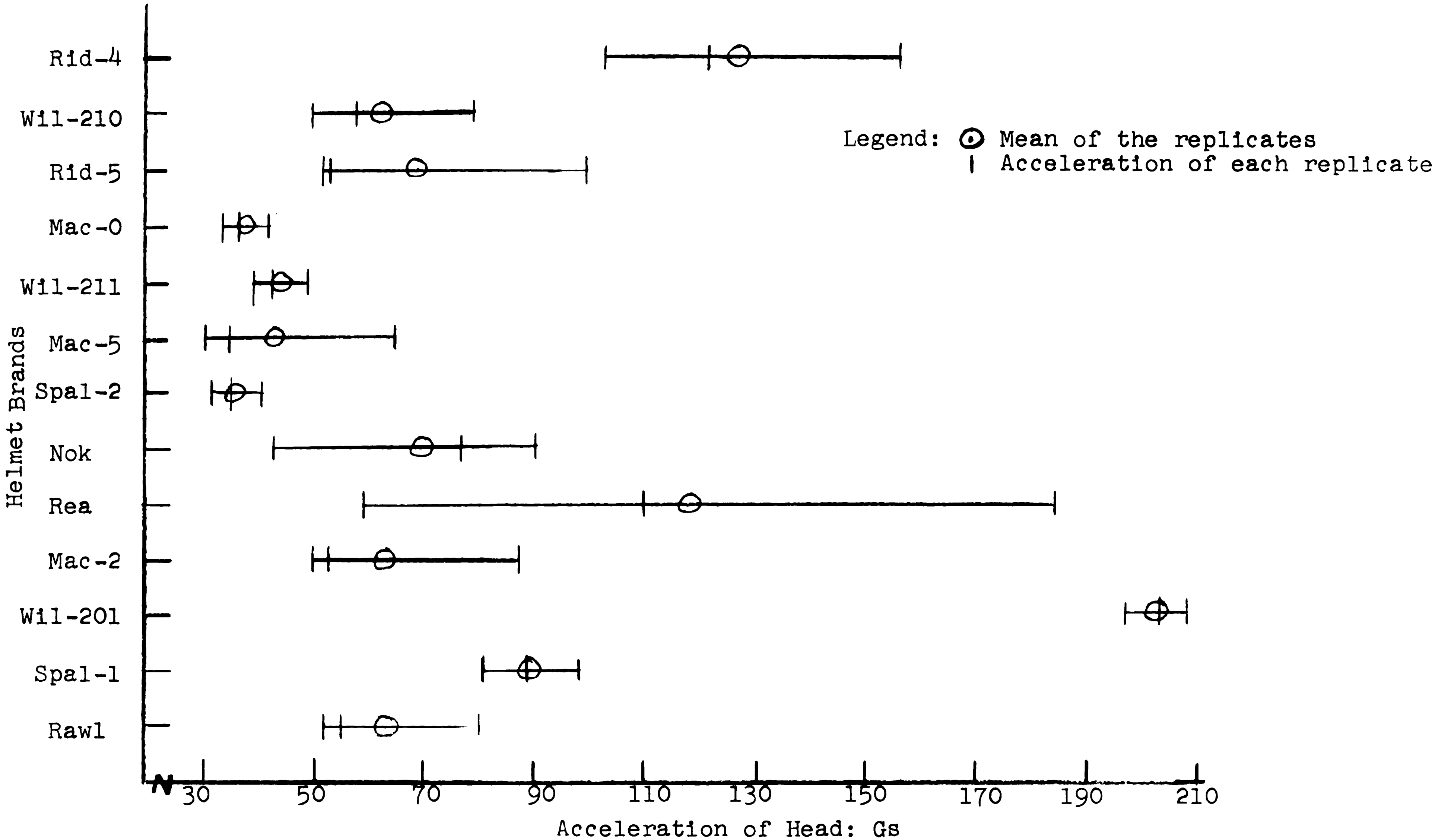

Fig. 20. Maximum Accelerations of All Helmets Following Impact in the Side Position at Twenty-one Feet Per Second.

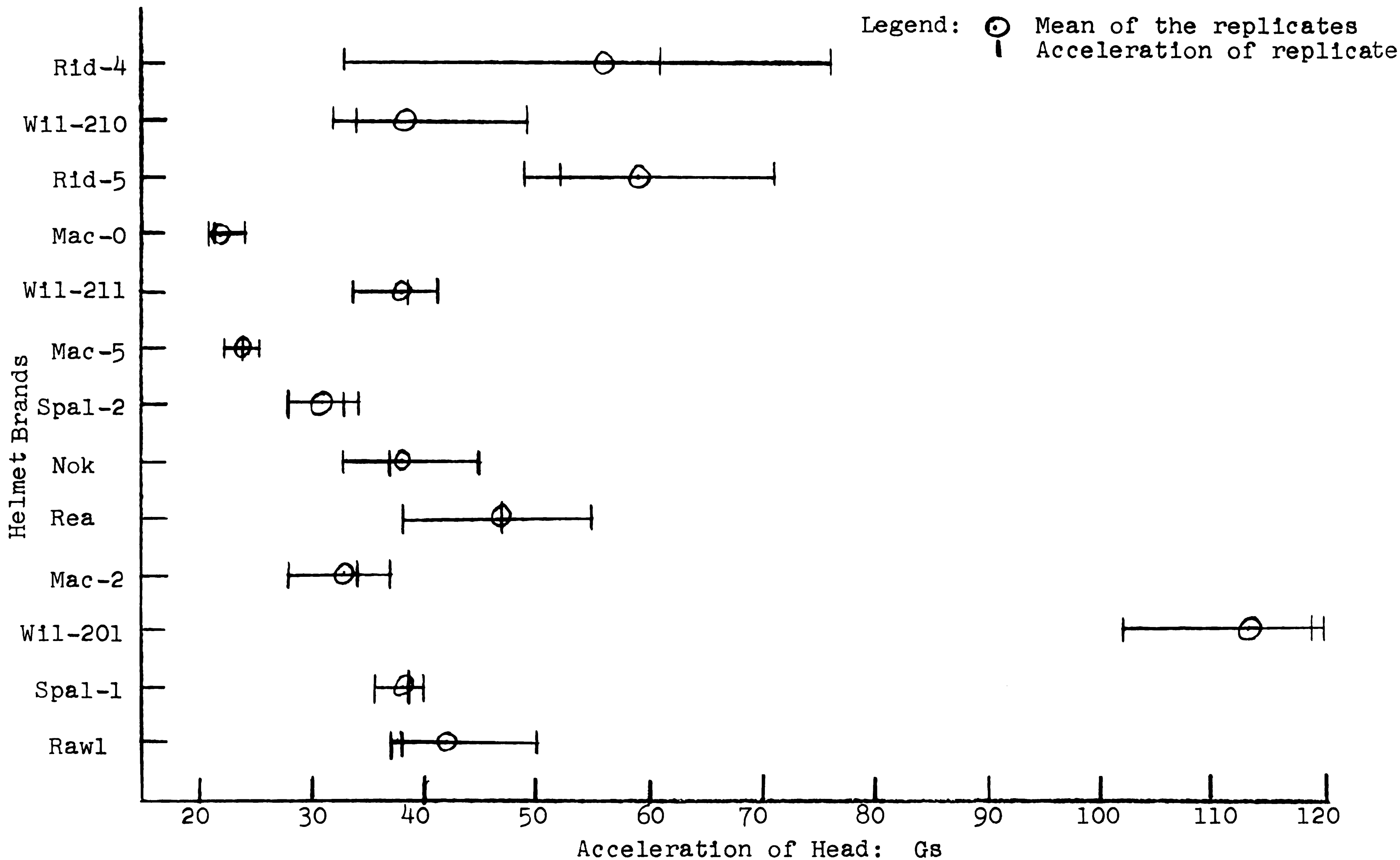

Fig. 21. Maximum Accelerations of All Helmets Following Impact in the Side Position at Eighteen Feet Per Second.

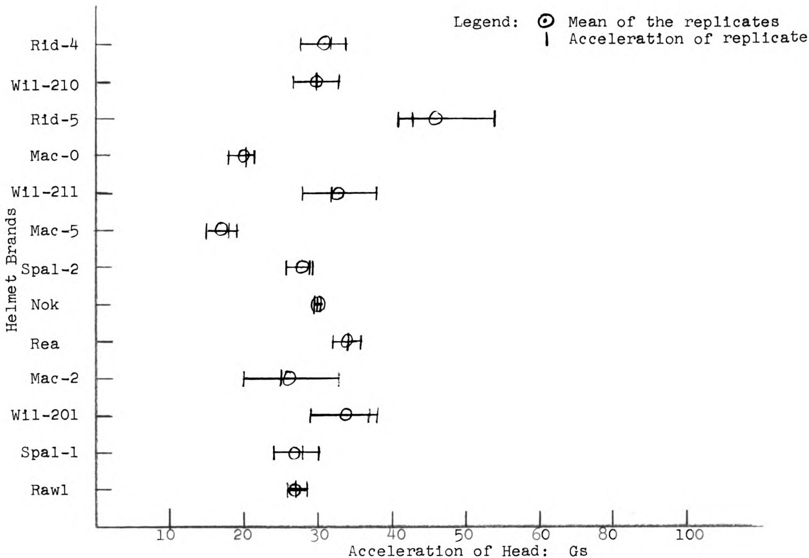

Fig. 22. Maximum Accelerations of All Helmets Following Impact in the Side Position at Fifteen Feet Per Second.

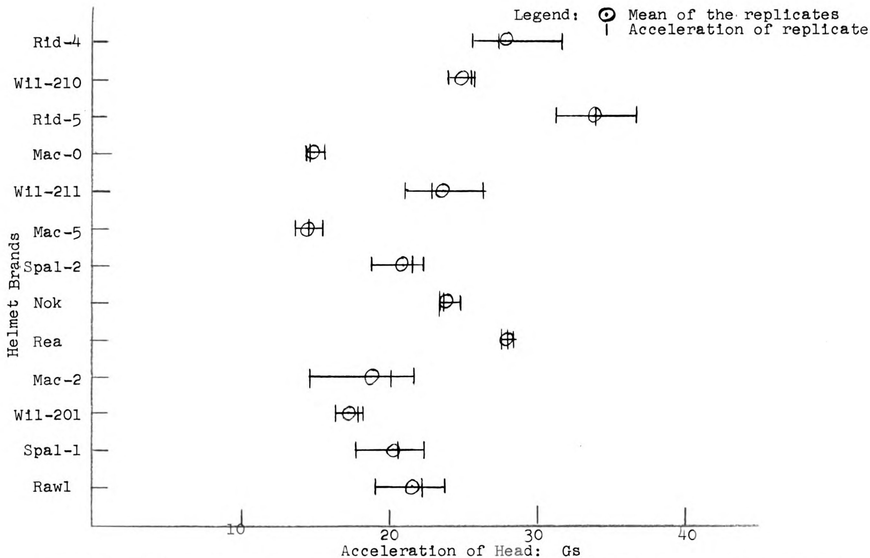

Fig. 23. Maximum Accelerations of All Helmets Following Impact in the Side Position at Twelve Feet Per Second.

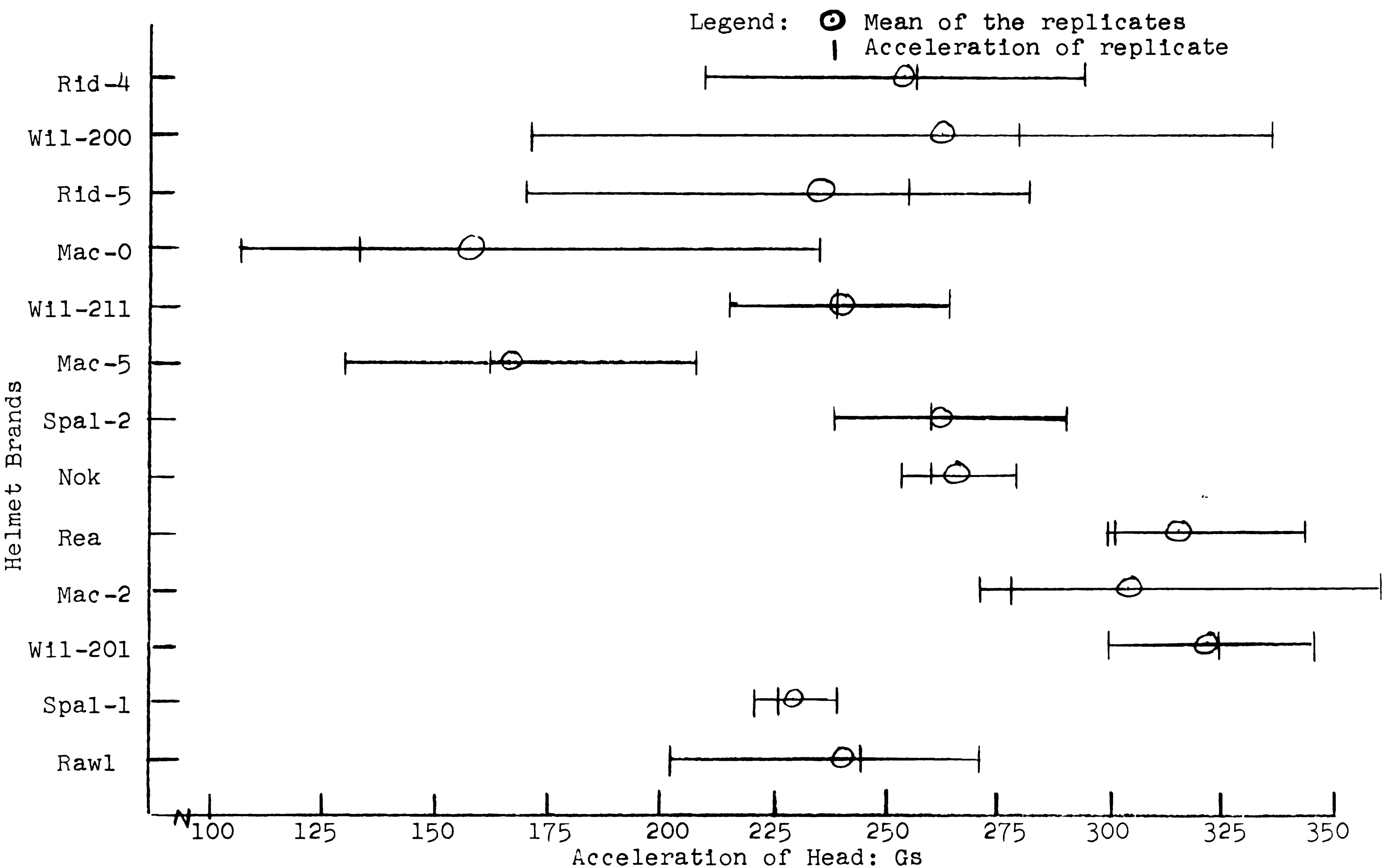

Fig. 24. Maximum Accelerations of All Helmets Following Impact in the Back Position at Twenty-one Feet Per Second.

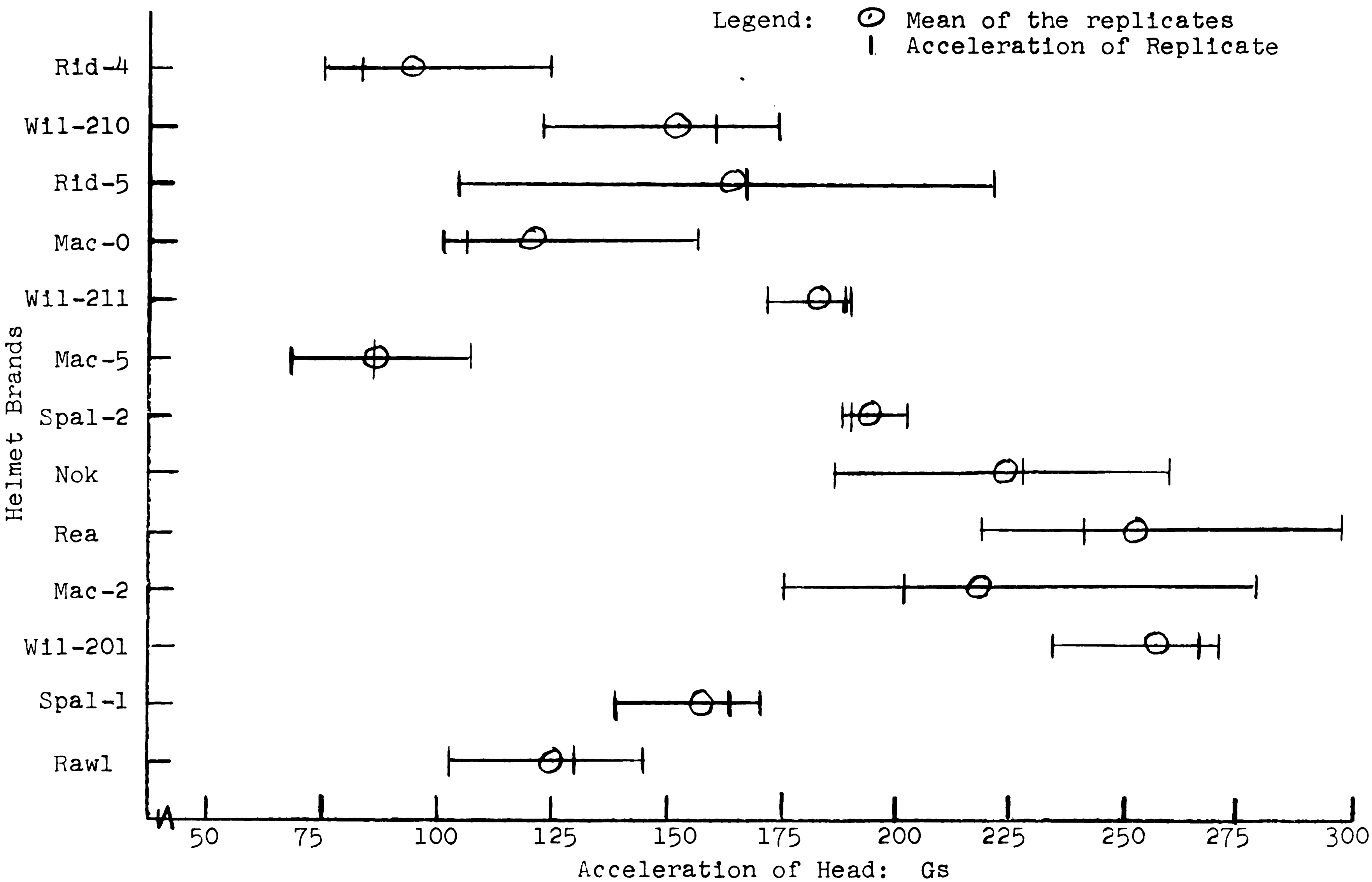

Fig. 25. Maximum Accelerations of All Helmets Following Impact in the Back Position at Eighteen Feet Per Second.

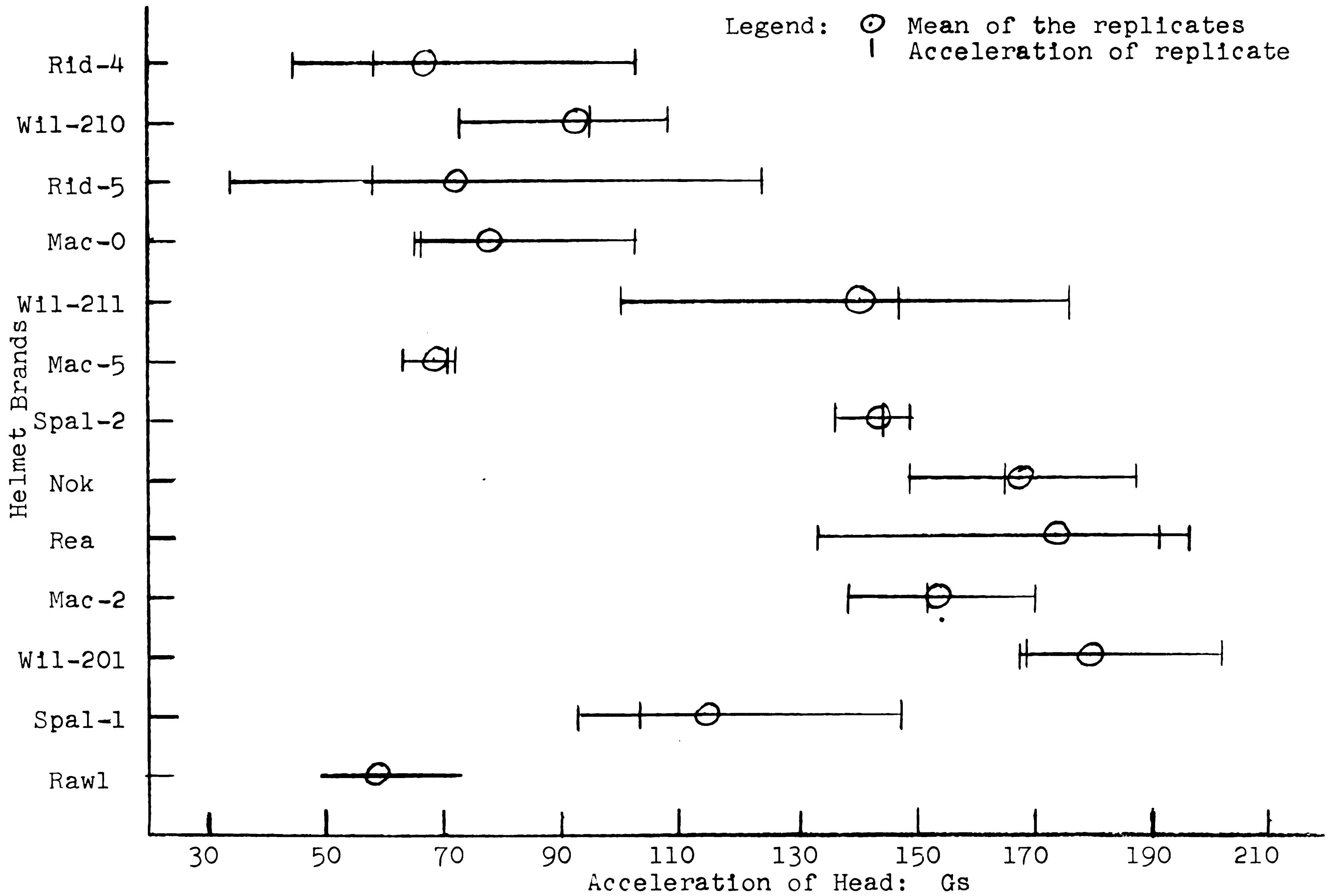

Fig. 26. Maximum Accelerations of All Helmets Following Impact in the Back Position at Fifteen Feet Per Second.

