Influence of Block Angle and Diver Stance on Power Production and Takeoff Velocity in Swim Starting

by

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Dedication

To Emmett,
perhaps the only person who understands this project as intimately as I do.
Thank-you for your encouragement, patience and constant support,
and
To Avery, "...*vade mecum*...".

Abstract

This research examined three different diving stances during the competitive grab start of swimming—that of the standard position, called the Toes-Over position, the Toes-Back position where the swimmers were not permitted to curl their toes over the edge of the -10 degree inclined starting block and the Level position where the platform was levelled. A starting position was being sought which would increase a swimmer's projection angle from the blocks and thus flight time before entry. Eight female swimmers were filmed using a stationary cinecamera while reaction forces were collected, simultaneously, by a force platform mounted on the starting block. Net forces and moments of force at the three leg joints were calculated using inverse dynamics (Winter, 1979). The powers produced by these net moments were then computed to determine which muscle groups contributed to the work done during the start.

Based on the results of this study there were no significant differences in the performances of female swimmers using the grab start technique in terms of takeoff velocity, takeoff angle or horizontal distance for the dive when starting from a level surface or -10 degree inclined surface. The hip extensor muscles provided the greatest amount of power during the propulsive (thrust) phase of the swim start.

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Introduction

The start is an important aspect of every swimming race especially the sprint and relay events. Over the years various techniques for competitive swim starts have been used and many studies have attempted to determine the effectiveness of each (Hanauer, 1967; Ayalon et al., 1975; Bowers and Cavanagh, 1975; Nelson and Pike, 1978; Shierman, 1979; Hay, 1985; Stewart, Barden and Robertson, 1989). Studies have been concerned primarily with the airborne phase of the start after the swimmer has left the blocks or with the reaction time of the athlete after the start command is given.

Few studies have employed both kinematic and kinetic measures to investigate the importance of the initial phase of a start when the swimmer generates the momentum that will carry him or her through the air and into the water during the dive. Fewer researchers have qualified the components of a starting technique that will generate the effective thrust of a swimmer from the blocks. Biomechanical investigation of the competitive swim start, which includes kinetic and kinematic analysis of swimmers' stance and starting block angle, may provide valuable information about the use of the muscles of the legs as to power production, takeoff angle and velocity of the start. This information may then be applied by coaches and swimmers to improve starting techniques with hope of improving the overall outcome of a swimming race.

Theory

Essentially, the starting technique used for the three prone strokes (butterfly, breaststroke and front crawl) are the same. The quality of the start plays a more important role in a short sprint race or a relay event than it does in a middle or long distance event. In a short race a swimmer will endeavour to achieve a strong and fast start that will permit him or her to enter the water ahead of the other athletes in the race. In a short race, the quality of the start is a strong indicator of the outcome of the race.

At the command of the starter the swimmer assumes his or her starting position. If the traditional 'grab start' technique is used, the swimmer will place his or her feet comfortably apart with the toes curled over the forward edge of the starting platform. This allows the athlete to grip the starting block with his or her feet and greatly reduces slippage. Knees are bent, hips flexed and the upper body is inclined forward and downward. The arms are extended downward and the hands are also used to grip the forward edge of the starting block, either between or outside the placement of the feet. This position enables the swimmer to maintain a balanced stance on the starting block while allowing the centre of gravity to move forward in anticipation of the start.

The 'track start' has become a method recently chosen by some athletes. As the name implies, the swimmer assumes a stance that is similar to that used during sprint races in track and field. One leg is placed forward with the toes curled over the edge of the starting block while the opposite foot is positioned near the rear of the platform. The body is inclined forward and downward as in the grab start. The arms are extended downward and the hands are again used to grip the forward edge of the starting block. The exact position of the swimmer using either method will vary with respect to individual technique and the desired angle of entry into the water. In either case the swimmer must 'explode' from a compact starting stance and thrust the arms and body forward until a fully extended diving position over the water is achieved. The athlete should strive to attain maximum horizontal distance in the air as quickly as possible. The required thrusting action and full body extension demands the use of the muscles of the trunk, hip, knee and ankle in a coordinated sequence.

The projection angle of the swimmer's centre of gravity at takeoff has also been studied (Heusner, 1959; Groves and Roberts, 1972; Bowers and Cavanagh, 1975) but the findings have not been conclusive. It would be beneficial for a researcher to establish an optimum angle of takeoff that will allow an athlete to utilize the large muscles of the hip, in generating power to perform an effective thrust when diving from the starting block.