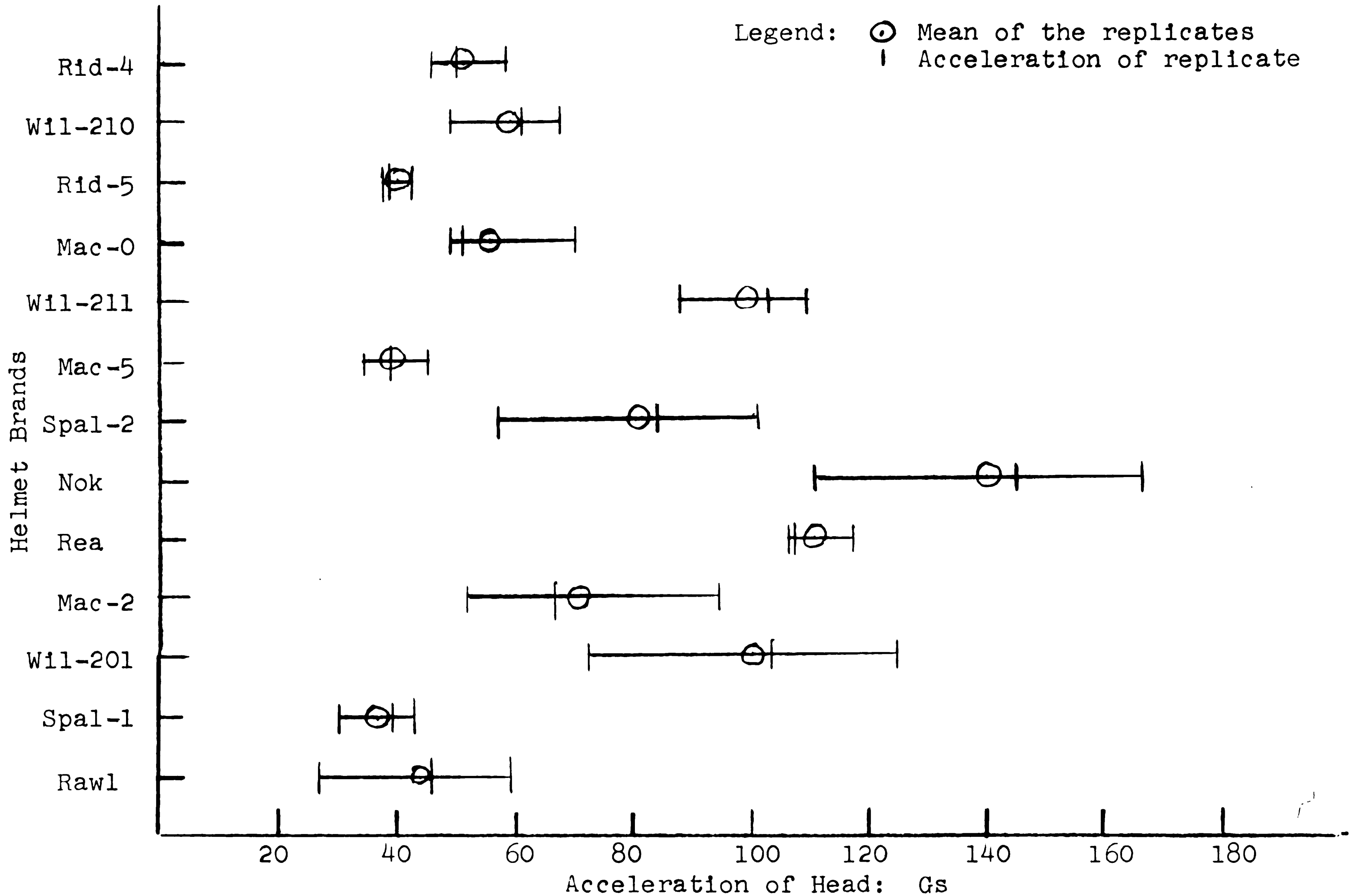

Fig. 27. Maximum Accelerations of All Helmets Following Impact in the Back Position at Twelve Feet Per Second.

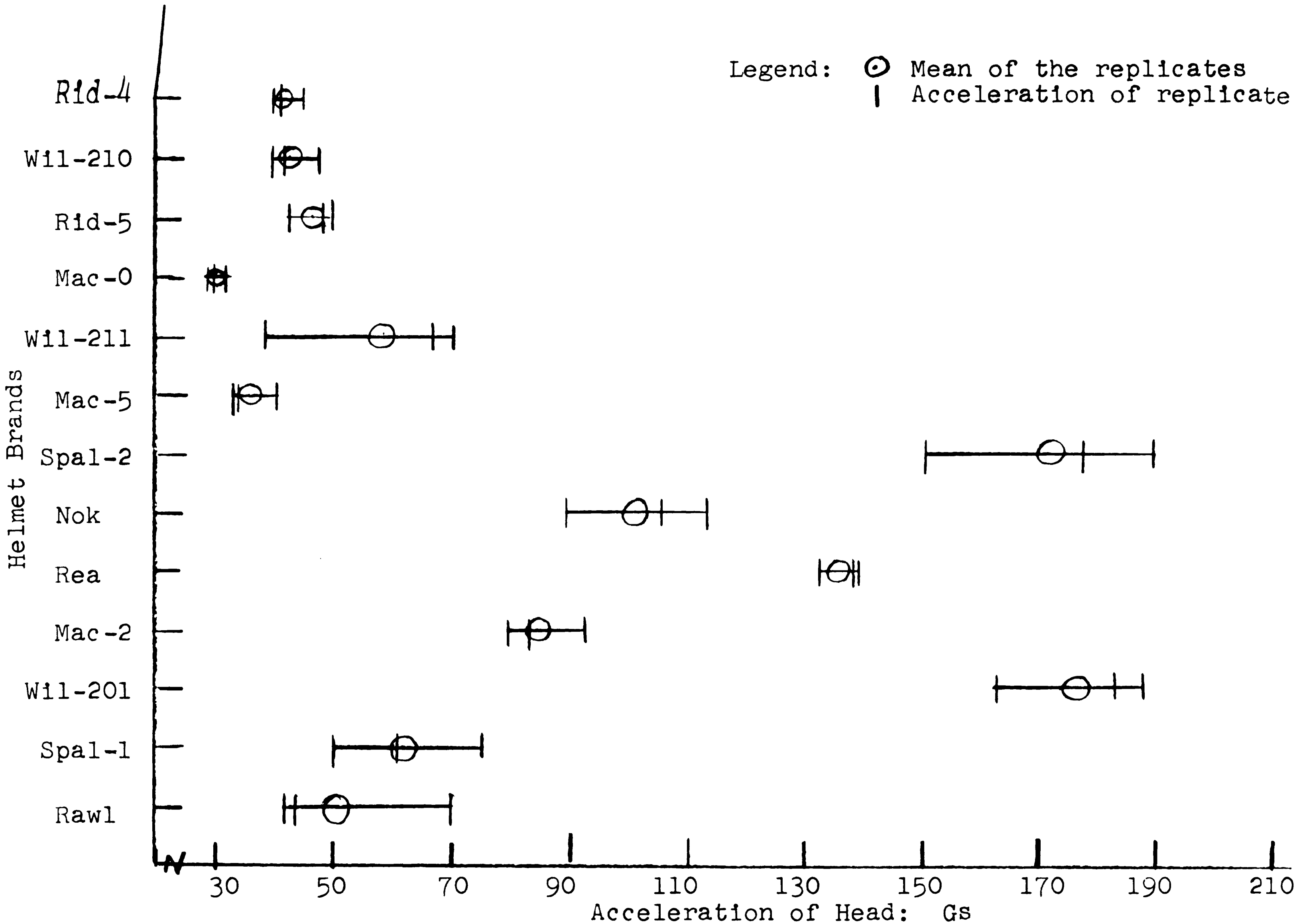

Fig. 28.Maximum Accelerations of All Helmets Following Impact in the Top Position at Twenty-one Feet Per Second.

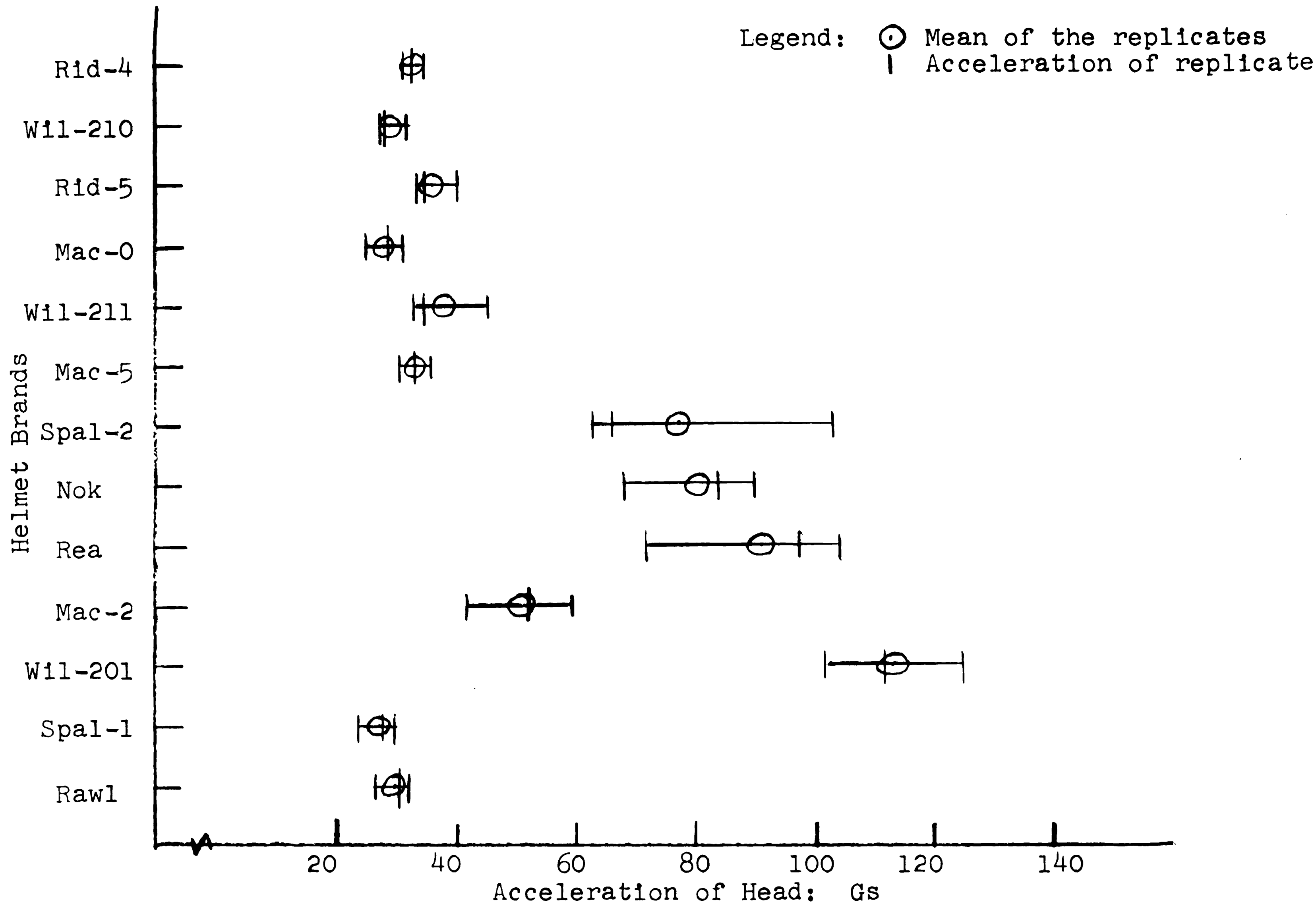

Fig. 29. Maximum Accelerations of All Helmets Following Impact in the Top Position at Eighteen Feet Per Second.

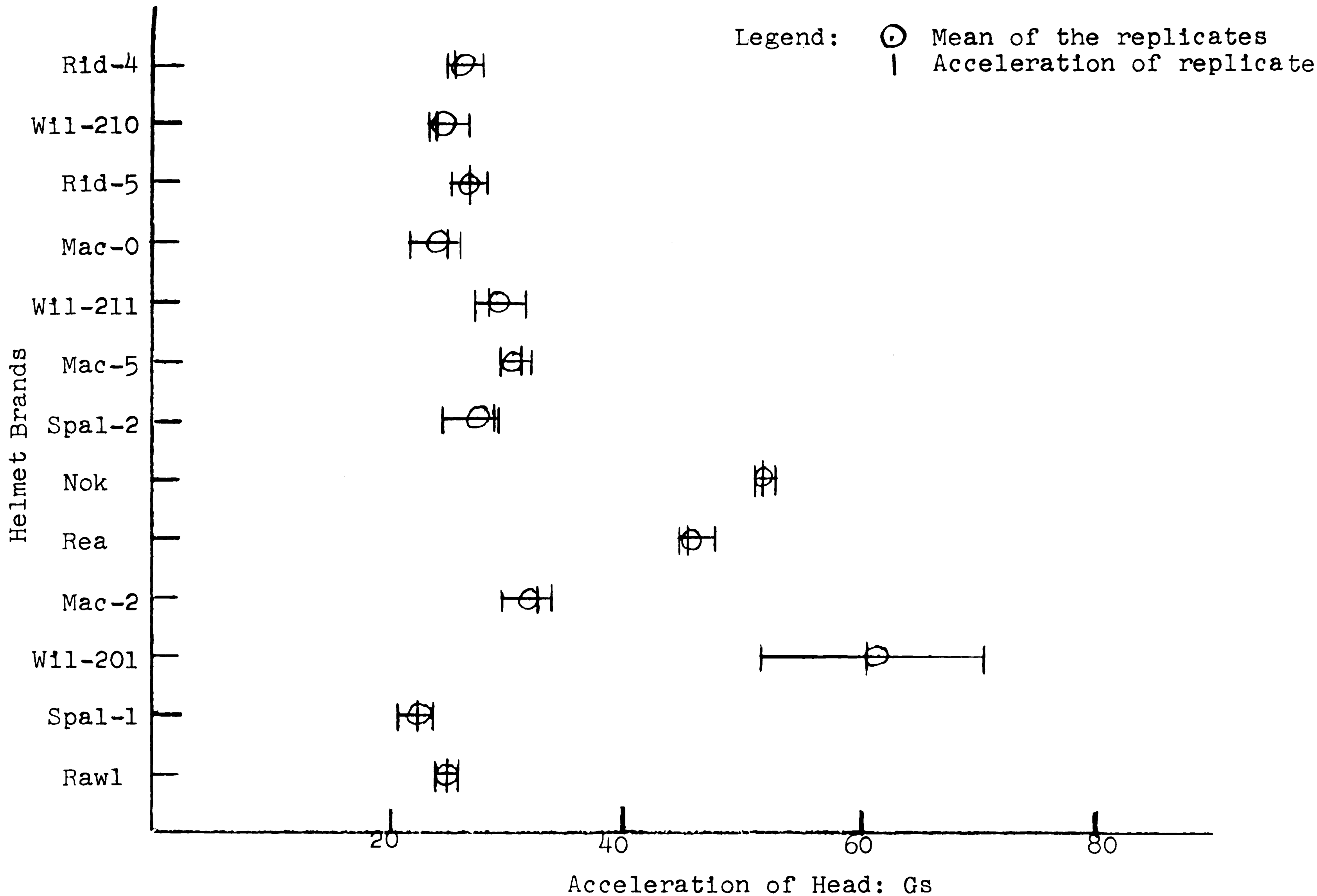

Fig. 30. Maximum Accelerations of All Helmets Following Impact in the Top Position at Fifteen Feet Per Second.

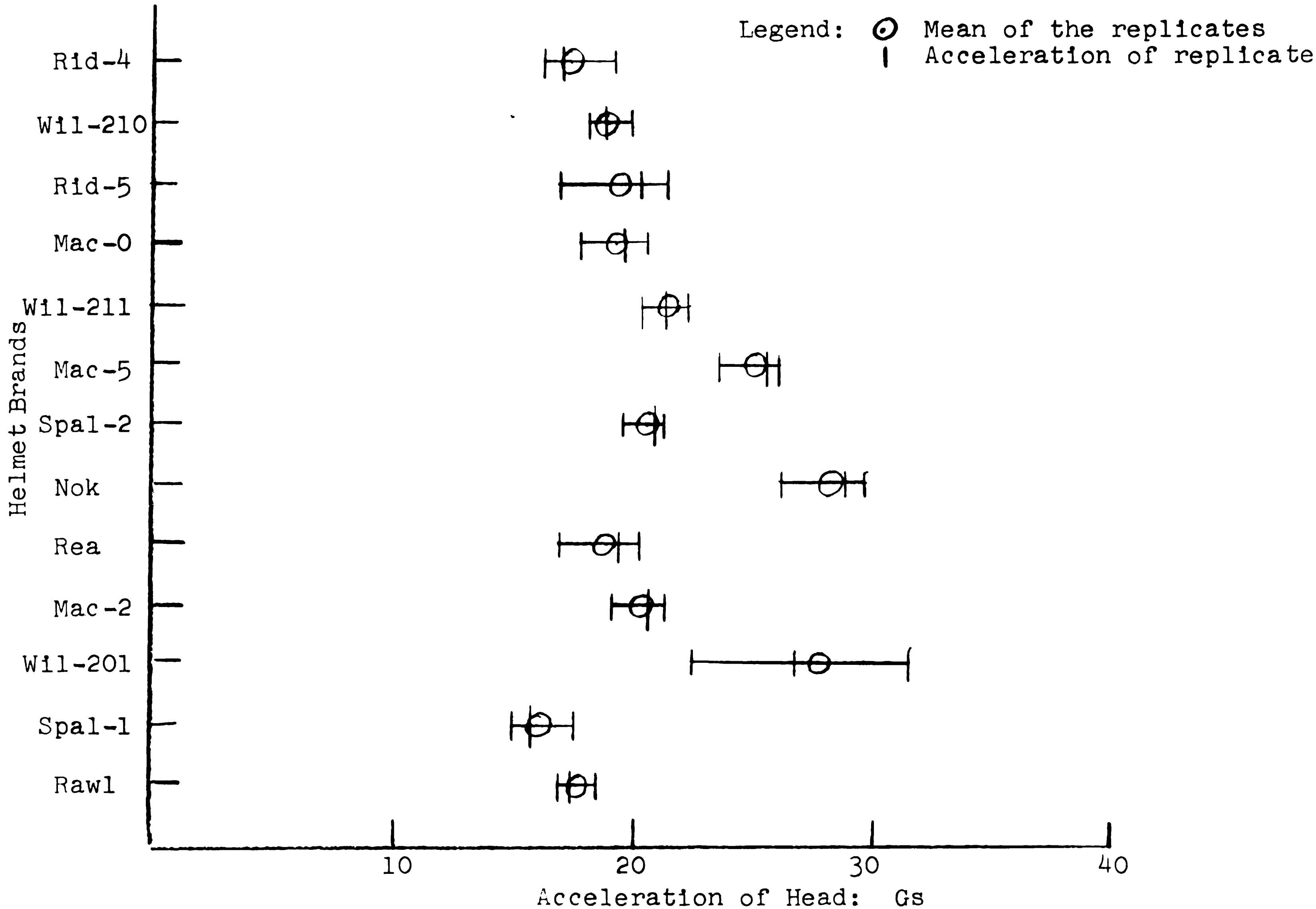

Fig. 31. Maximum Acceleration of All Helmets Following Impact in the Top Position at Twelve Feet Per Second.

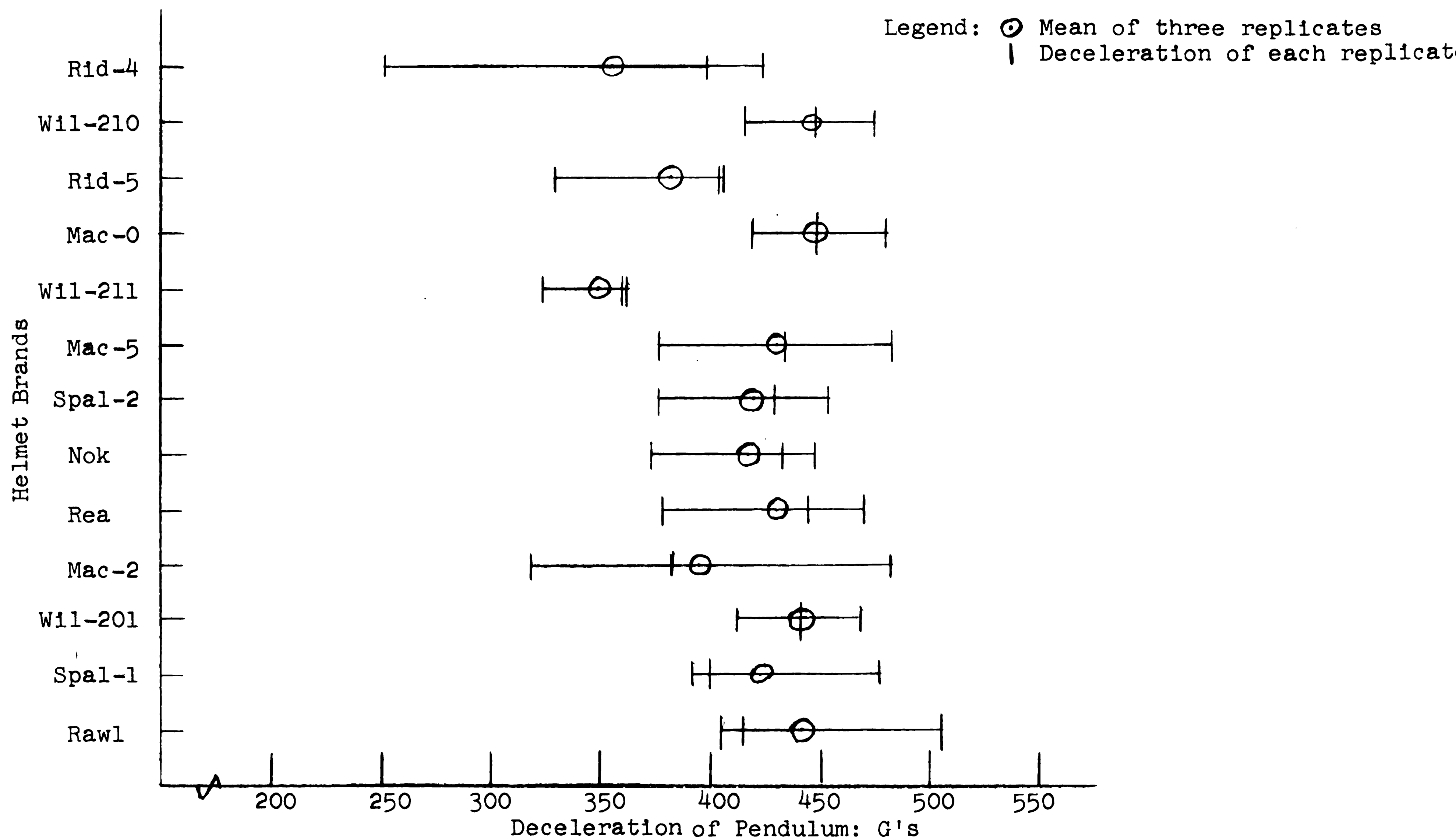

Fig. 32. Maximum Decelerations of the Pendulum Following Impact in the Front Position at Twenty-one Feet Per Second.

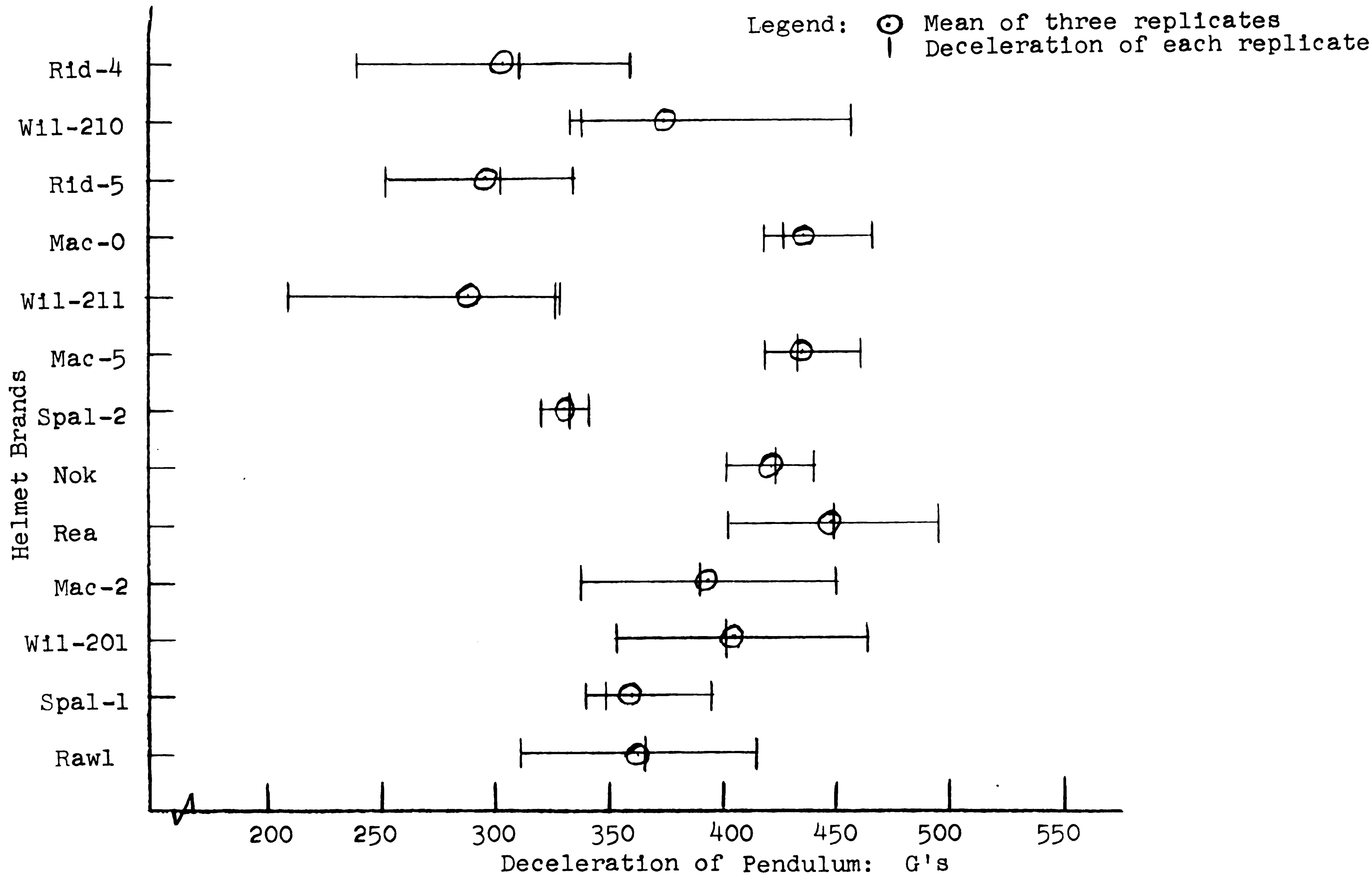

Fig. 33. Maximum Decelerations of the Pendulum Following Impact in the Front Position at Eighteen Feet Per Second.

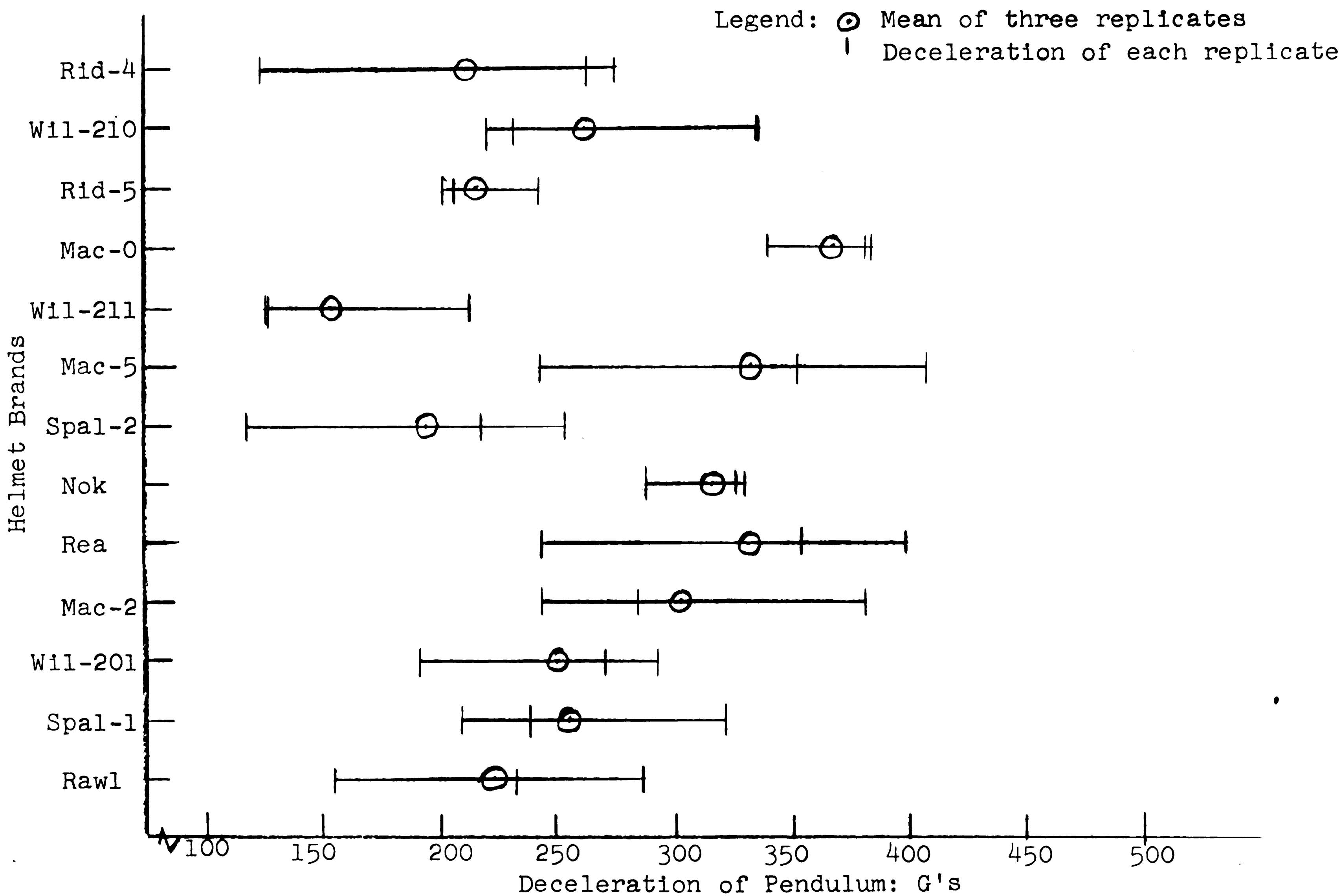

Fig. 34. Maximum Decelerations of the Pendulum Following Impact in Front Position at Fifteen Feet Per Second.

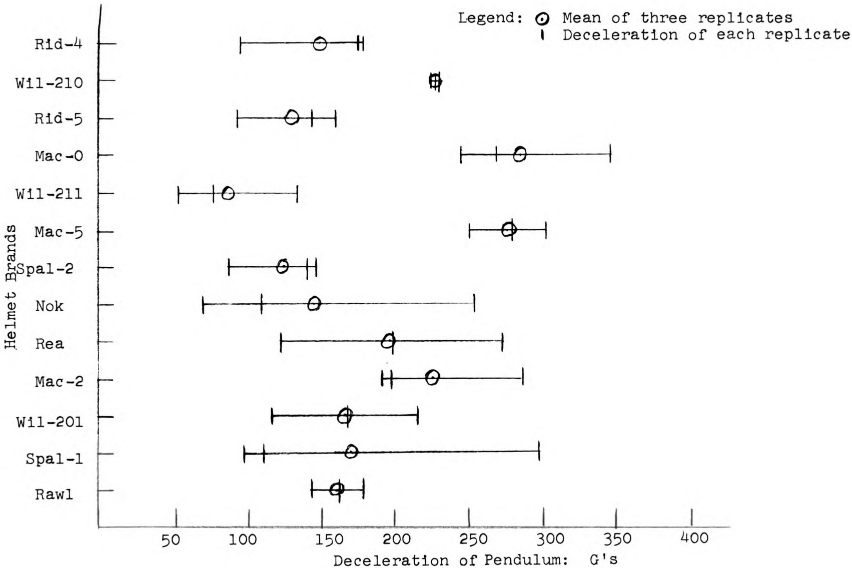

Fig. 35. Maximum Decelerations of the Pendulum Following Impact in the Front Position at Twelve Feet Per Second.

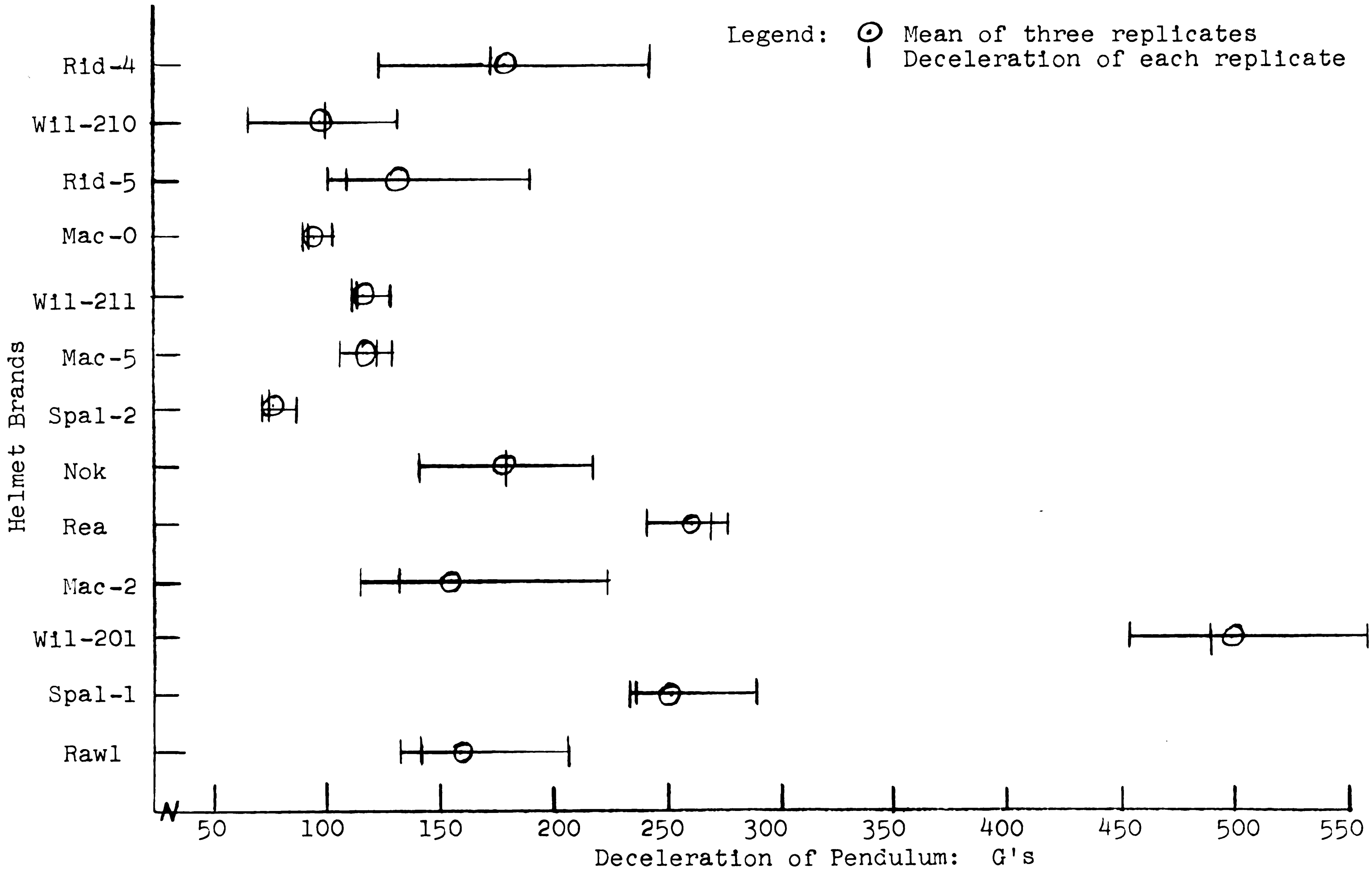

Fig.36. Maximum Decelerations of the Pendulum Following Impact in the Side Position at Twenty-one Feet Per Second.

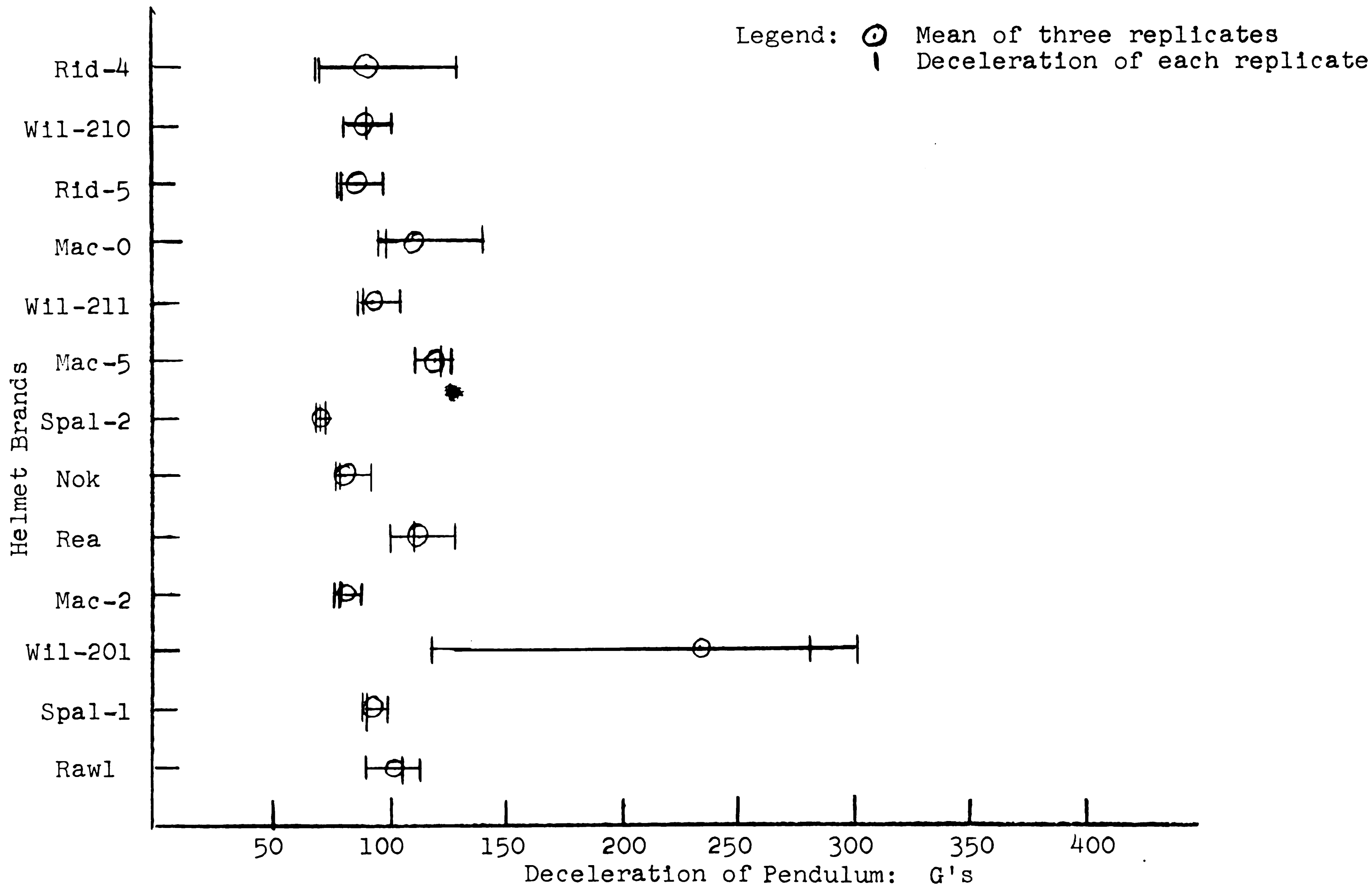

Fig. 37. Maximum Decelerations of the Pendulum Following Impact in the Side Position at Eighteen Feet Per Second.

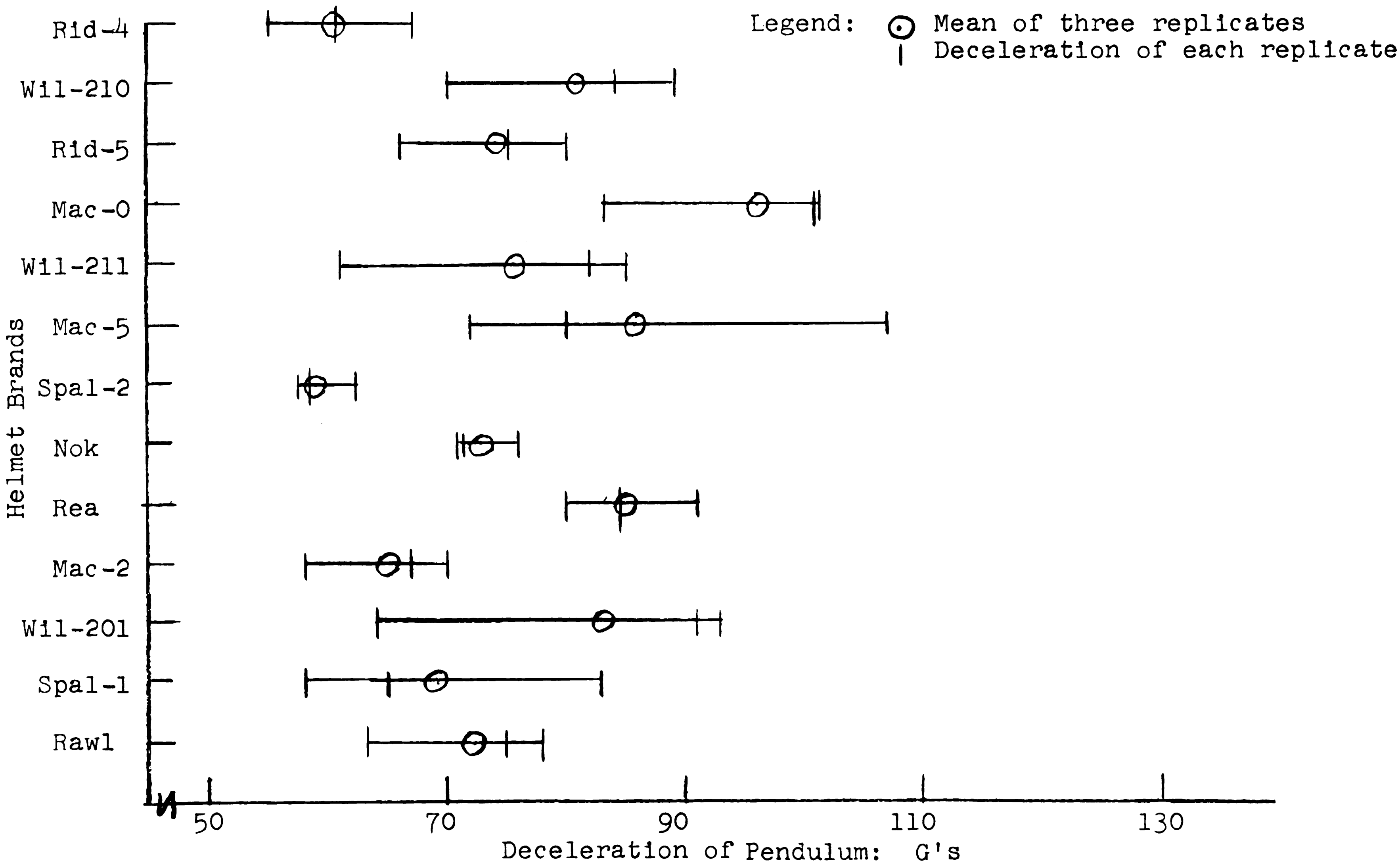

Fig. 38. Maximum Decelerations of the Pendulum Following Impact in the Side Position at Fifteen Feet Per Second.

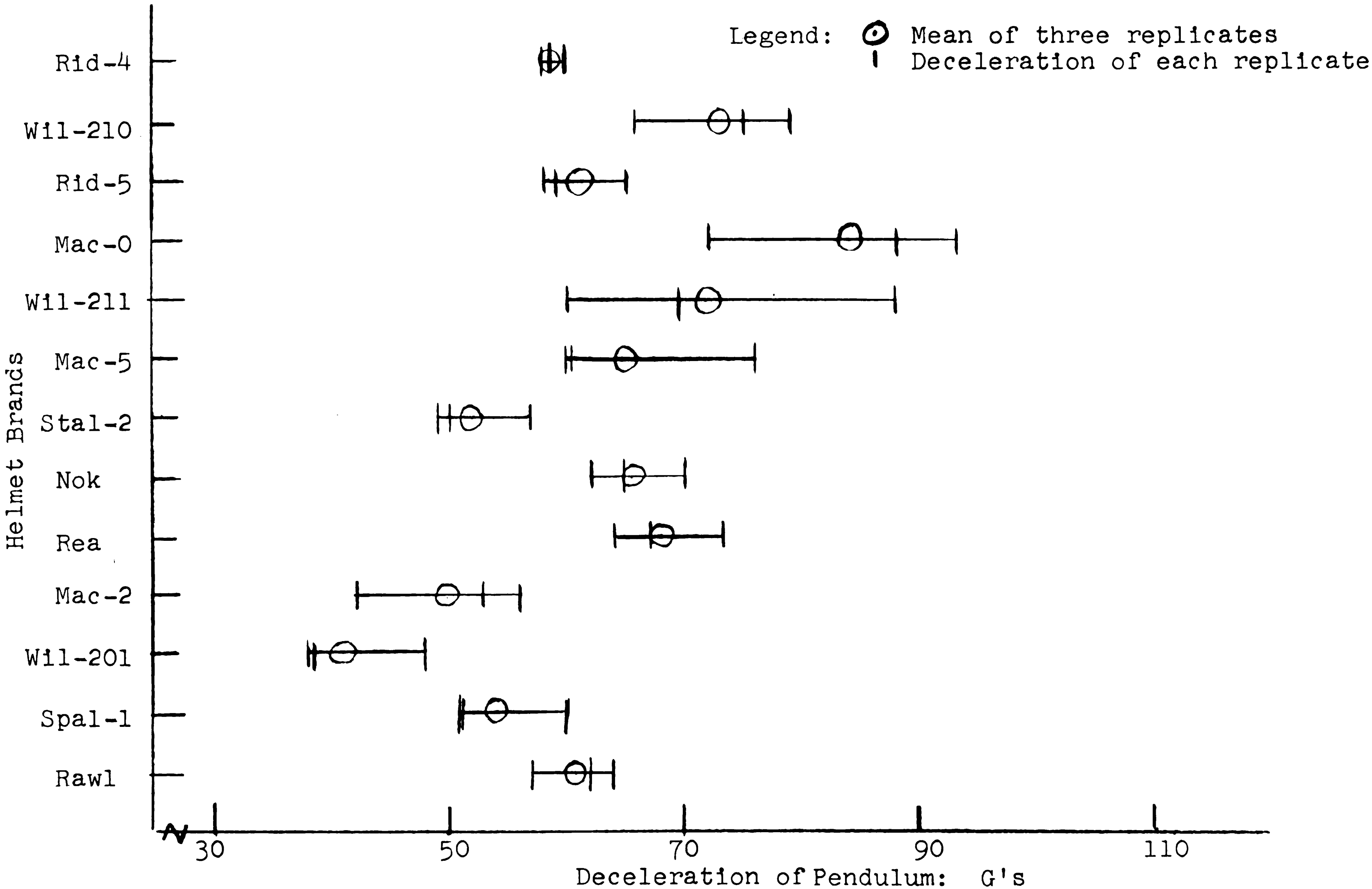

Fig. 39. Maximum Decelerations of the Pendulum Following Impact in the Side Position at Twelve Feet Per Second.