Strength and power generated by the legs are a significant aspect of sprint starting in running activities and standing broad jumping and vertical jumping (Luhtanen and Komi, 1978; Robertson and Fleming, 1987). When the power generated by the legs in swim starting was compared to jumping activity research (Stewart et al., 1989) it was found that the knee extensors were responsible for the largest component of positive work done by the legs during the takeoff. This is contrary to the results found in long jump research (Robertson and Fleming, 1987). In the swim start the hip was found to perform negative work, and absorbed more energy than was generated by the knee (Stewart et al., 1989).

Standing broad jump and vertical jump research has shown that the large muscles of the hip are major contributors in the generation of power and the positive work done by the legs (Robertson and Fleming, 1987). If these muscles could be used in a manner, which created the same sort of positive work during the execution of the swim start greater horizontal distance over the water might be achieved during the dive. Stewart et al. (1989) suggested that the hip extensor muscles were being used to apply forces that redirect a swimmer's centre of gravity from a vertical to a horizontal plane during the start. If this were the case, the initial orientation of a swimmer in the block might influence the power generated by the leg muscles. Power generated by the athlete during the start is responsible for the momentum (and primary direction) of the dive that propels the swimmer into the water. During a short sprint event it is often the quality and speed of the start that will determine the outcome of a race. Reorientation of the swimmer by altering the angle of the starting platform may promote a more powerful hip extension and permit an increased thrust from the large gluteal muscles.

During competition swimmers must perform within the guidelines provided by *Swimming/Natation Canada*. These rules restrict the parameters of the starting platforms and therefore the performance, to a certain extent, of the athletes. These rules state the following:

1) Starting platforms (starting blocks) shall not exceed 75 cm in height or be lower that 50 cm as measured from the normal competitive height of water.

2) The top surfaces of the platform shall have a minimum size of 0.5 x 0.5 m.

3) The top of the platform shall not slope towards the water more than 10 degrees from the horizontal (Swimming Rules, 1987).

In this study the starting platform was adjusted such that the extreme of the angular (slope) parameters were examined. An evaluation such as this can suggest new or different starting guidelines that can be used to enhance the overall performance of swimmers.

Purpose

This study examined two different angles for the takeoff surface of a swim starting block. Two different diver stances for the grab start were also investigated. Subjects performed under three different conditions: Level where the swimmer used a traditional grab start, with the toes curled over the forward edge of the starting block, from a surface that was not inclined toward the water, Toes-Over where the swimmer performed a traditional grab start with the toes curled over the forward edge of the starting block from a surface inclined -10 degrees toward the water, and Toes-Back where the swimmer used a grab start with the toes held back from the edge of the starting block and not curled over from a starting surface inclined -10 degrees toward the water. A condition was being sought which allowed the athlete to increase the total velocity of his or her centre of gravity during takeoff and increase horizontal (airborne) distance achieved before entry. Research included measurements of takeoff velocity, takeoff angle, horizontal displacement of the swimmer and power production by the legs. The starting technique was also examined to this end in terms of movement sequencing and summation of forces during the grab start.

The study examined whether there were significant differences in the powers produced by the moments of force of the joints of the lower extremity or in the takeoff angle, takeoff velocity or horizontal distance of the dive under the three starting conditions.

Scope of the Study

Certain delimitations were placed on this research in the interest of time, expense, equipment and subject availability. These restrictions designate the extent of this investigation and are described as follows:

1. The starting technique used for this study was restricted to the grab method. There are various starting techniques suitable for use in competition, of these, the grab start is currently the most widely used among athletes. This method was also the simplest to investigate using planar methods due to its symmetrical nature.
2. The study was confined to analysis in the sagittal plane. The magnitude of the forces and moments in the transverse and coronal (frontal) planes were assumed relatively small during the grab start.
3. Body segment parameters for the subjects were limited to those measures that can be collected readily and effectively or obtained from currently accepted anthropometric tables (i.e., segment lengths, proportional segment mass, total body mass, etc.)
4. Dynamographic data were limited to the vertical (Z) and horizontal (Y) components of the ground reaction forces for each subject performing the double leg projection from the starting platform.