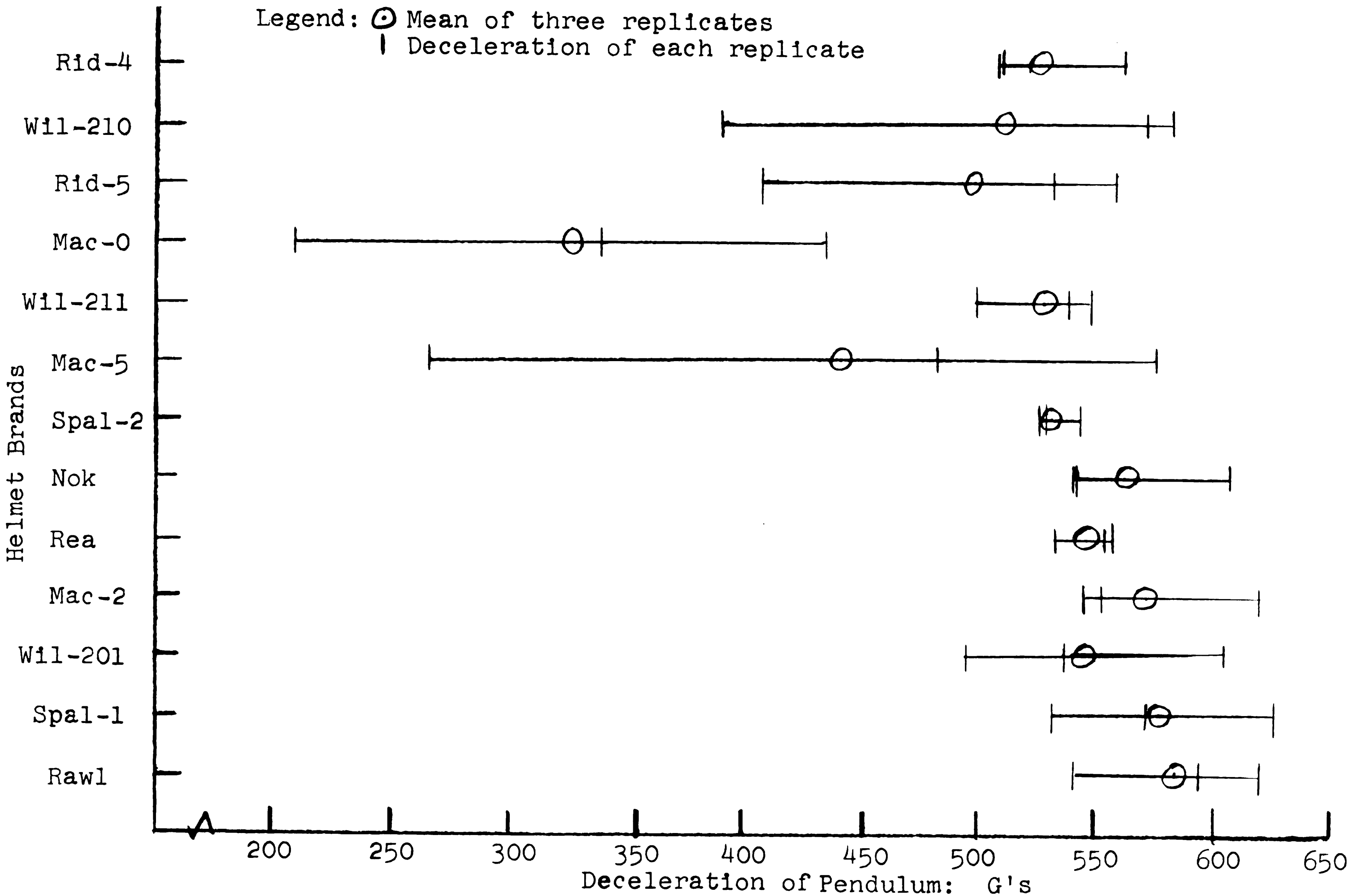

Fig. 40. Maximum Decelerations of the Pendulum Following Impact in the Back Position at Twenty-one Feet Per Second.

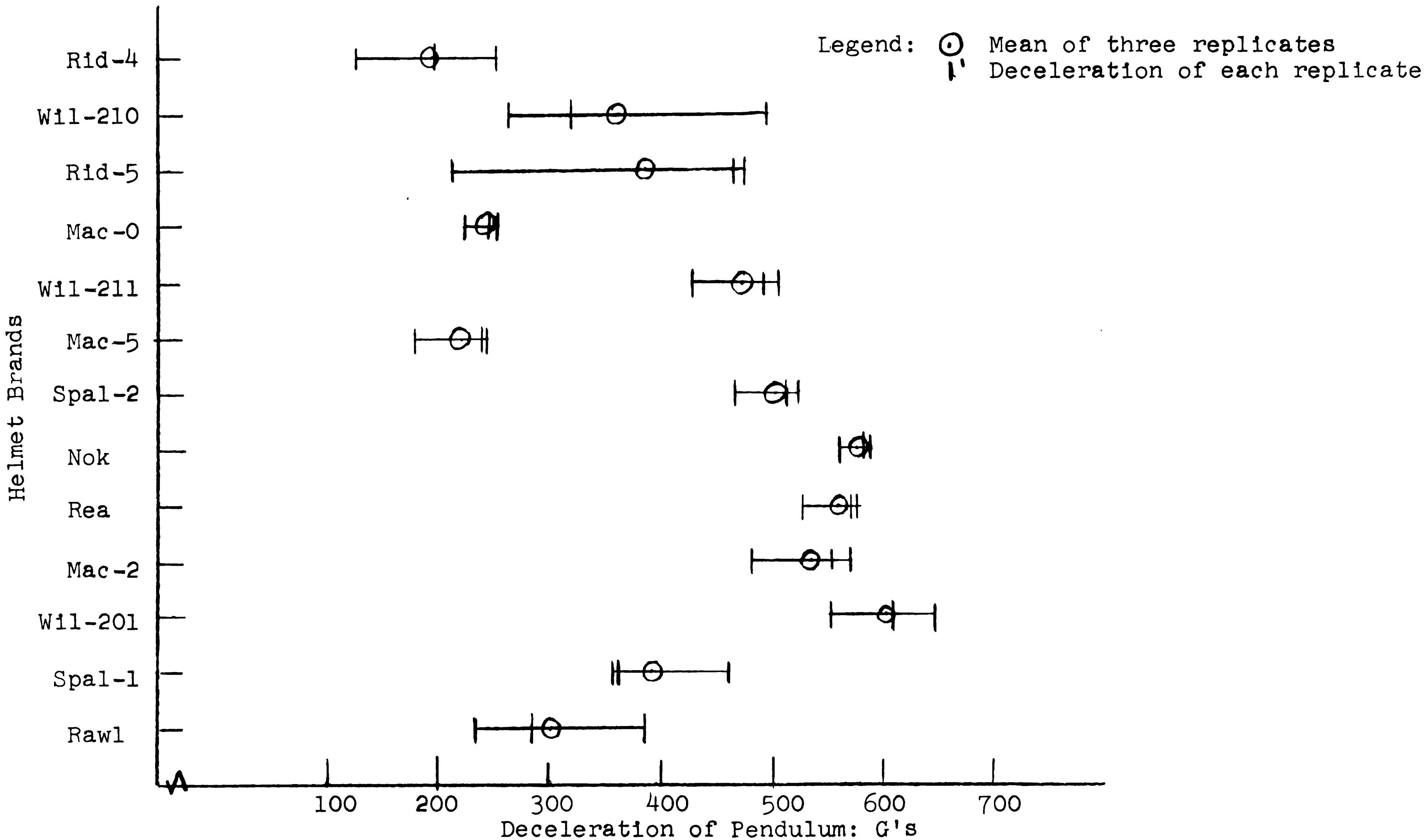

Fig. 41. Maximum Decelerations of the Pendulum Following Impact in the Back Position at Eighteen Feet Per Second.

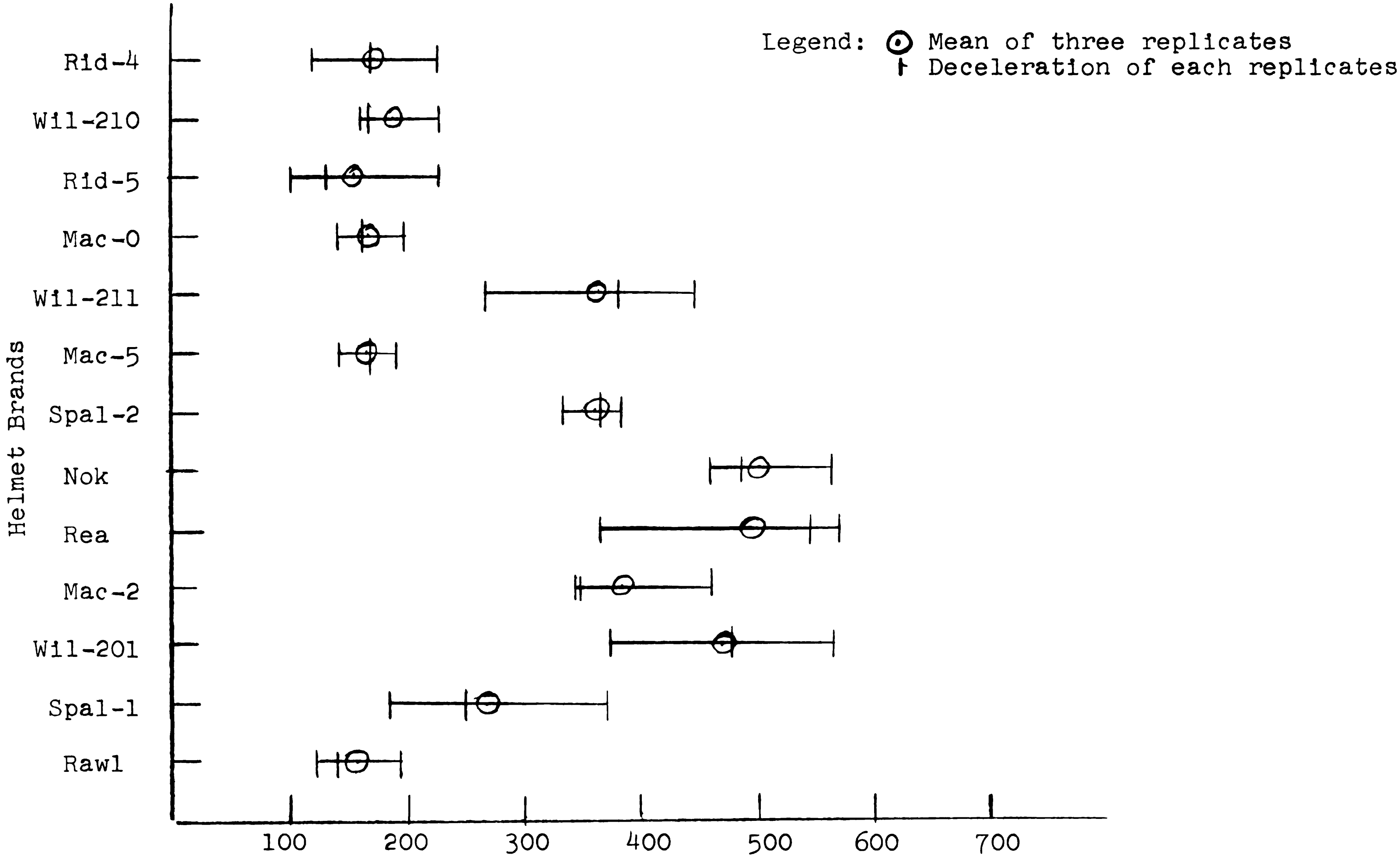

Fig. 43. Maximum Decelerations of the Pendulum Following Impact in the Back Position at Fifteen Feet Per Second.

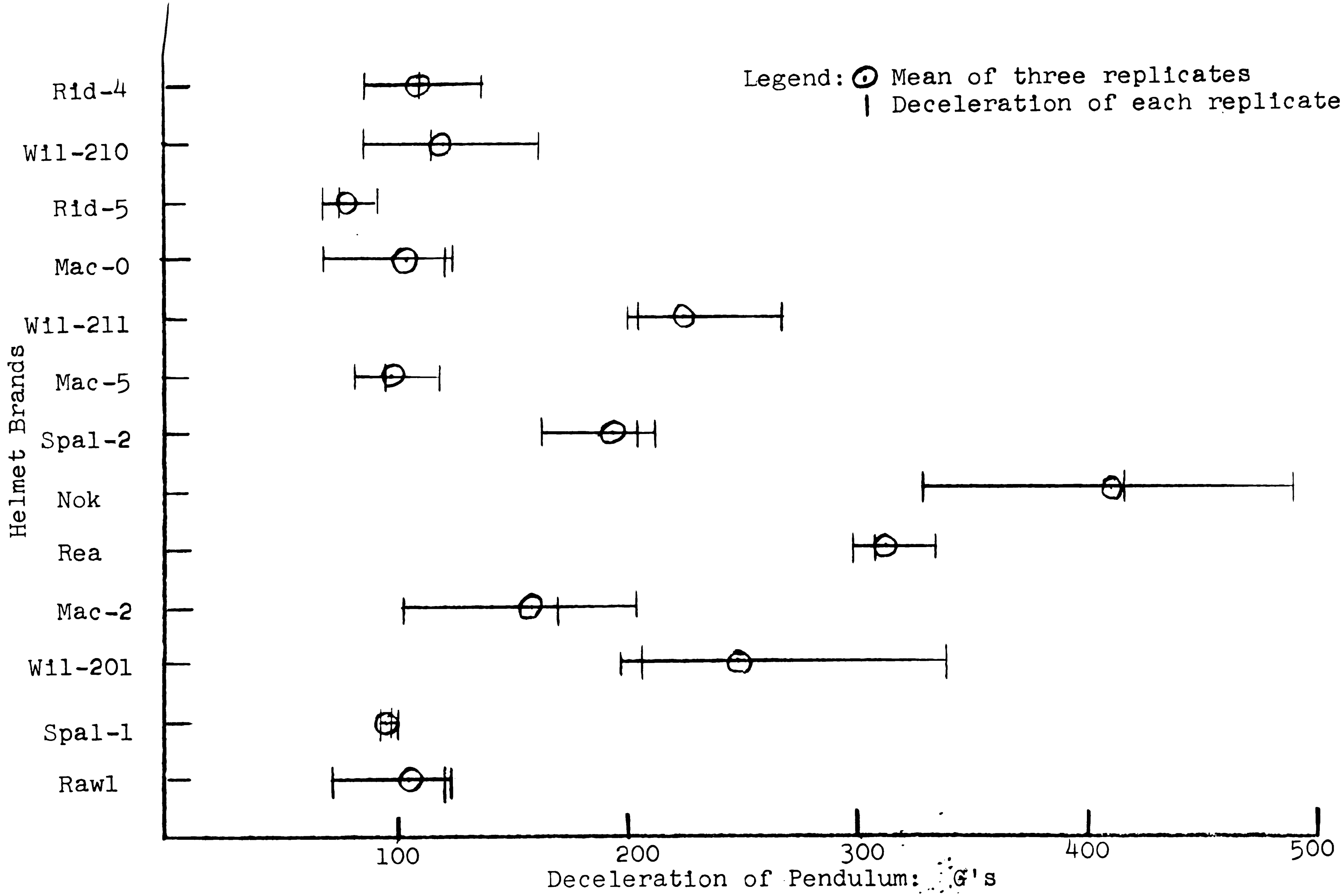

Fig. 43. Maximum Decelerations of the Pendulum Following Impact in the Back Position at Twelve Feet Per Second.

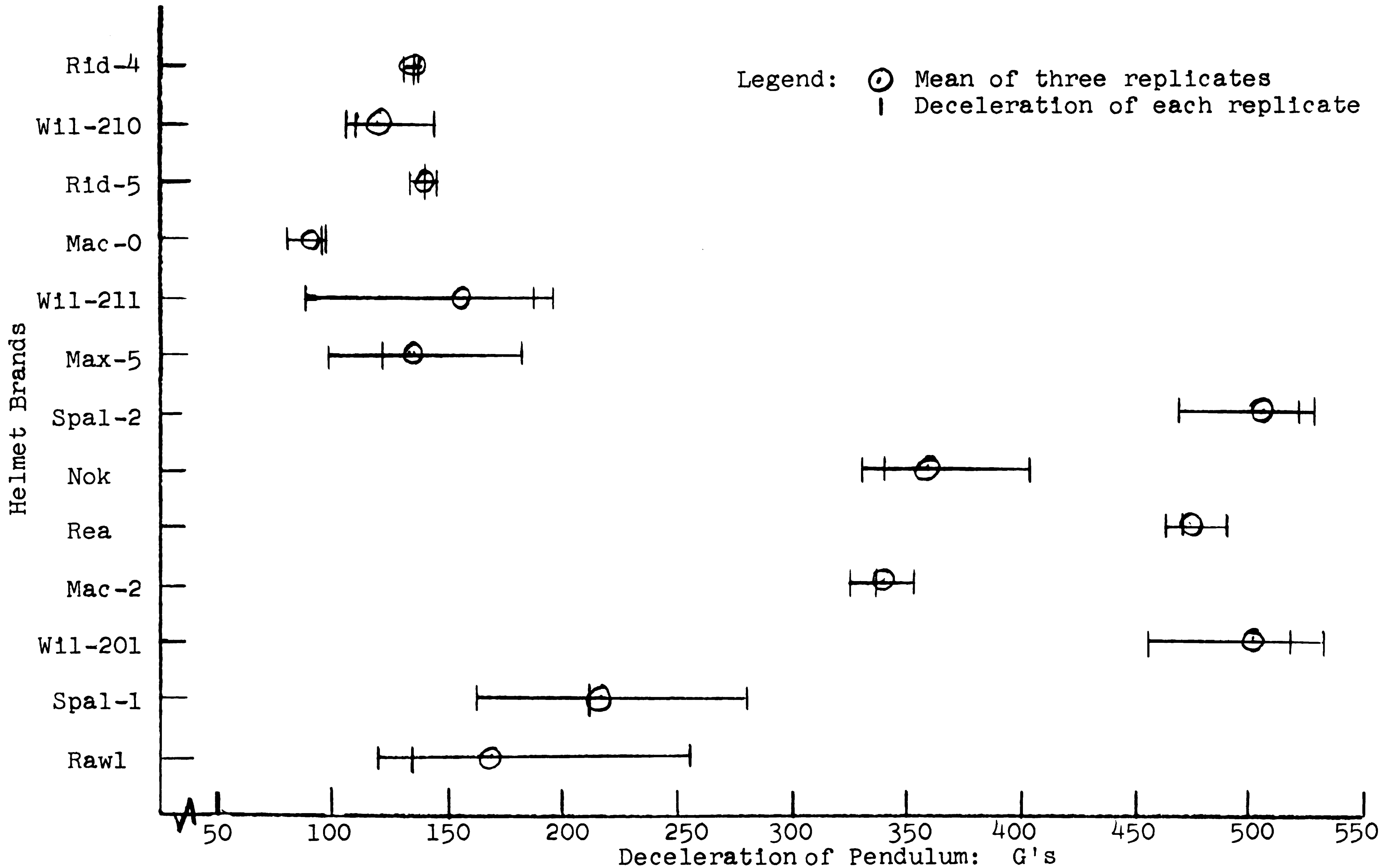

Fig. 44. Maximum Decelerations of the Pendulum Following Impact in the Top Position at Twenty-one Feet Per Second.

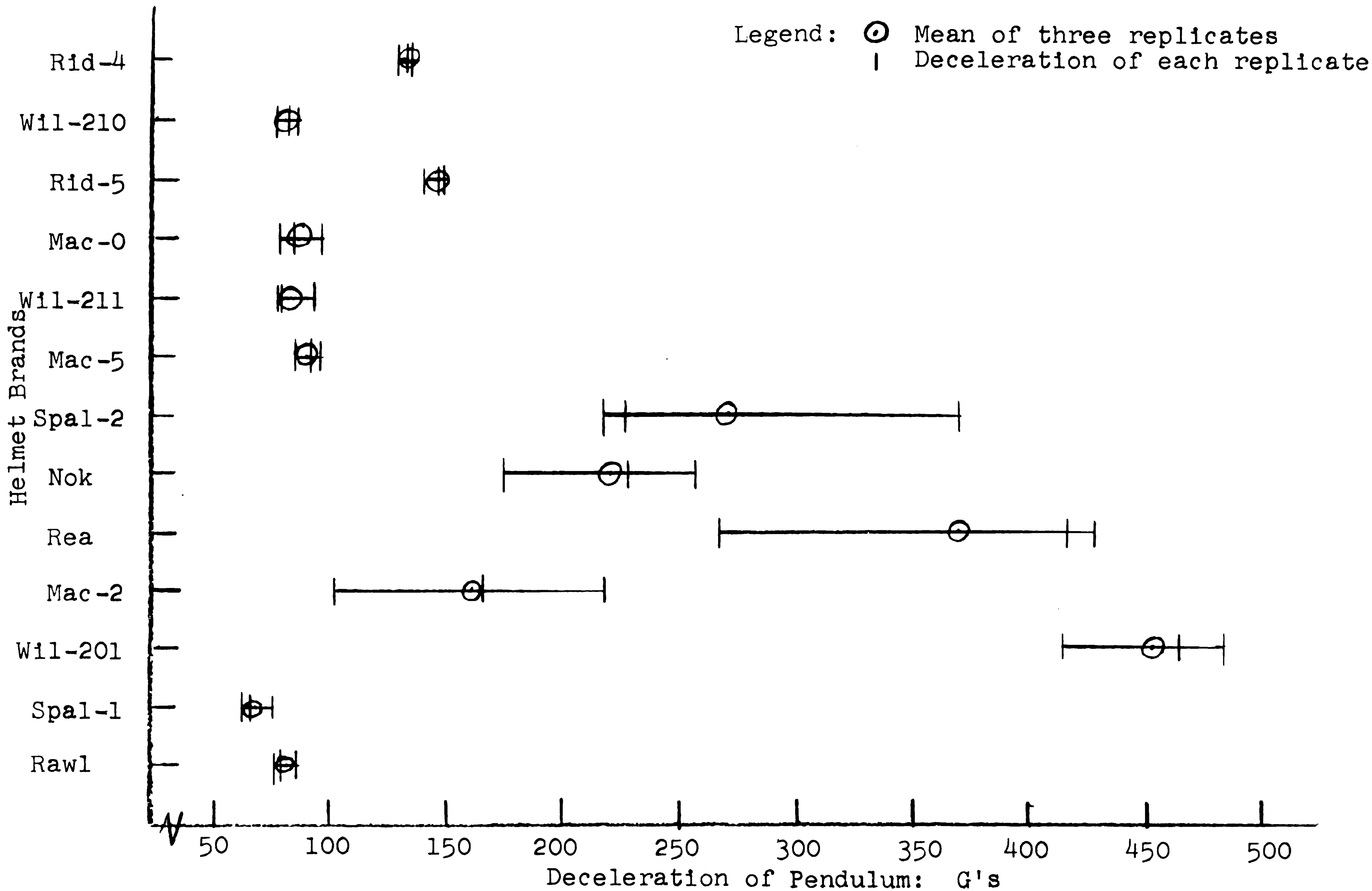

Fig. 45. Maximum Decelerations of the Pendulum Following Impact in the Top Position at Eighteen Feet Per Second.

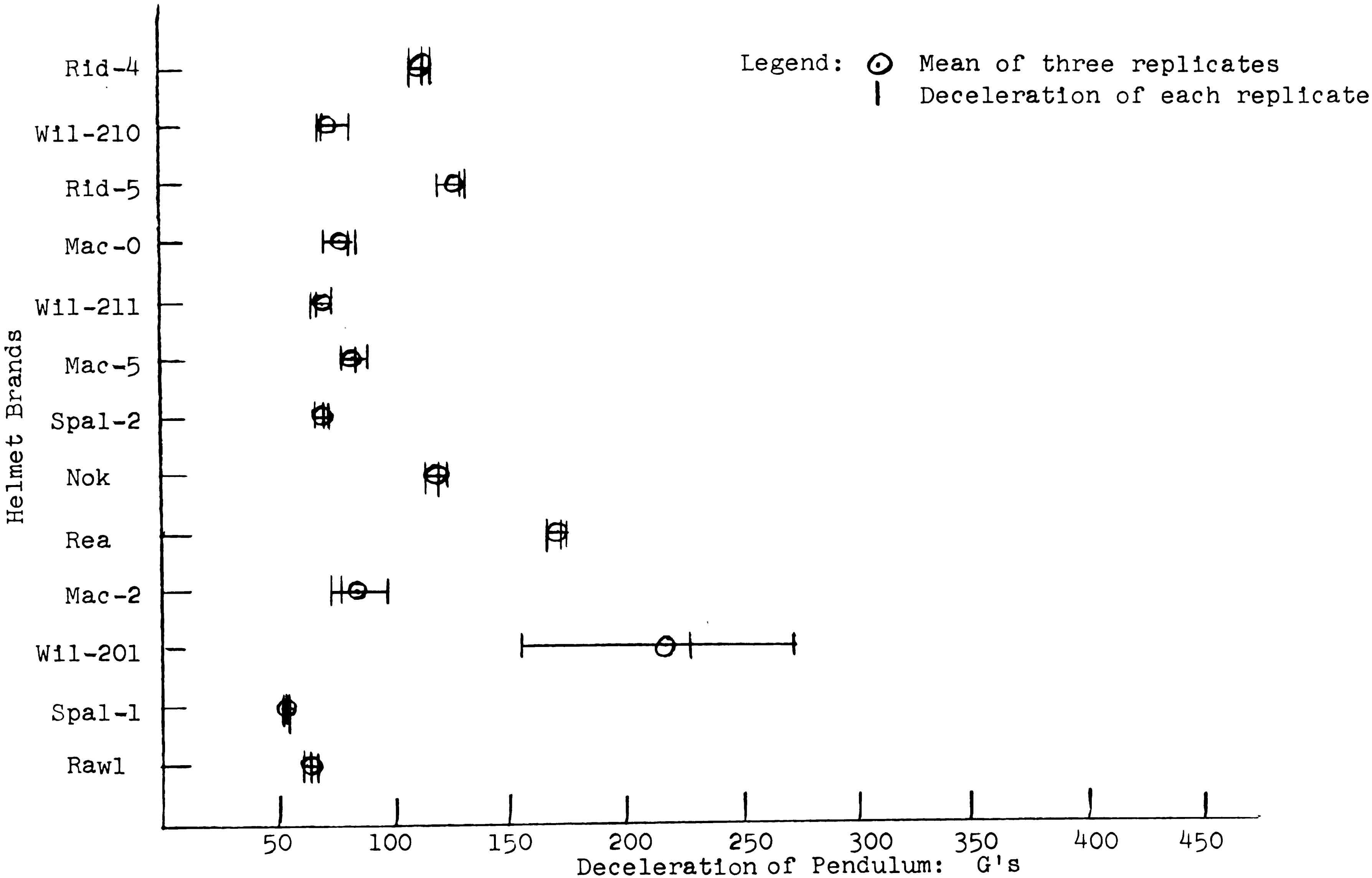

Fig. 46. Maximum Decelerations of the Pendulum FollowingImpact in the Top Position at Fifteen Feet Per Second.

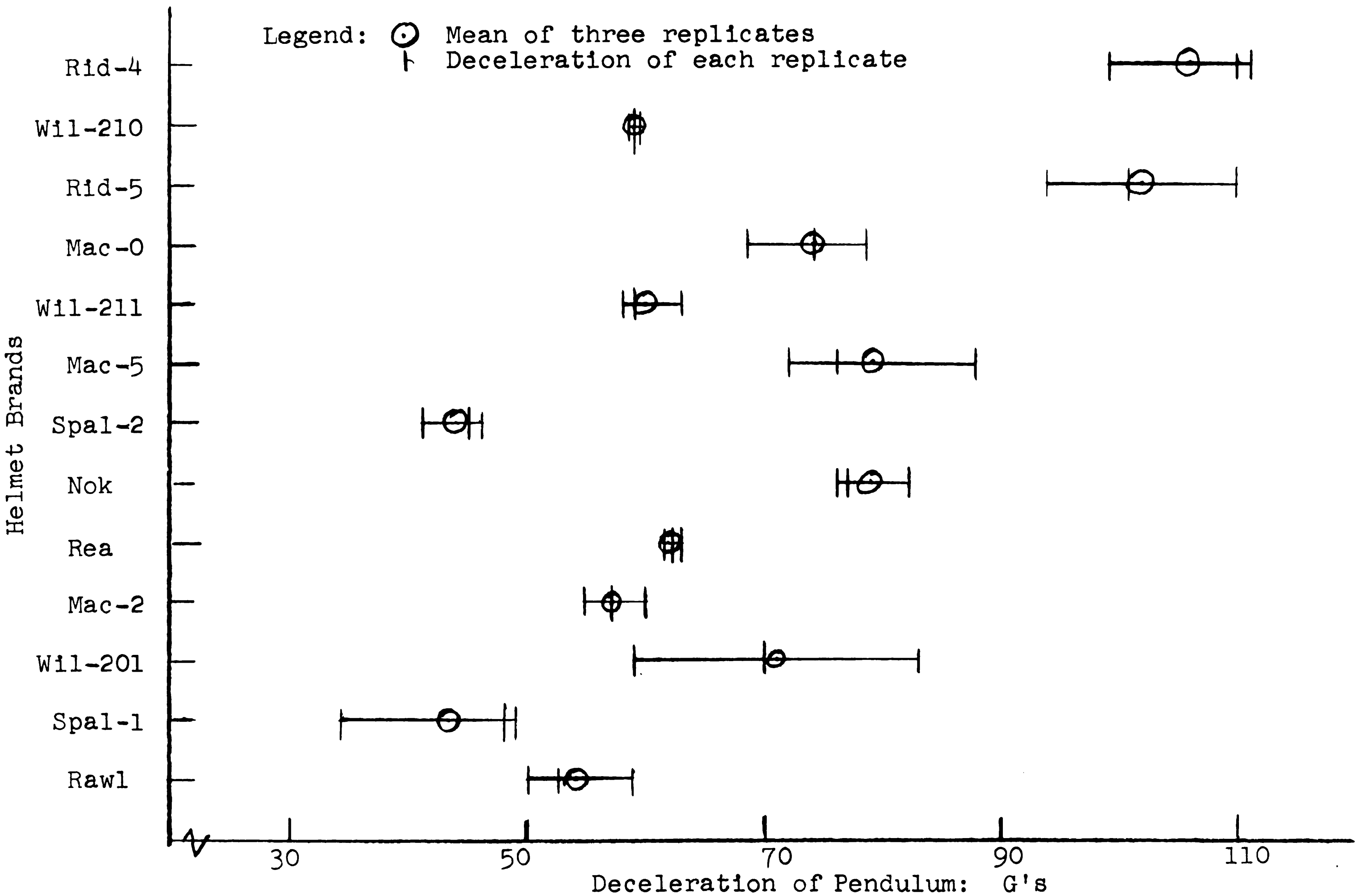

Fig. 47. Maximum Decelerations of the Pendulum Following Impact in the Top Position at Twelve Feet Per Second.

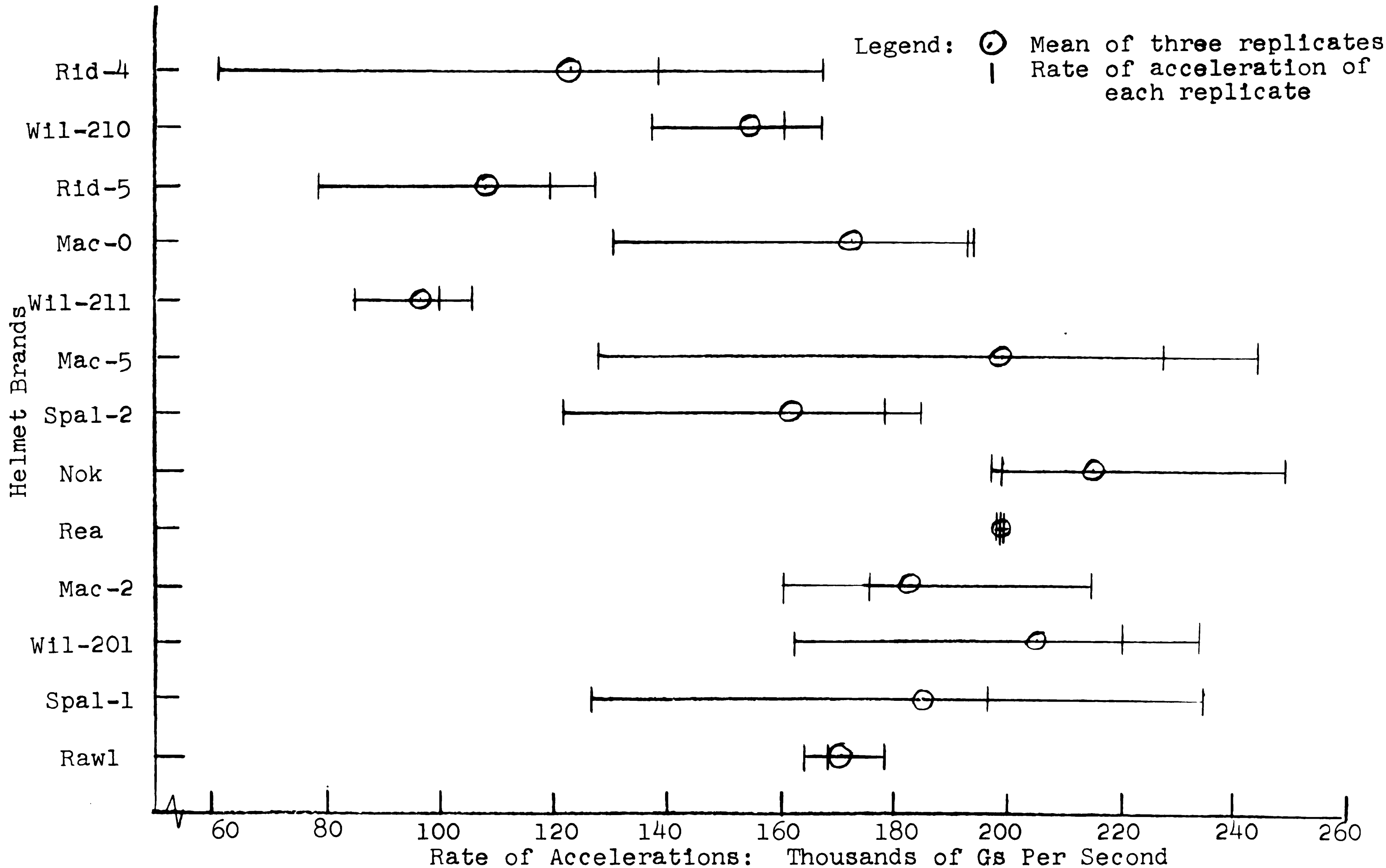

Fig. 48. Rates of Acceleration of All Helmets Following Impact in the Front Position at Twenty-one Feet Per Second.

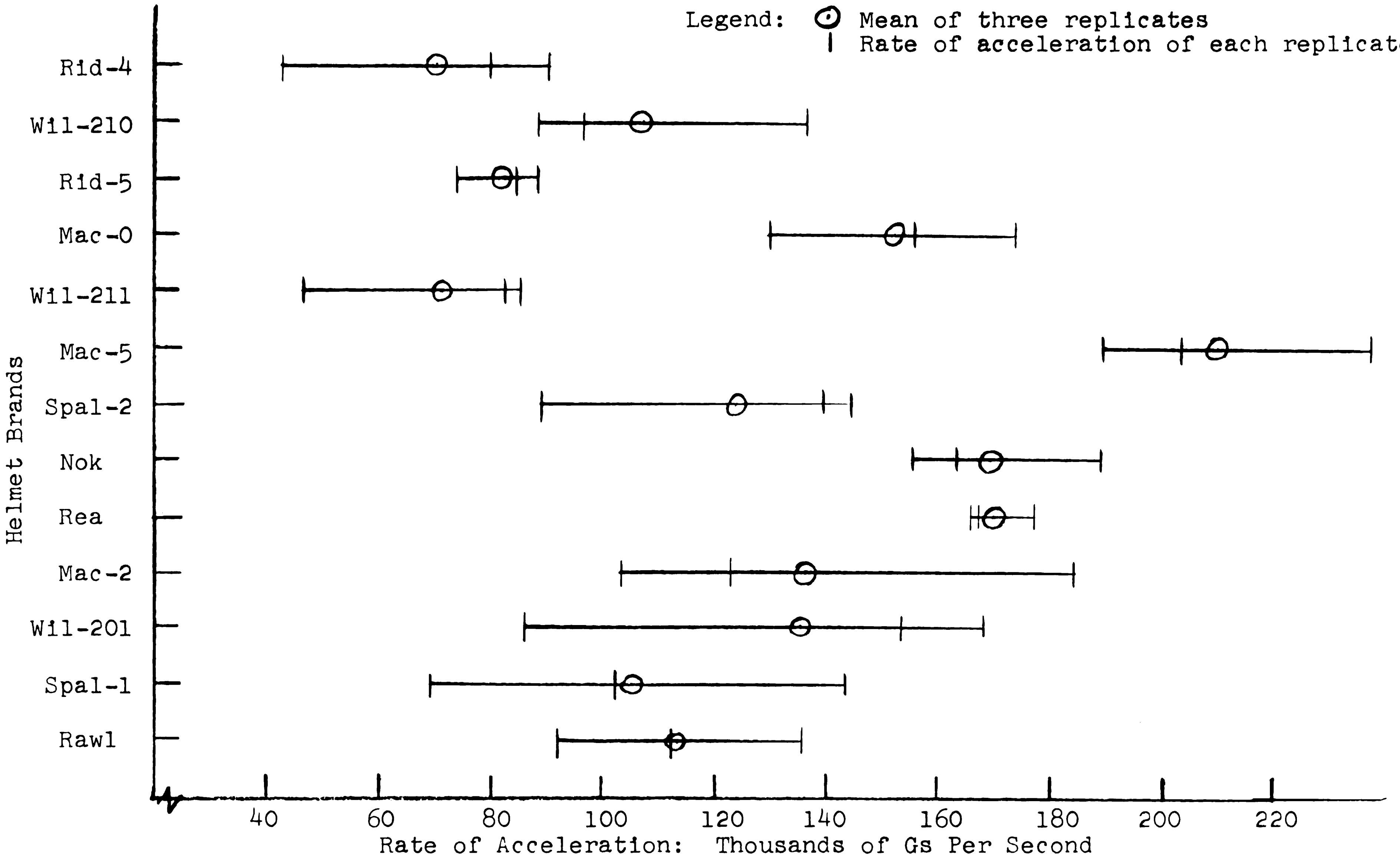

Fig. 49. Rates of Acceleration of All Helmets Following Impact in the Front Position at Eighteen Feet Per Second.

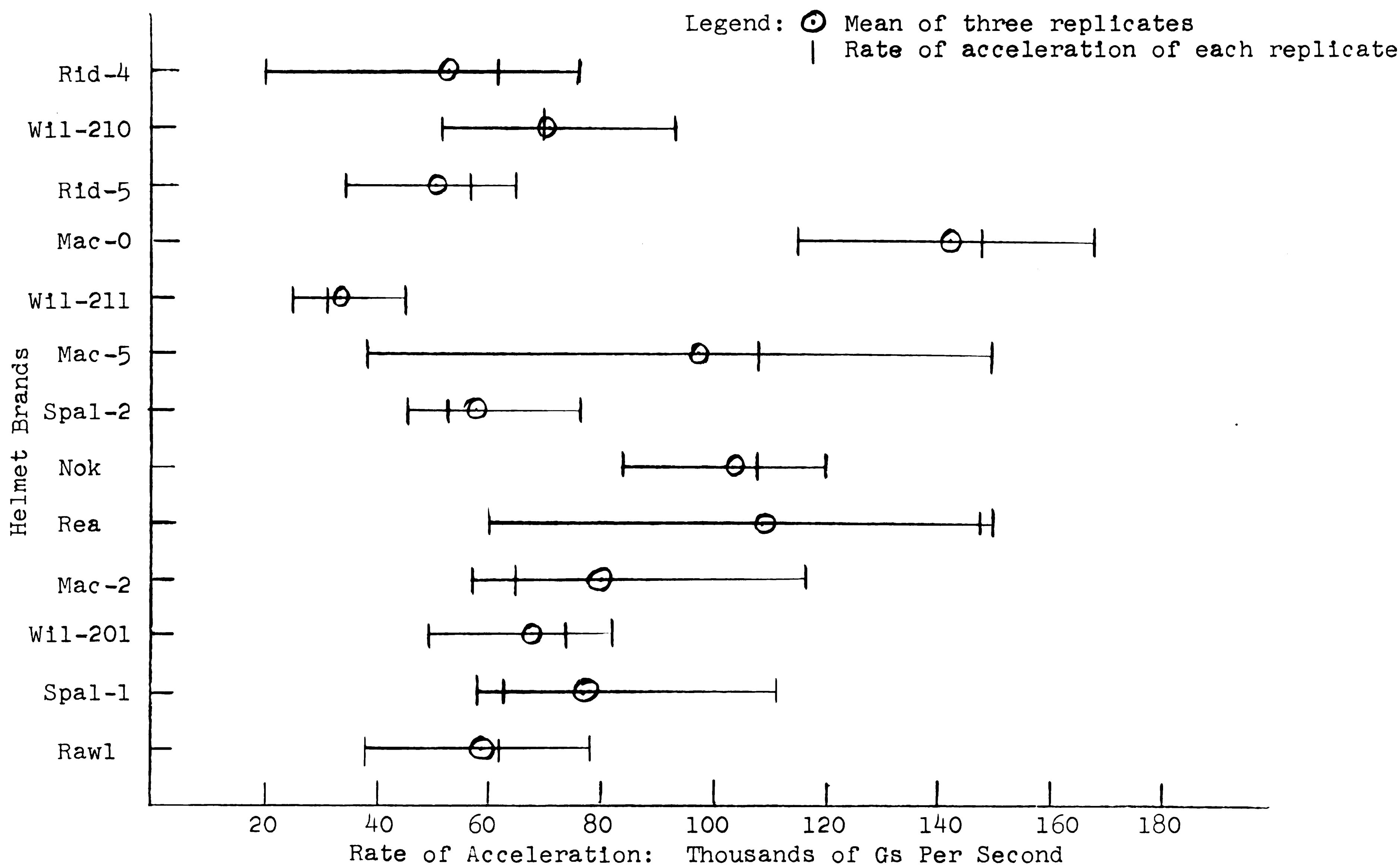

Fig. 50. Rates of Acceleration of All Helmets Following Impact in the Front Position at Fifteen Feet Per Second.

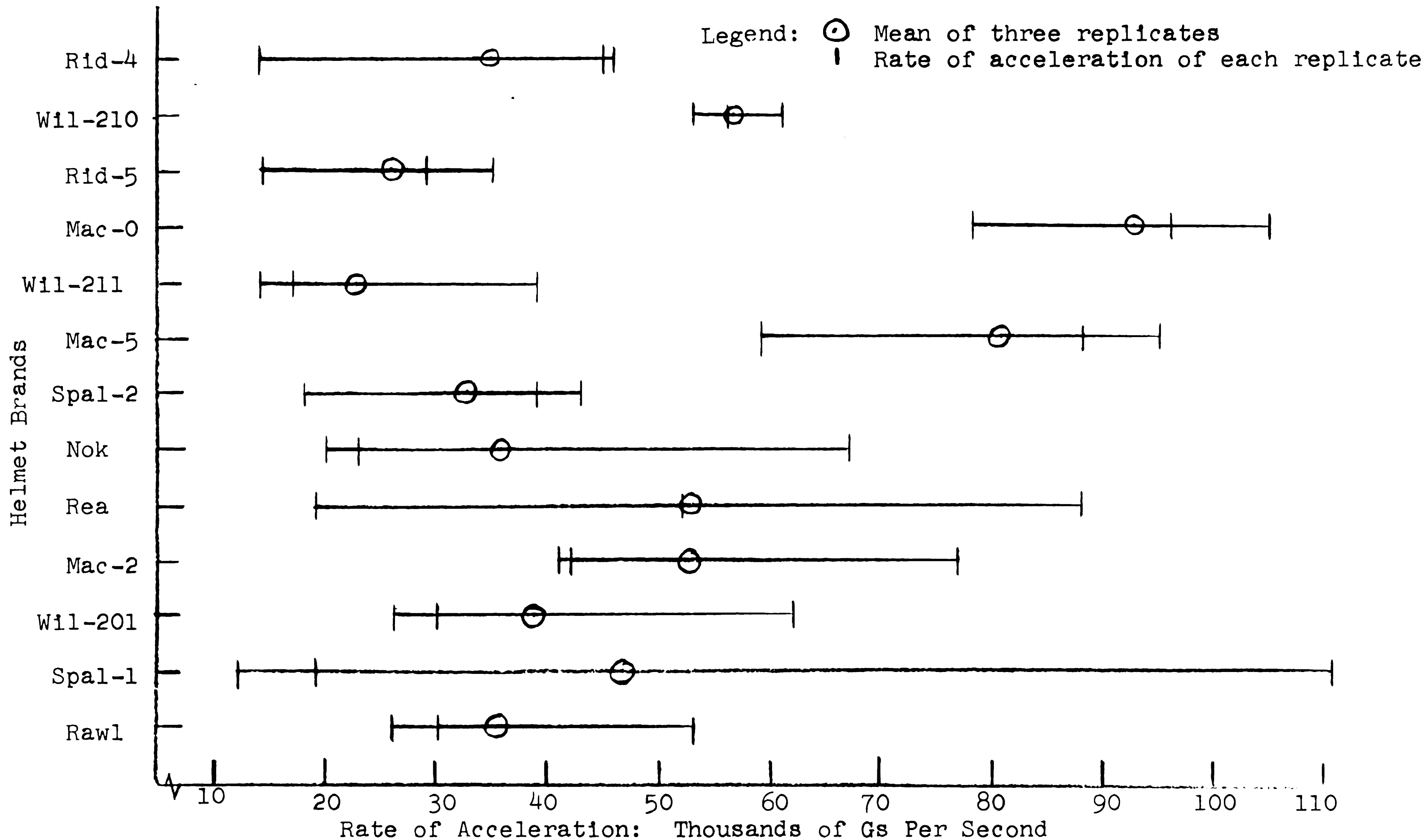

Fig. 51. Rates of Acceleration of All Helmets Following Impact in the Front Position at Twelve Feet Per Second.

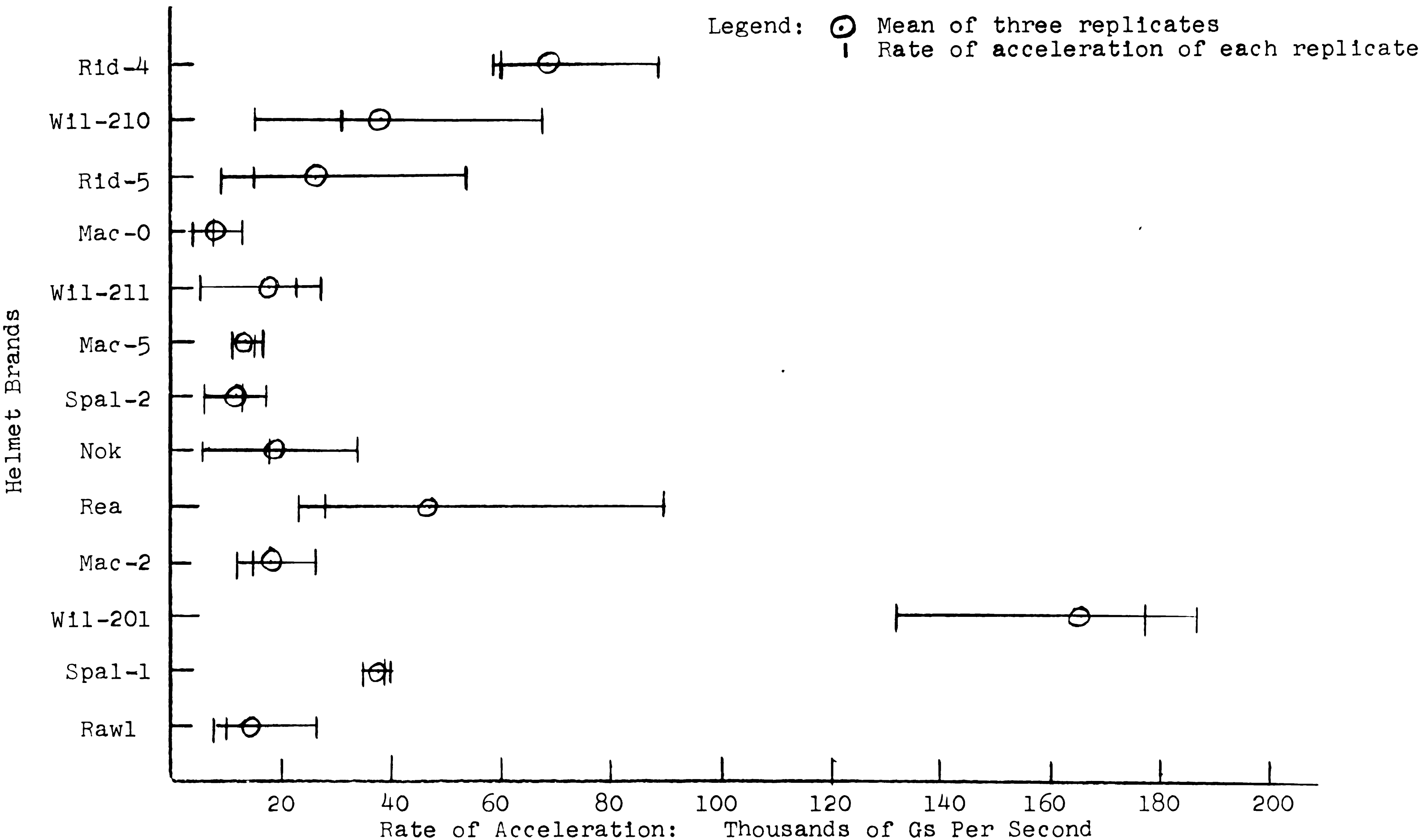

Fig. 52. Rates of Acceleration of All Helmets Following Impact in the Side Position at Twenty-one Feet Per Second.

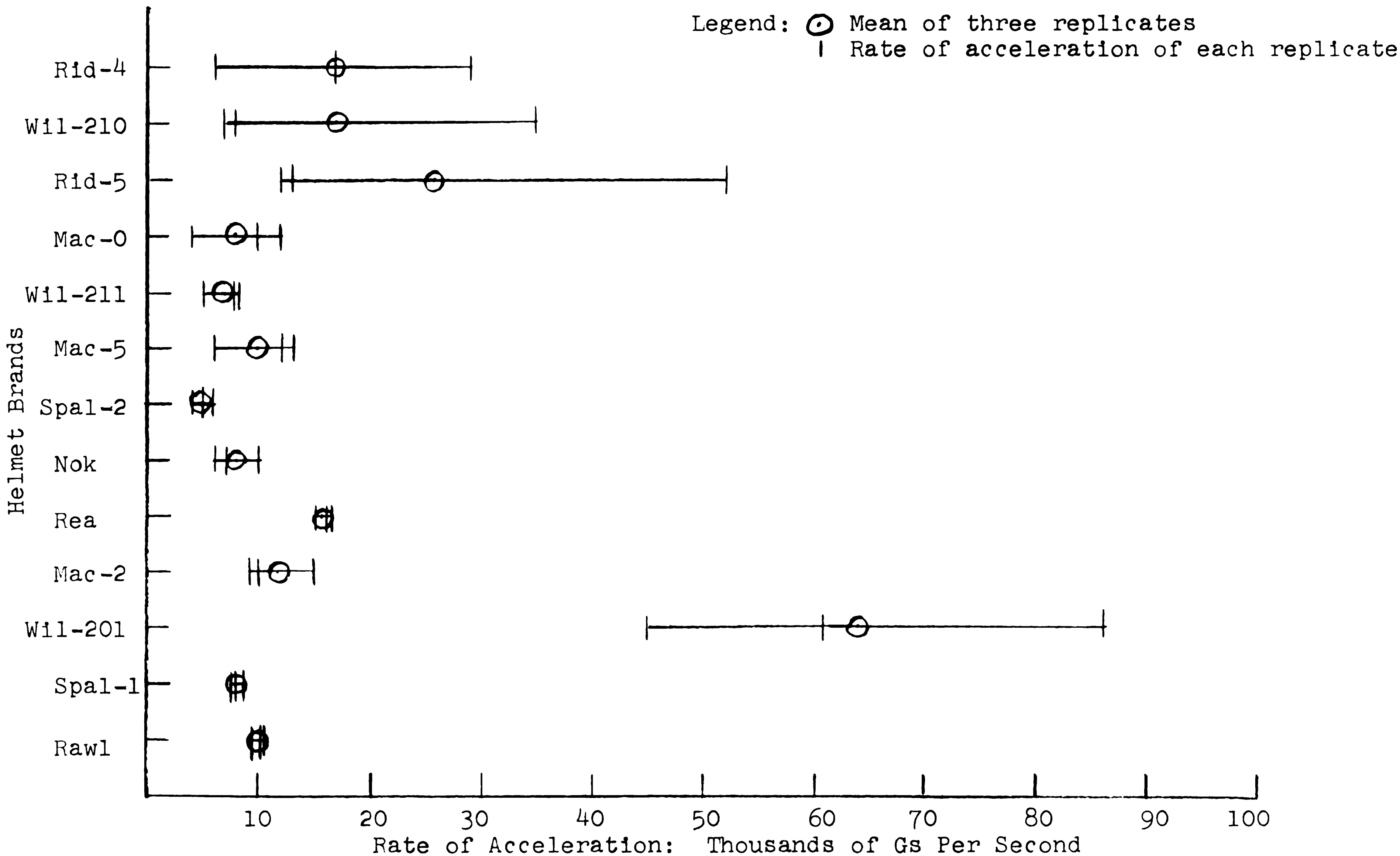

Fig. 53. Rates of Acceleration of All Helmets Following Impact in the Side Position at Eighteen Feet Per Second.

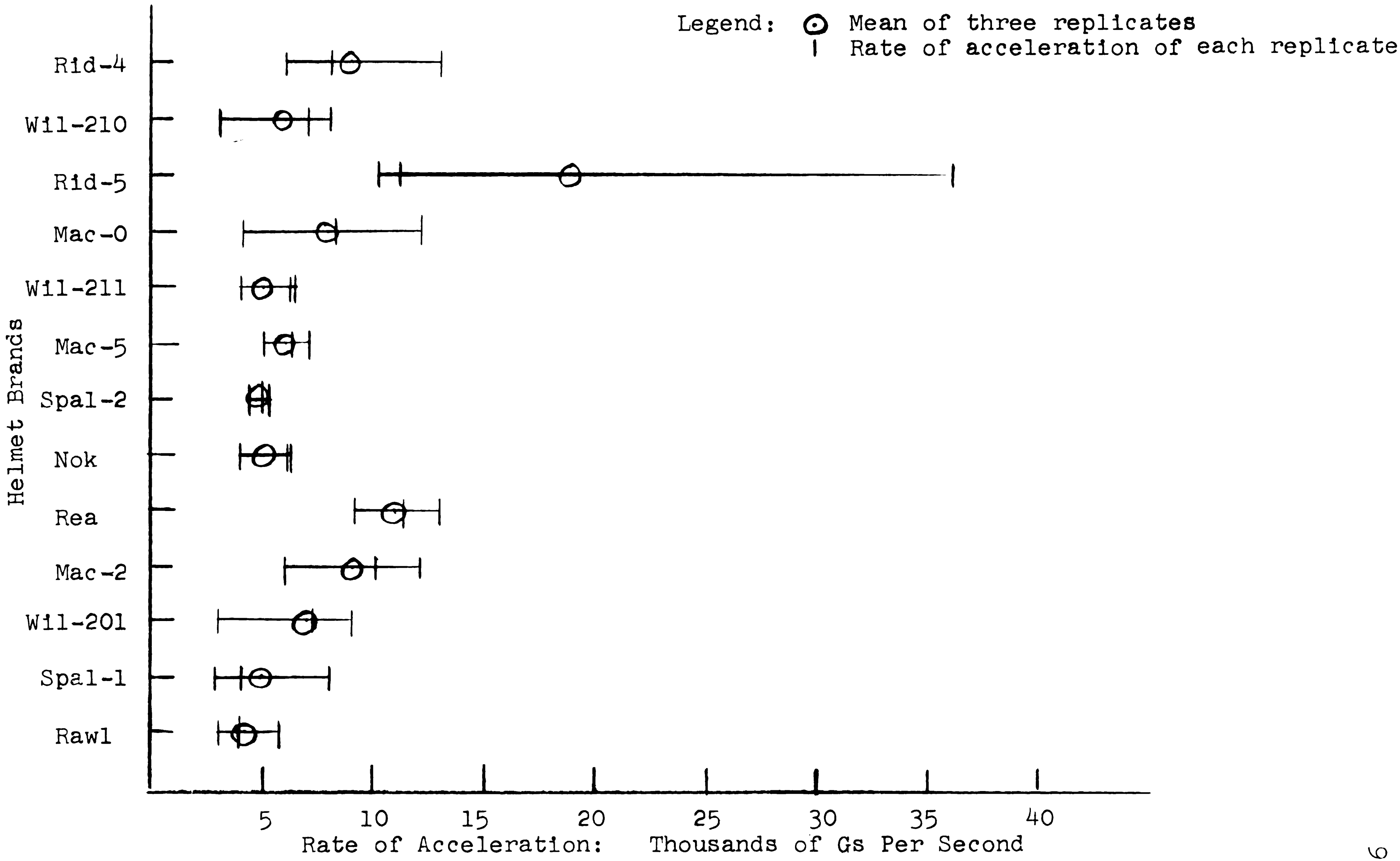

Fig. 54. Rates of Acceleration of All Helmets Following Impact in the Side Position at Fifteen Feet Per Second.

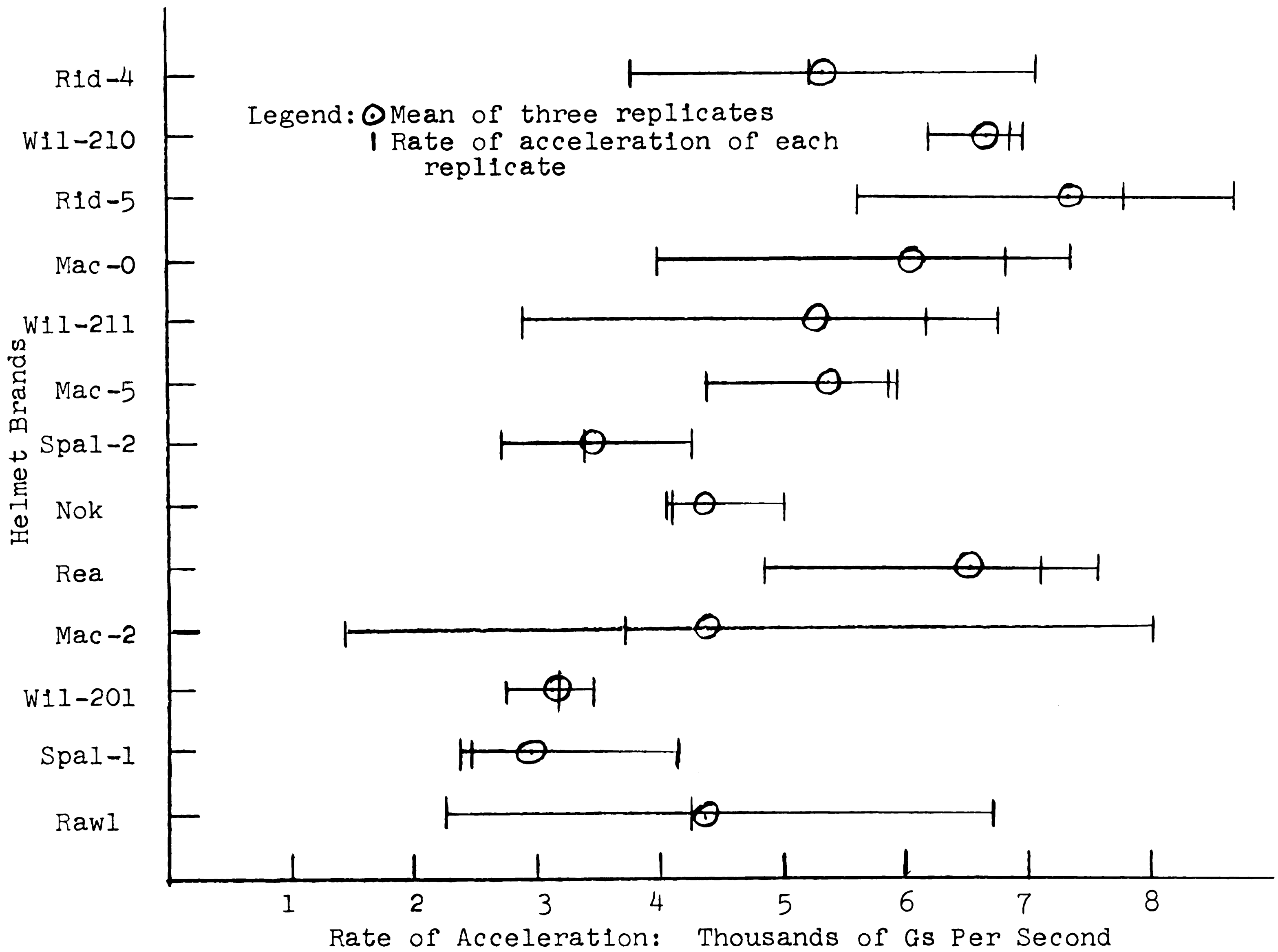

Fig. 55. Rates of Acceleration of All Helmets Following Impact in the Side Position at Twelve Feet Per Second.

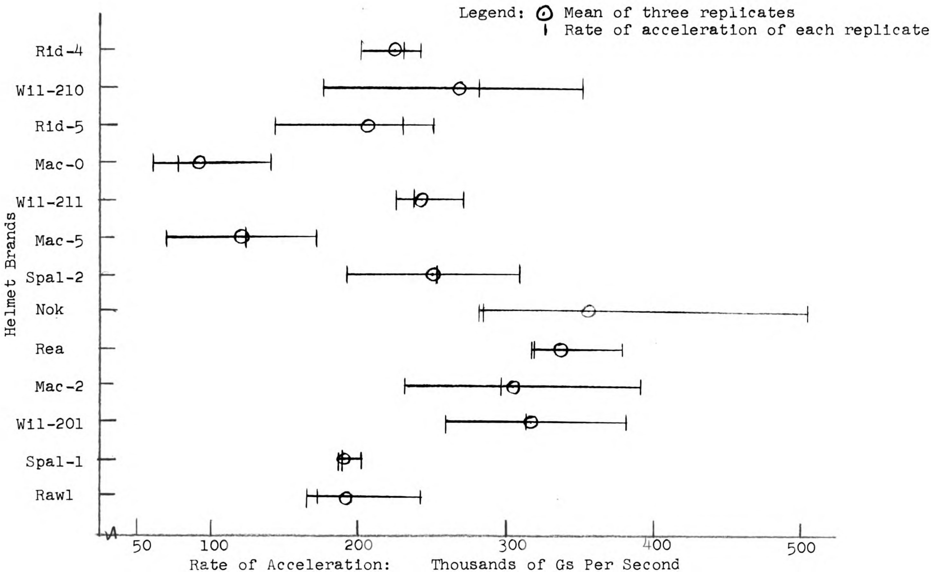

Fig. 56. Rates of Acceleration of All Helmets Following Impact in the Back Position at Twenty-one Feet Per Second.

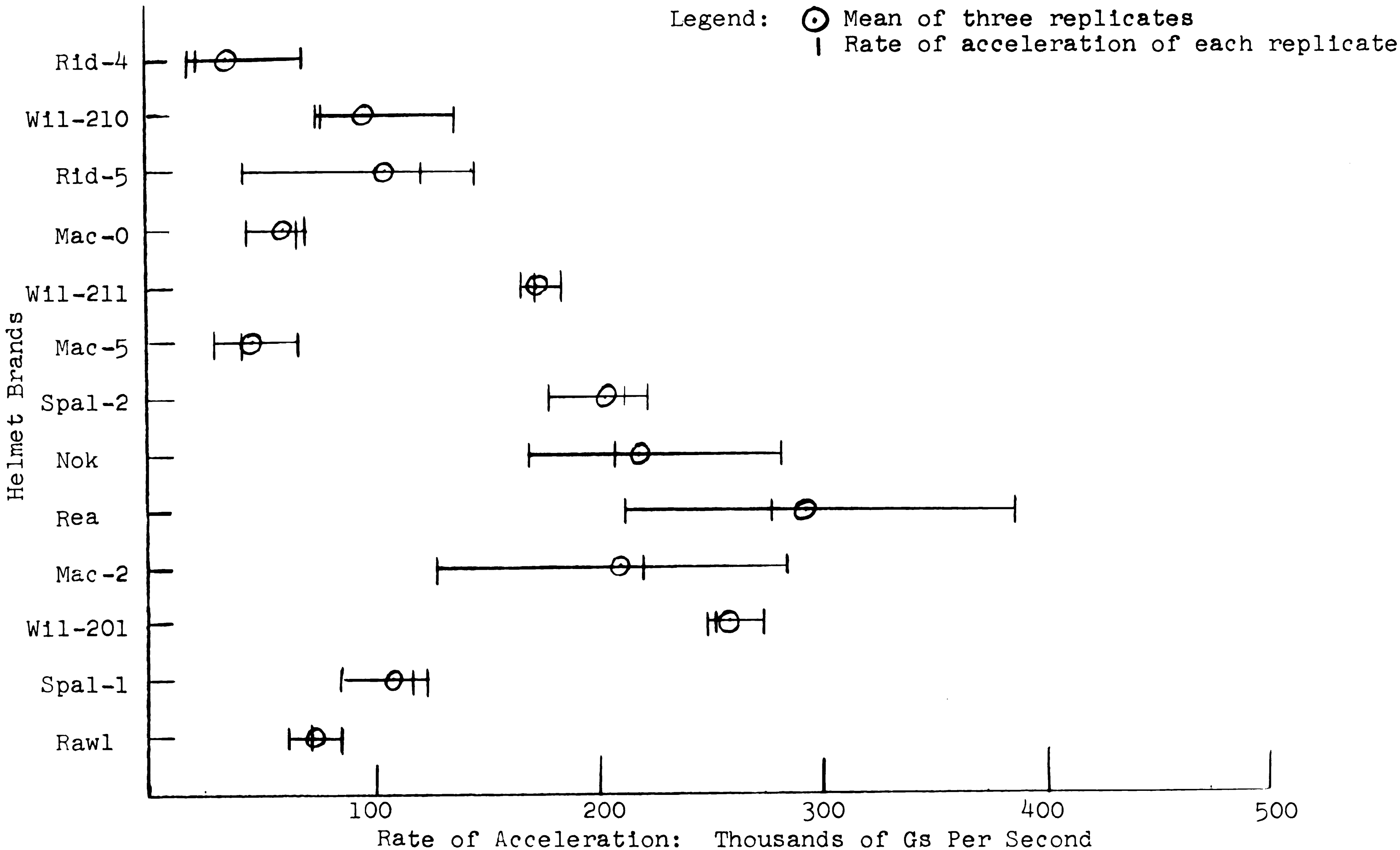

Fig. 57. Rates of Acceleration of All Helmets Following Impact in the Back Position at Eighteen Feet Per Second.

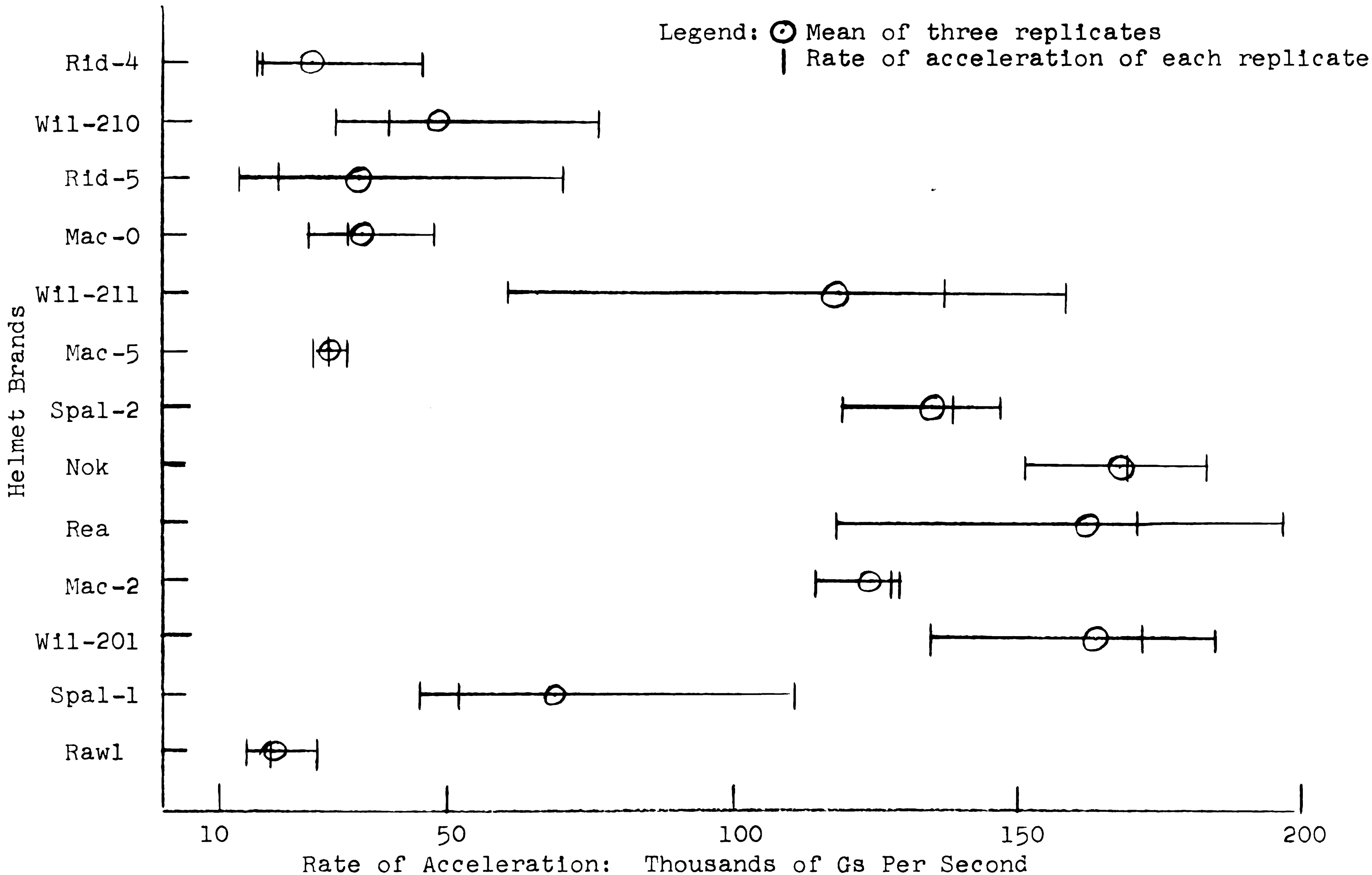

Fig. 58. Rates of Acceleration of All Helmets Following Impact in the Back Position at Fifteen Feet Per Second.

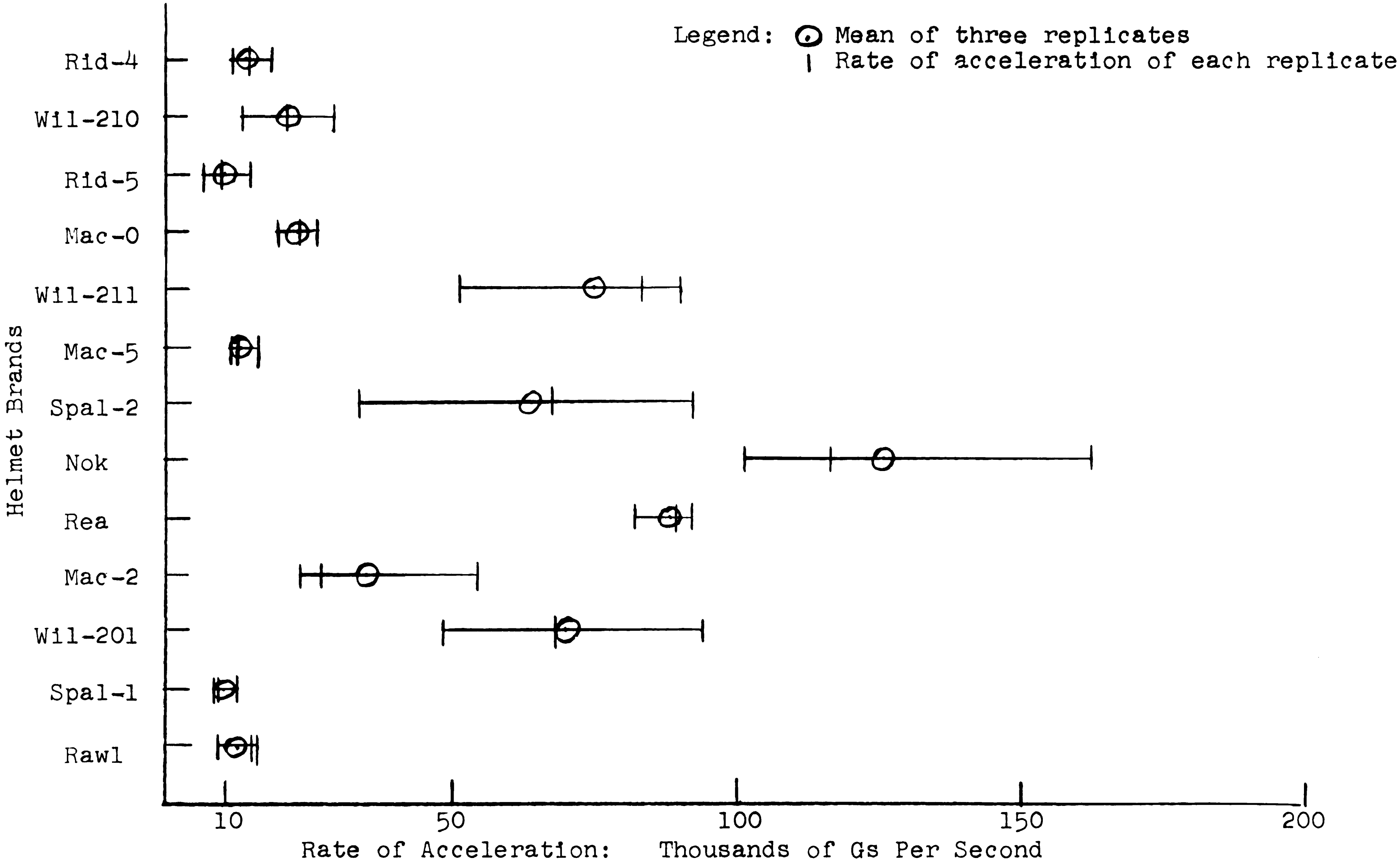

Fig. 59. Rates of Acceleration of All Helmets Following Impact in the Back Position at Twelve Feet Per Second.

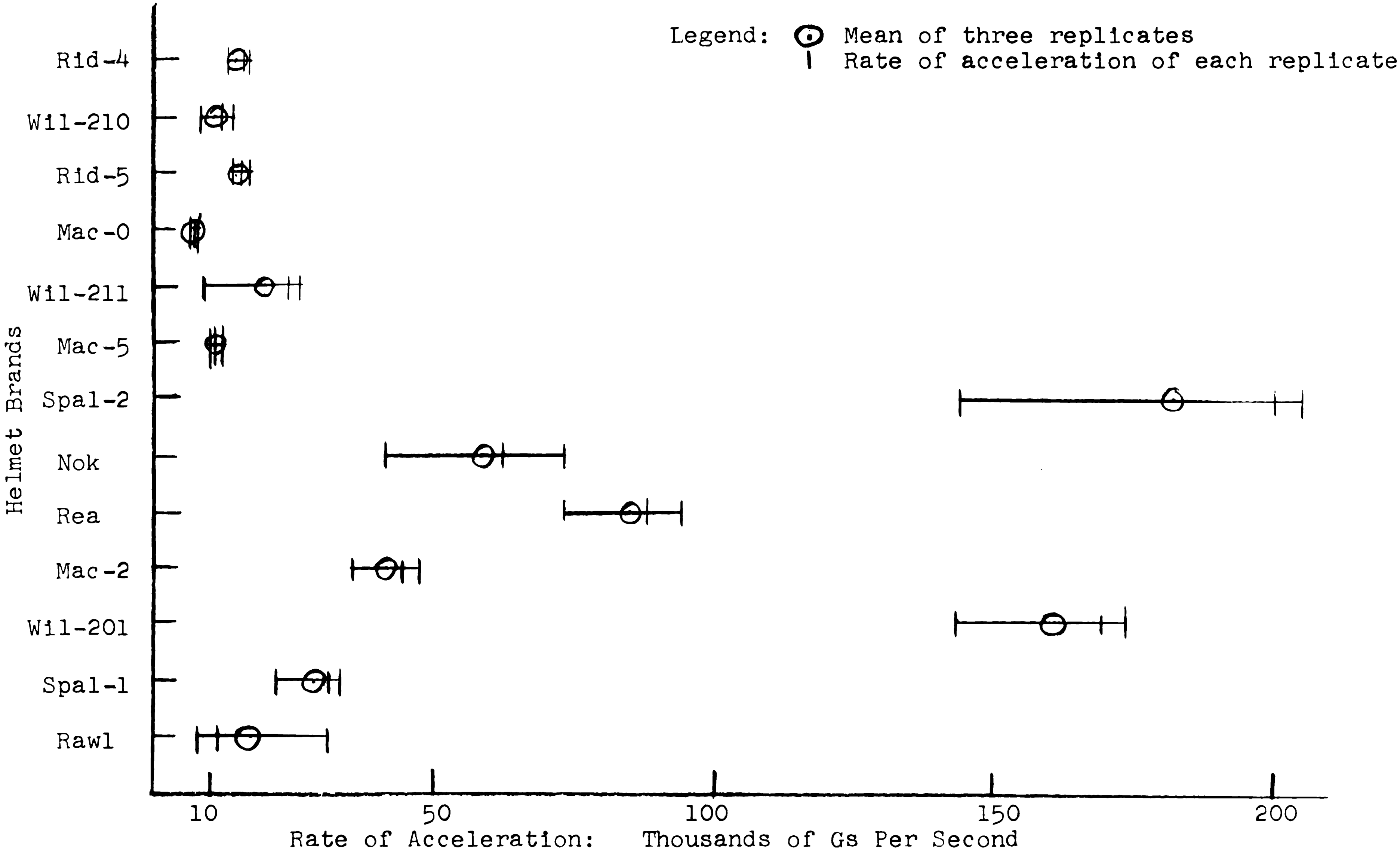

Fig. 60. Rates of Acceleration of All Helmets Following Impact in the Top Position of Twenty-one Feet Per Second.

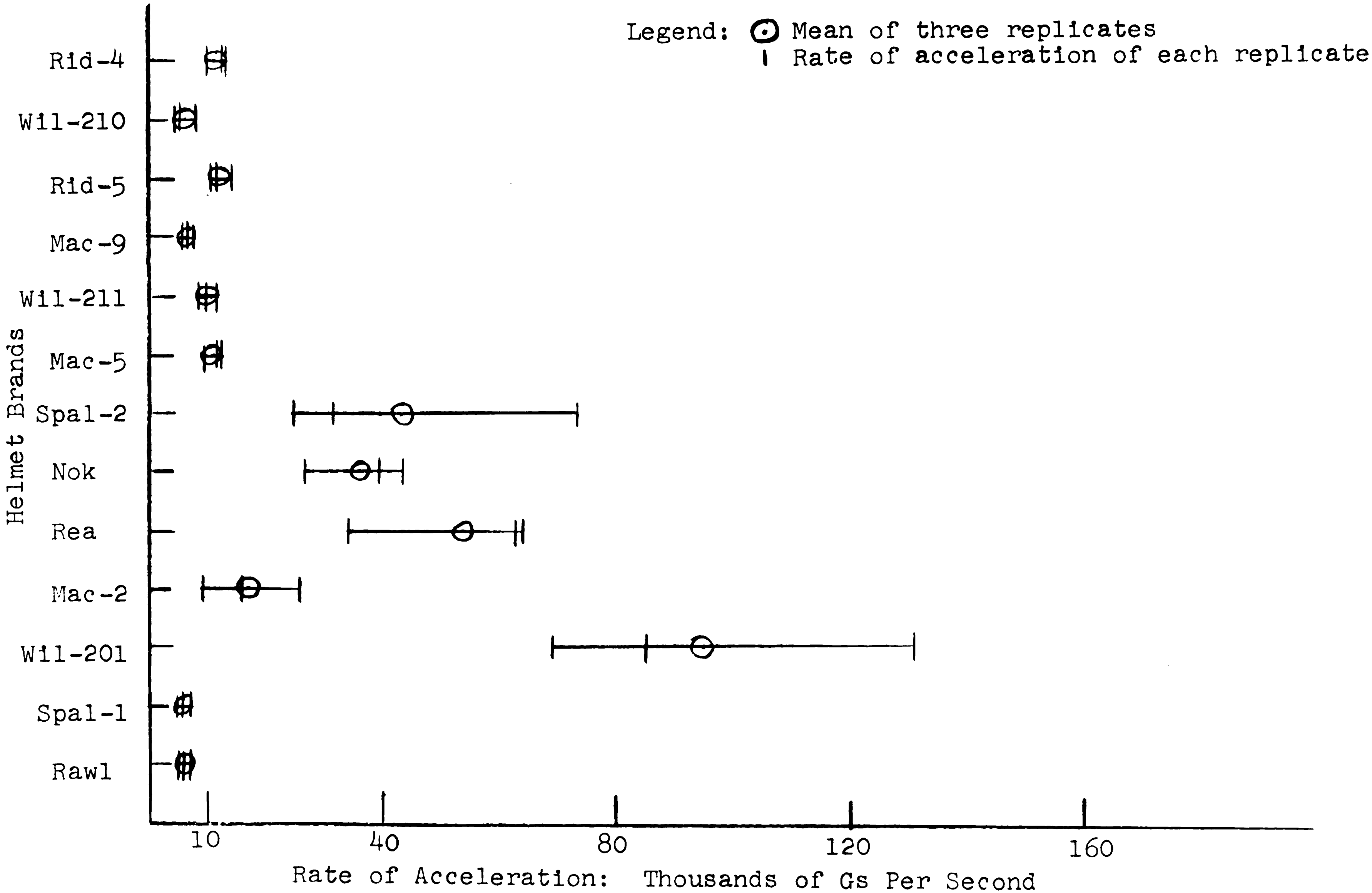

Fig. 61. Rates of Acceleration of All Helmets Following Impact in the Top Position at Eighteen Feet Per Second.

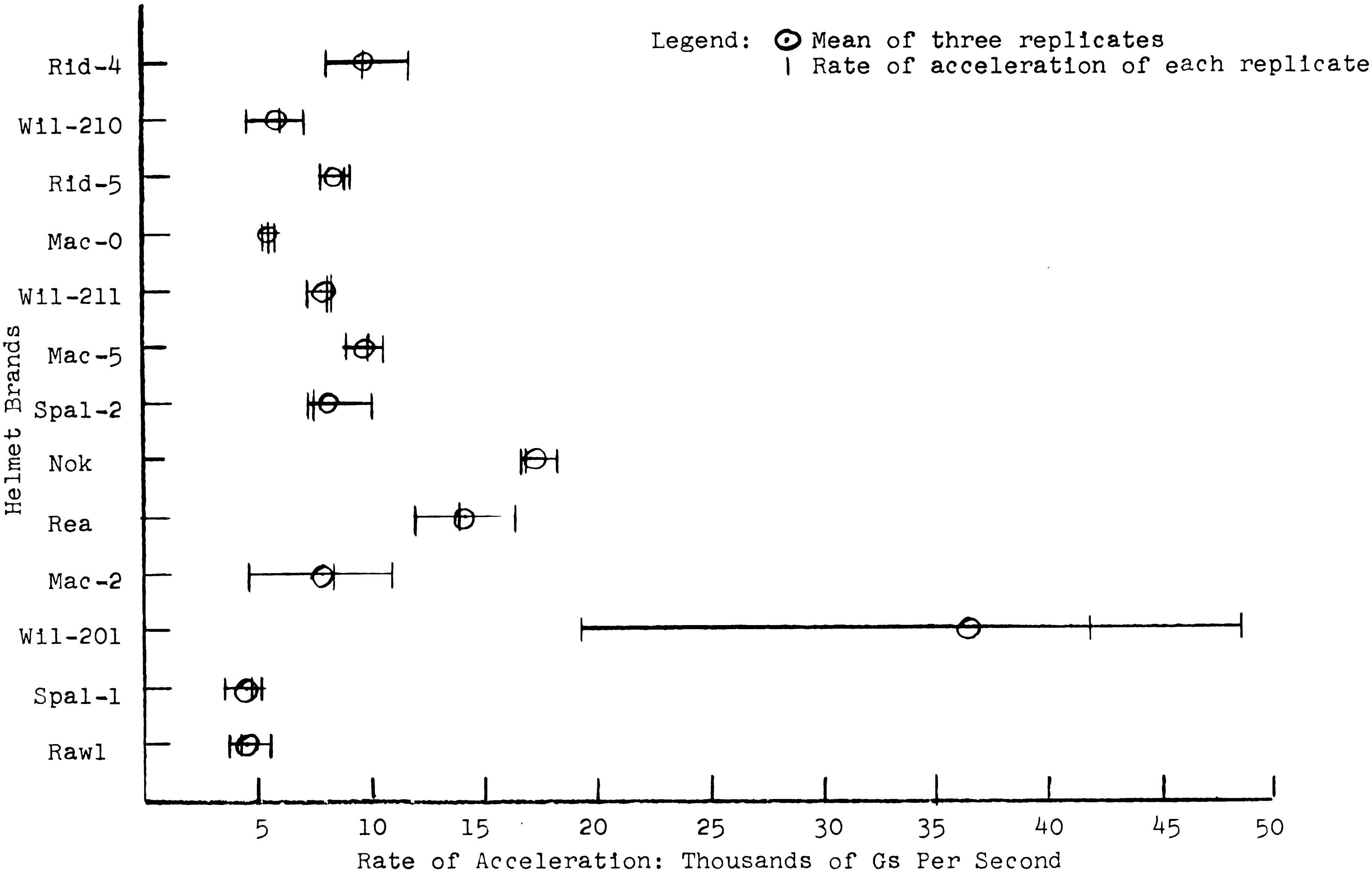

Fig. 62. Rates of Acceleration of All Helmets Following Impact in the Top Position at Fifteen Feet Per Second.

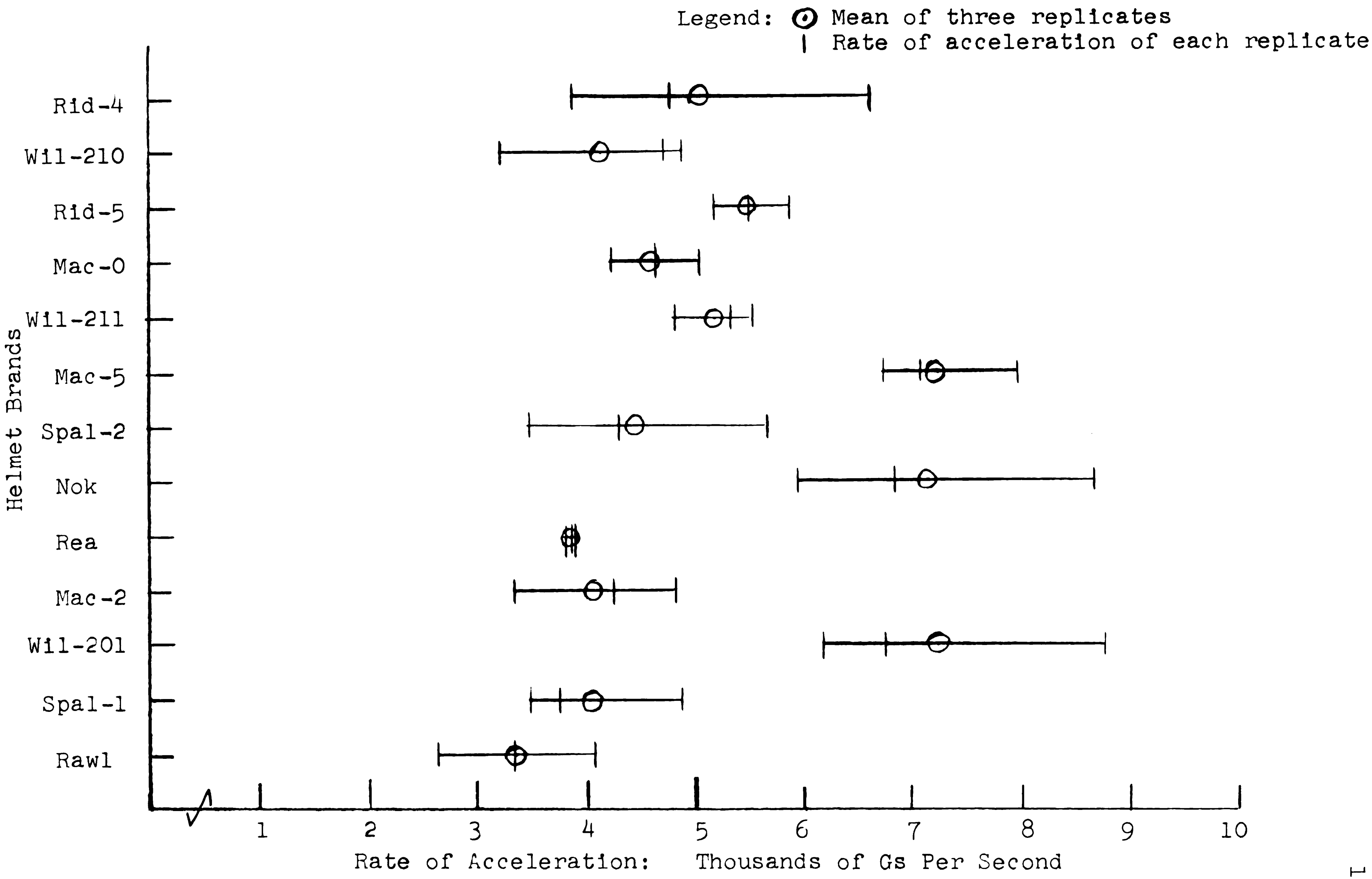

Fig. 63. Rates of Acceleration of All Helmets Following Impact in the Top Position at Twelve Feet Per Second.

Fig. 64. Wooden Head, Insert with Accelerometer and Striking Pendulum with Accelerometer

Fig. 65. Polaroid Camera, Dual Trace Oscilloscope, and Oscillator.

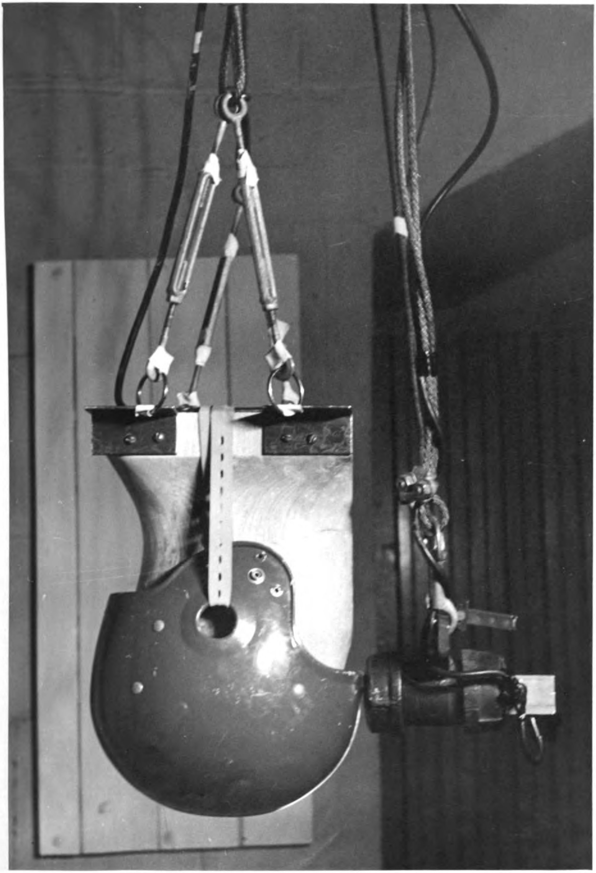

Fig. 66. Wooden Head with Helmet--Pendulum Upon Impact at the Front Position.

Fig. 67. Helmet Brands Used in the Study

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The purposes of this dissertation have been to: (1) evaluate thirteen brands of football helmets regarding maximum and rate of acceleration of the head, and maximum deceleration of a striking pendulum; and (2) statistically analyze the data on the basis of the responses of the helmet to impact.

The evaluation was done by ranking the helmets according to their responses at various impact velocities and positions. A separate analysis of variance was applied to each of the three evaluating criteria involving the variance of the three main effects and four interactions.

The experimenting was done by impacting thirty-nine helmets, which were mounted on a wooden head, with a free swing flat surfaced pendulum. The helmets were tested at four randomly distributed impact velocities (12, 15, 18, and 21 feet per second), and at four positions, front, side, back, and top). The responses to impact were measured by two accelerometers mounted within the head and at the back of the pendulum, the output of which was fed into a dual trace oscilloscope. Oscilloscopic traces resulting from these impacts were photographed by an attached polaroid camera, projected, analyzed, and measured in terms of Gs, and Gs per second.

The helmets were ranked according to their efficiency in terms of lower values for all three evaluating criteria. Graphs were plotted to show the mean responses of each helmet brand for all velocities and positions, and to compare the responses of all helmets at a given velocity and position for each measure of evaluation.

Conclusions

1. Helmet brands, positions, and impacting velocities are significantly different for all three evaluating measures. The highest F ratios are for position: acceleration $F = 1234.76$, deceleration $F = 1005.30$, rates of acceleration $F = 519.62$.
2. For all three evaluating criteria, brands vary significantly according to the position and the impact used. Helmets varied mostly at the highest impact velocities. Excepting for helmet Mac-O and Mac-5, the back is the worst position for all brands.
3. Helmets responded differently to the various impact velocities within all given positions. The back position contributed mostly to the within variance for measures of acceleration and rates of acceleration. The front position produced the most within variance for the measure of deceleration.

4. Leather and rubber shelled helmets were generally inferior to other types of helmets. Mac-2, consistently among the best helmets at the side position, is the only exception to this.
5. Firm, pliable plastic-type shells with suspended padded liners were seemingly superior to rigid plastic-type shells with webbed suspension liners.

Recommendations

1. Various combinations of assorted types of shells and liners should be tested to determine the best football helmet.
2. Fatiguing effects from a prolonged series of impacts on the helmets should be studied.
3. Because of the range in temperatures experienced in football games, the effects of both temperature extremes on helmets should be studied.
4. Much of the literature relates concussive levels to pressure distribution over the head. It would be beneficial to test the effects of impact in terms of pressure distribution and its time duration at selected points on the head as the result of impact.
5. For comparable results, standardized testing equipment should be used in future testing of this kind. Mass, texture, size, and content of the head, as well as mass and shape of the impacting pendulum should be uniform.

6. Kinetic energy, absorbtion, and dissipation by the head as a result of impacting the helmet should be determined.
7. The incidence of concussive head injuries incurred in games and practices in relation to the brands of football helmets used should be studied.
8. More research must be done to determine the various types and magnitudes of impact incurred in football games.

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APPENDIX

APPENDIX A

SAMPLE QUESTIONNAIRE SENT TO MANUFACTURERS

Football Helmet Statistic Sheet

Please be specific:

Helmet Model ______________________________

Shell Composition:	Fiberglass, leather, plexiglass, etholite, other ______________________
Shell Thickness	__________ inches (nearest one hundredth)

Liner Type:	Strap, pad, suspension, geodetic suspension, other ______________________

Liner Material	Styrefoam, ensolite, polystyrene, polyethylene, cotton, suspension, other _____
Liner Thickness	__________ inches

Distance between liner and inside of shell at the:	
--top	________ inches (nearest one hundredth)
--back	________ inches
--sides	________ inches
--front	________ inches

Total weight of helmet without face and nose quards	________ lbs. (nearest one hundredth)

Attachment material of liner to shell	Cotton stitching, metal rivets, cotton rivets, other ______________________

Comments:
Other worthy physical features of helmets not included above

APPENDIX B

TABLE 7

TOTALS FOR ANALYSIS OF VARIANCE OF DECELERATION

Source		Sums of Squares
Correction term	21,657,036,866.89 ÷ 624	34,706,789.85
Total	53,495,503.15 - 34,706,789.85	18,788,713.30
Brands	1,735,215,755.87 ÷ 48 = 36,150,328.27 - 34,706,789.85 =	1,443,538.42
Position	6,540,935,165.15 ÷ 156 = 41,929,071.57 6 34,706,789.85=	7,222,281.72
Velocity	6,121,250,625.57 ÷ 156 = 39,238,786.06 - 34,706,789.85=	4,531,996.21
Brand x vel.	494,348,800.13 ÷ 12 = 41,195,733.34 - 5,975,534.63 - 34,706,789.85 =	513,408.86
Brand x pos.	538,756,076.49 ÷ 12 = 44,896,339.70 - 8,665,820.14 - 34,706,789.85 =	1,523,729.71
Pos. x vel.	1,840,122,869.67 ÷ 39 = 47,182,637.68 - 11,754,277.93 - 34,706,789.85 =	721,569.90
Brand x pos.x vel.	155,527,043.11 ÷ 3 = 51,842,347.23 + 13,197,816.35 - 29,154,341.17 =	1,179,033.06
Within pos.	583,043.12 + 5,837.69 + 62,284.82 + 24,938.96 =	676,104.59
Error		977,050.83

Adjustment Factors of Position Replicate Totals --

Position	Replicate 1	Replicate 2	Replicate 3
Front	.734	1.111	1.000
Side	1.100	1.000	.953
Back	1.084	1.000	.942
Top	.867	1.000	1.045

TABLE 8

TOTALS FOR ANALYSIS OF VARIANCE OF ACCELERATION

Source		Sums of Squares
Correction term	3,330,294,055.69 ÷ 624	5,337,009.70
Total	8,670,586.51 - 5,337,009.70	3,333,576.81
Brands	267,102,237.97 ÷ 48 = 5,564,629.95 - ct =	227,620.25
Positions	1,053,701,190.55 ÷ 156 = 6,754,494.81 - ct =	1,417,485.11
Velocities	970,195,432.61 ÷ 156 = 6,219,201.49 - ct =	882,191.79
Brands x vel.	78,450,389.17 ÷ 12 = 6,537,532.43 - 1,109,812.04 - 5,337,009.70 =	90,710.69
Brands x pos.	85,181,759.12 ÷ 12 = 7,098,479.92 - 1,645,105.36 - 5,337,009.70 =	116,364.86
Pos. x vel.	305,737,971.77 ÷ 39 = 7,839,435.17 - 2,299,676.90 - 5,337,009.70 =	202,748.57
Brands x pos.x vel.	25,404,042.79 ÷ 3 = 8,468,014.26 - 2,527,297.15 - 5,464,418.42 =	193,883.29
Within	2,682.53 + 2,214.71 + 38,405.71 + 3,145.43 =	46,448.38
Error		156,123.87

Adjustment Factors of Position Replicate Totals--

Position	Replicate 1	Replicate 2	Replicate 3
Front	1.045	1.000	.966
Side	.938	1.163	1.000
Back	1.000	.912	1.181
Top	1.067	1.000	.857

TABLE 9

TOTALS FOR ANALYSIS OF VARIANCE OF RATE OF ACCELERATION

Source		Sums of Squares
C.T.	177,305,839,929 ÷ 624=	284,143,974
Total	6,667,321.53 - 284,143,974 =	382,588,179
Brands	15,141,189,217 ÷ 48 = 315,441,442 - 284,143,974 =	31,297,468
Position	64,762,921,721 ÷ 156 = 415,146,934 - 284,143,974 =	131,002,960
Velocity	57,460,478,277 ÷ 156 = 368,336,399 - 284,143,974 =	84,192,425
Brands x vel.	4,963,252,635 ÷ 12 = 413,604,386 - 115,489,893 - 284,143,974 =	13,970,519
Brands x pos.	5,852,921,419 ÷ 12 = 487,743,452 - 162,300,428 - 284,143,974 =	41,299,050
Pos. x vel.	20,656,907,777 ÷ 39 = 529,664,301 - 215,195,385 - 284,143,974 =	30,324,942
Brands x pos. x vel.	1,885,383,555 ÷ 3 = 628,461,185 + 246,492,853 - 578,580,217 - 284,143,874 =	12,229,847
Within	128,116 + 279,950 + 2,985,791 + 589,892 =	3,983,749
Error		34,287,219

Adjustment Factors of Position Replicate Totals--

Position	Replicate 1	Replicate 2	Replicate 3
Front	.956	1.000	1.019
Side	.690	1.161	1.000
Back	1.000	.993	1.288
Top	1.166	1.000	.671

TABLE 10

DATA SHEET--MAXIMUM ACCELERATIONS OF THE HEAD IN GS

Position	Velocity	Helmet Brands												
		Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Front	21	99.3	181.8	120.4	170.9	122.7	157.3	136.4	188.2	198.3	197.4	184.4	200.0	177.4
		158.2	187.3	150.0	197.3	135.5	228.2	196.4	190.0	240.0	186.4	194.6	169.1	181.8
		166.0	202.0	159.0	201.0	147.0	226.0	217.0	241.0	244.0	220.0	217.0	210.0	220.0
	18	93.1	175.5	107.3	157.3	119.6	178.2	127.3	160.0	169.6	180.0	155.7	140.0	162.6
		120.7	137.3	118.6	170.9	119.8	187.3	130.9	162.7	193.6	130.0	131.8	136.4	120.9
		131.2	148.0	124.2	195.0	102.4	201.0	160.0	187.0	213.0	183.0	194.0	136.0	161.0
	15	54.5	96.4	99.4	149.1	62.0	120.0	89.5	123.1	135.7	141.7	120.0	125.2	69.6
		98.4	130.9	87.6	134.6	89.3	158.2	101.5	115.3	171.8	120.9	112.7	94.6	117.3
		97.6	97.0	80.4	158.0	67.8	110.0	66.8	132.0	100.0	112.0	95.0	111.0	106.0
	12	41.3	79.6	61.5	120.0	37.3	86.4	64.2	95.3	103.6	100.3	82.1	108.2	54.3
		76.0	89.5	67.8	93.8	68.6	110.2	69.3	60.2	84.7	73.1	46.9	41.5	79.3
		74.8	85.6	48.4	104.0	43.0	110.0	58.4	42.8	52.0	74.4	69.2	39.6	66.8
Side	21	130.3	61.3	99.9	39.9	42.5	33.0	34.5	81.5	117.2	93.2	209.9	104.8	54.9
		135.4	67.8	44.9	29.3	41.8	30.4	29.9	37.1	158.5	43.0	174.5	69.9	47.3
		102.9	49.9	53.1	42.0	42.9	64.8	40.8	89.1	59.3	52.5	208.0	88.5	80.0
	18	80.6	52.1	81.3	22.6	36.7	23.0	35.0	35.5	50.3	36.6	109.0	42.6	39.7
		28.0	28.9	44.7	20.6	35.4	21.0	23.8	31.9	33.0	24.4	102.2	30.8	32.5
		61.2	32.4	48.7	21.6	38.1	25.1	33.9	44.7	54.9	36.9	119.7	38.4	50.4
	15	29.8	35.5	57.5	19.2	29.3	16.1	30.4	31.5	34.1	21.0	31.0	25.1	28.6
		27.3	25.2	35.6	17.7	27.5	15.2	22.4	26.3	30.3	21.5	32.5	25.9	24.7
		34.3	27.3	42.5	20.9	38.1	18.9	28.5	29.5	33.9	32.9	36.5	26.7	25.6

TABLE 10--Continued

Position	Velocity	Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
		Helmet Brands												
Side con't.	12	27.6	27.6	33.4	16.7	22.6	14.7	20.1	25.1	29.7	15.7	19.3	19.0	20.4
		23.8	22.2	29.3	13.2	22.8	12.6	18.6	20.4	24.4	17.3	15.5	19.3	20.4
		31.8	24.3	36.7	14.6	23.1	15.4	22.0	24.9	28.5	21.9	16.4	20.7	22.3
Back	21	210.8	280.0	254.6	133.1	263.9	206.9	259.2	276.9	300.8	361.2	344.8	225.7	271.4
		281.9	188.6	187.4	117.2	235.8	141.0	261.0	285.5	375.5	297.3	355.5	258.2	267.3
		249.1	284.6	239.1	198.2	202.1	137.2	244.8	215.2	253.8	234.5	253.1	188.3	170.7
	18	82.5	173.1	166.2	106.2	189.5	68.0	189.2	227.7	219.2	278.1	265.7	166.9	129.5
		137.5	135.2	114.3	112.4	208.6	117.2	221.9	282.7	325.5	192.7	295.5	179.6	159.1
		63.3	136.4	187.3	131.8	145.1	72.8	159.3	157.9	204.1	170.3	197.9	117.9	86.9
	15	45.2	73.1	34.0	65.5	100.2	69.2	136.9	165.2	133.1	152.4	168.6	102.5	54.1
		112.2	118.1	63.8	71.3	192.8	78.1	156.9	204.7	209.1	186.4	220.0	160.9	54.2
		50.2	80.4	104.7	86.6	124.1	53.8	126.1	126.3	166.2	117.2	142.8	78.6	60.9
	12	50.5	66.5	41.9	48.8	88.0	35.1	84.0	144.9	107.7	93.9	102.5	41.5	58.7
		64.0	66.7	41.7	56.0	119.2	48.8	111.2	181.5	128.6	73.1	136.4	42.5	49.8
		38.6	41.1	33.8	58.6	87.3	33.4	48.6	93.8	90.6	44.0	62.1	26.2	22.9
Top	21	38.6	45.4	40.6	28.3	66.0	32.0	167.1	84.6	124.6	76.0	152.9	47.1	41.4
		43.9	39.7	49.4	30.3	67.6	38.9	189.7	112.6	138.2	83.9	183.2	60.7	69.7
		49.7	48.7	58.3	35.8	44.0	39.3	175.8	123.7	161.0	107.3	218.2	87.7	48.7
	18	31.6	26.1	30.6	26.6	42.1	28.7	96.9	84.0	97.4	49.1	105.7	25.7	30.4
		32.8	27.6	34.8	25.2	32.8	34.8	62.9	68.1	72.3	58.2	102.1	23.9	26.8
		36.5	36.7	46.5	36.3	41.3	40.0	76.7	97.7	113.7	49.3	145.3	35.0	35.7

TABLE 10--Continued

Position	Velocity	Helmet Brands: Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Top con't.	15	24.7	22.6	23.4	20.3	25.7	29.4	27.0	49.0	42.3	30.6	48.3	21.1	24.0
		27.6	23.2	26.9	24.6	28.3	30.9	24.7	52.7	44.7	33.9	60.7	23.2	24.0
		29.3	29.7	32.7	30.2	37.2	34.3	33.2	59.5	55.5	34.3	83.7	25.5	28.2
	12	15.3	17.4	15.7	16.6	20.9	24.4	19.9	26.9	18.2	19.1	24.9	16.4	16.8
		17.0	18.1	20.1	19.5	20.2	25.5	20.7	29.6	20.1	19.2	31.5	16.8	17.8
		22.2	23.1	24.9	23.9	24.6	27.7	23.0	30.4	19.6	24.8	28.9	18.7	19.7

TABLE 11

DATA SHEET--MAXIMUM DECELERATION OF THE PENDULUM IN Gs

		Helmet Brands												
Position	Velocity	Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Front	21	341.9	609.5	448.6	611.4	441.9	590.5	512.4	507.9	514.8	521.8	561.8	535.7	551.3
		357.6	375.8	367.9	375.8	324.3	339.4	386.1	401.2	400.0	286.1	396.4	360.1	373.3
		423.0	475.6	408.2	478.5	362.3	481.5	451.9	433.4	469.6	483.0	468.2	472.0	506.7
	18	326.7	620.9	344.8	580.9	448.6	568.8	464.8	547.9	547.9	532.2	546.2	537.4	565.2
		280.6	300.6	273.3	375.8	296.4	385.4	288.5	380.6	403.6	304.2	317.6	313.9	280.0
		360.8	339.3	334.8	465.2	210.4	460.8	333.4	440.0	494.8	450.4	463.7	340.8	365.9
	15	168.4	316.2	283.8	522.9	170.5	478.1	297.2	443.5	482.6	519.2	399.2	439.2	211.3
		236.4	301.2	217.0	306.1	190.3	367.9	226.7	259.4	358.8	256.4	243.7	187.2	257.6
		250.4	220.0	200.8	381.5	126.2	240.8	116.5	338.6	243.0	243.0	190.4	238.5	231.9
	12	130.3	310.5	195.5	471.4	72.8	340.0	190.9	346.1	370.5	389.6	292.2	407.8	194.8
		160.9	207.3	142.8	220.6	121.0	272.1	132.1	98.9	178.2	173.4	106.1	100.0	160.6
		176.0	225.2	92.7	268.2	75.6	279.3	88.2	69.9	123.0	199.3	166.7	99.3	160.8
Side	21	110.5	89.5	171.1	83.2	100.5	96.3	64.7	162.6	250.5	203.7	445.3	261.1	120.0
		172.1	66.8	107.6	101.4	122.6	120.7	86.2	140.7	268.9	115.9	558.6	235.9	140.7
		253.3	136.9	104.9	95.2	119.4	132.7	78.2	226.7	251.7	130.3	475.1	243.6	217.6
	18	64.8	92.6	72.8	87.6	81.7	102.7	65.3	72.2	93.1	74.5	255.8	89.3	96.6
		72.3	90.8	99.3	141.8	103.7	126.8	72.6	94.1	112.6	88.3	118.6	93.8	90.2
		137.5	86.3	84.6	104.0	93.1	129.7	76.1	80.7	135.3	88.5	316.4	96.0	120.0
	15	50.3	76.0	60.0	95.4	74.7	73.1	52.3	64.0	76.8	52.8	58.5	59.4	70.5
		66.8	89.4	80.0	104.8	85.2	106.8	62.1	76.4	90.8	69.5	92.7	83.0	75.3
		63.3	73.2	78.8	82.2	64.0	75.2	61.3	75.4	84.1	70.1	95.5	61.1	65.7

TABLE 11--Continued

Position	Velocity	Helmet Brands												
		Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Side Con't.	12	54.7	60.2	53.5	80.0	64.0	54.7	45.7	63.8	60.6	38.5	43.6	46.7	57.9
		58.5	79.2	64.6	93.2	87.6	75.9	57.1	62.3	73.1	52.7	38.1	59.9	61.5
		60.9	78.2	61.3	75.4	61.8	63.0	51.6	68.6	67.2	58.4	40.2	53.8	59.4
Back	21	469.1	527.7	514.2	313.6	504.6	530.3	485.2	498.1	491.6	509.3	496.0	492.0	548.0
		510.0	389.3	406.0	208.7	498.7	264.7	542.7	605.7	557.2	620.0	564.3	625.7	620.0
		596.4	612.9	565.0	460.7	570.0	511.4	560.0	575.7	587.2	578.6	567.1	607.2	572.9
	18	178.7	458.1	431.6	233.6	469.1	167.8	484.5	518.7	534.2	510.7	600.0	330.7	264.7
		251.4	262.3	222.0	224.0	430.7	242.7	468.7	591.4	575.7	485.7	610.0	458.6	385.7
		137.2	341.4	505.7	265.0	526.4	257.2	545.7	622.9	560.0	608.6	585.7	385.7	250.7
	15	154.9	156.1	123.9	147.1	245.2	152.3	336.2	445.2	337.4	320.5	344.0	168.0	129.3
		224.0	225.3	99.5	140.0	380.0	138.7	334.0	558.6	568.6	458.7	566.4	372.3	126.4
		126.4	176.4	237.9	209.3	469.3	202.1	407.2	487.2	578.6	370.7	506.4	264.3	209.3
	12	125.7	149.7	84.3	114.3	189.1	87.5	195.5	383.3	274.2	186.0	190.7	88.7	109.3
		110.7	115.3	67.5	67.7	201.3	81.1	205.3	487.9	332.2	169.3	337.2	100.0	122.9
		91.4	91.4	80.0	133.0	283.6	124.0	172.9	348.6	327.2	107.9	208.6	92.9	76.4
Top	21	155.0	165.2	160.9	108.9	224.3	112.3	540.0	380.7	565.0	374.3	597.2	186.4	153.7
		135.3	105.7	133.9	95.3	187.1	183.3	521.2	404.2	464.2	335.9	455.3	211.2	255.3
		124.5	105.1	138.7	75.9	82.8	116.8	506.3	326.7	450.1	337.6	509.7	267.9	113.7
	18	148.3	90.9	171.2	101.4	108.6	99.1	428.6	295.7	493.6	191.4	536.4	73.7	98.0
		146.9	81.9	141.4	98.4	79.5	96.0	217.7	174.7	265.9	218.9	414.8	65.7	77.4
		123.7	79.8	143.8	76.1	77.0	88.7	216.5	218.2	398.7	97.1	463.2	73.1	76.3

TABLE 11 --Continued

Position	Velocity	Helmet Brands												
		Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Top con't.	15	134.3	78.6	150.9	83.1	78.3	101.1	82.9	137.2	192.0	93.4	178.3	64.0	76.3
		105.7	69.2	118.8	83.5	64.9	76.9	70.4	124.2	173.0	95.5	227.1	57.9	60.9
		111.1	73.1	123.2	76.1	69.7	78.9	63.3	109.0	167.5	68.8	261.0	54.9	60.1
	12	114.0	67.9	117.2	85.7	68.0	83.1	47.4	87.4	71.1	66.0	68.3	56.9	57.7
		110.9	59.1	94.6	78.6	58.4	75.5	44.9	82.4	62.6	60.2	83.3	47.5	52.5
		105.1	56.6	105.6	65.8	60.8	84.3	43.9	74.1	60.6	52.3	67.0	32.7	56.5

TABLE 12

DATA SHEET--RATES OF ACCELERATION OF THE HEAD IN Gs PER SECOND

		Helmet Brands												
Position	Velocity	Rid-4	Wil-210	Rid-5	Mac-O	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Front	21	64713	143861	82565	136837	88856	133656	127201	208857	209146	225086	230162	205761	172400
		138754	160290	127751	194355	99799	227621	184630	197711	198352	175480	162301	126300	168664
		164356	164228	117343	189802	103740	239915	175227	244422	196616	157895	230361	230769	175437
	18	44171	142303	76775	135695	86383	213134	93480	171306	185613	192716	160144	149893	141902
		79075	88975	88909	155373	85657	189978	139414	155137	167799	103011	86304	102681	92520
		89130	95066	82855	170157	46003	233449	141718	186070	163546	121152	165794	68129	110563
	15	21807	73955	67045	120428	27122	112994	55549	113379	157160	122083	86517	116810	40051
		76130	93687	57272	148902	45154	150504	76268	84280	148573	65981	74871	58696	78463
		61538	50269	33570	164927	31144	38008	45074	117962	59163	56588	48515	61905	61146
	12	15540	58718	30857	110143	15638	62489	41205	70177	92876	81398	65725	116187	27924
		46033	61508	35739	78708	39135	95331	43402	23529	52339	42963	26326	19123	53070
		44179	52665	13793	94545	17143	86957	18183	19820	19120	40371	29917	12014	29893
Side	21	87610	99720	79364	7140	8658	16943	20000	26583	41141	38787	191777	58466	12299
		77199	27535	8176	11639	23290	14451	5381	5592	78223	13131	153616	30658	8764
		59724	15647	15789	8182	23938	15818	17518	34375	23582	12215	187878	39839	26918
	18	42561	51176	75792	6787	8237	9836	7041	9215	23288	13201	65481	12853	15180
		5788	6764	11764	10400	7115	10807	4491	6795	12994	9084	52828	6735	7960
		17734	8989	12763	10292	8025	13196	6869	10546	16846	15484	86966	7521	10586
	15	19963	12124	52393	7085	5878	8442	6432	6505	13639	9605	4922	6003	8383
		5553	6581	9679	10381	5294	6477	4178	5418	9888	8655	8549	6753	3403
		8214	3404	10837	8905	6266	6705	4919	6051	13359	12758	7850	3946	4181

TABLE 12--Continued

Position	Velocity	Rid-4	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
		Helmet Brands												
Side con't.	12	5420	10080	8113	5790	4142	6354	3920	5882	10973	5372	3991	3389	9525
		4487	5902	6707	6369	5301	5025	3642	3538	6101	1253	2975	2144	1928
		7034	6175	8643	6826	6731	5905	3377	5011	4876	8003	3158	4123	4224
Back	21	202907	281308	230425	79972	271647	172537	310839	282269	318653	391564	382797	203102	242830
		244678	176466	143447	62933	227218	71114	193473	506766	381937	232804	259597	189680	176071
		180588	273886	194728	108115	184604	96944	196925	220884	248358	229888	244329	147317	128626
	18	21879	136859	122902	66457	166013	29735	178420	168596	211657	284443	271117	124790	85915
		69137	76263	47748	44074	175323	66913	211833	284512	388514	128387	253131	118133	73277
		14705	59483	113313	54705	142318	32941	172947	160436	214725	170826	193737	66692	48350
	15	16849	30510	13321	32403	60403	32727	119276	169112	118483	114663	135198	52310	19034
		46273	77331	20280	25837	159288	26952	140242	184884	172445	129647	187305	112647	15424
		12790	30723	54425	36652	106943	22989	114577	117947	153667	100921	133654	34980	21496
	12	14652	29548	14237	22326	51755	11867	67010	116258	88772	54274	68737	9427	14842
		18411	21213	7015	19336	90975	16459	92935	163488	83392	27629	94986	9464	14884
		8786	10346	7624	20841	65113	9714	25777	78909	72126	18609	37538	9509	7119
Top	21	13920	11085	12039	5941	20654	8943	176006	35973	62860	38166	122926	28617	9736
		13787	8158	17395	7658	26991	12949	200753	73135	88746	47938	169405	22954	31851
		26383	21218	23724	10487	14505	14969	211652	93013	140882	52310	258242	47447	13727
	18	11008	6165	9066	5876	10258	8366	63403	37458	55015	14245	73270	5396	6130
		9354	5187	11421	6678	8518	11365	24481	26735	34626	26443	69811	5878	5747
		18750	10553	20236	9754	13243	16155	46903	59459	95299	14898	195489	8515	8759

TABLE 12--Continued

		Helmet Brands												
Position	Velocity	Rid-5	Wil-210	Rid-5	Mac-0	Wil-211	Mac-5	Spal-2	Nok	Rea	Mac-2	Wil-201	Spal-1	Rawl
Top con't.	15	10232	6047	7475	5056	6301	8349	6239	14527	10285	7044	16542	4098	4745
		8028	4571	7624	5560	8362	10498	10059	18271	13707	10759	41796	5261	4323
		14890	9083	13269	7932	12380	12984	10992	25092	24854	6847	72468	5351	5642
	12	4092	3920	4711	4301	4720	5749	4827	5060	3267	3653	5785	3001	3477
		3872	3203	5833	4610	4795	7978	4271	8665	3861	4588	8792	3737	3398
		9828	7064	7697	6272	7872	10483	5168	10156	5742	4951	9204	7297	3953