Assumptions and Limitations

Biomechanical investigation of complex human movements, such as the swim start, requires that certain assumptions or simplifications be made to enable quantification of the activity. These assumptions, as related to this research, are given below:

1. The human body will be modelled as a system of rigid bodies joined by pin connections. This assumption permits the calculation of segment kinematics based on the principles of rigid body mechanics. The segments with which this study was specifically concerned were the foot, lower leg and thigh. The trunk was included so that the work done by the moment of force at the hip could be measured. For the purposes of this study the trunk was modelled as two segments. The cervical region was one segment and the combined thoracic, lumbar and sacral regions were the second segment. This study was primarily concerned with this later segment and it will be called the trunk. The cervical segment will be called the head-neck. The arms were not used in the calculation as they were estimated to contribute less than 5% to the total work done during the start.
2. The paths of the joint centres of rotation were identified by placing external body markers at the approximate positions of the rotation centres and tracking the trajectories of the these markers using a cinecamera.
3. Approximately ±0.5 cm error was introduced due to digitizing. Some uncertainty was also expected due to movement that occurred out of the plane of the camera. These errors were relatively small since the motion was planar.

4. The potential for slippage of the athletes on the starting surface, this presented a risk to the subject. Slippage was reduced by covering the surface of the force platform with non-slip adhesive tape. While this did not duplicate precise starting conditions, the increased friction facilitated by the adhesive tape was quite sufficient as to the safety of the athletes and the values of the study.

5. The margin of error on the force platform (Kistler model 9281B) used in this study was given to be less than 1% within the axes of the piezoelectric crystals and up to 5% to the edges. Inaccuracies in the collection of the force data were introduced due to slight vibrations of the swim starting block. These vibrations were reduced by securing the force platform tightly to the starting surface with flexible, nonstretch straps and with the addition of a pliable material to the surface of the starting block to impede slippage of the force platform. The force data were also low-pass, digitally filtered at 10 Hz to reduce any resonance effects transferred from the starting block. A value of 10 Hz was chosen because prior research has shown that 95% of the signal powers from data were less than 10 Hz, so high frequency resonance of the force platform could be removed without compromising the data itself.

6. The determination of body segment parameters introduced another source of error. The approach taken in this research will be to use parameter values based on the data of Dempster (1955). It should be noted that anthropometric data generated in Dempster's study were obtained from subjects that are not

entirely compatible with those in this research. It was expected that the bone density and muscle mass of the subjects in this study was greater than of the cadavers used by Dempster. The two greatest discrepancies in comparing Dempster's subjects with those used in this study were that of gender and age, however, since the influences of body segment parameters are insignificant when applied to subjects who are under the influence of large ground reaction forces this source of error is not important.

7. A practice effect among swimmers who were being tested was also expected due to the novel nature of the "toes back" task. The researcher tried to account for this effect by allowing each subject to have several practice trials before the testing. The effect of fatigue among the subjects was also controlled by permitting the subjects to rest between trials.

Literature Review

Starting techniques. Starting methods for competitive swimming have changed over the years, consequently, many studies have been concerned with comparing and evaluating the various techniques. It was formerly believed that some sort of arm swing action would produce the most effective start, hence early studies were primarily concerned with the examination of various arm actions. Such "conventional" starting techniques were generally performed in a static position and involved a short back swing or circular arm action. One other method had the athlete begin with the arms held back, followed by a direct thrust forward with the arms and legs (Nelson and Pike, 1978).

The grab start has become the most popular starting technique. This method has the swimmer grasp the forward edge of the starting block (so the name "grab" start) and then pull his or her body downward, enabling the arms to assist the legs in thrusting the body forward horizontally (Nelson and Pike, 1978). This body position was thought to move the centre of gravity forward at the time of the start, while also providing a certain amount of stability. Studies have compared the grab start with the earlier conventional starts (Hanauer, 1967; Hanauer, 1972; Jorgensen, 1972). The grab start, in each case, was found preferable to the other starts due to the reduced time of the swimmer "on the blocks".

An attempt was made in 1975 (Cavanagh, et al.) to measure, using a strain gauged starting block, the magnitude and direction of the forces exerted by the hands in the grab start. Only one subject was tested. The researchers demonstrated that a steady-state force was present during the set position. The forces exerted by the hands, before the athlete leaving the block, were reported to be in an upward direction. The starting block was positioned on a forward incline so the forces exerted by the hands would be more accurately described as being in the positive normal direction since the applied forces were in neither the geometric vertical nor horizontal plane. (Normal is defined as the direction perpendicular to the surface that receives the force). The forces applied by the hands were thought to retard the horizontal direction of the swimmer. The advantage in this technique was attributed to a prestretch of the leg muscles that provided a greater resultant force at takeoff. This was the first research that attempted to study the mechanics of any swim start.

Shierman (1979) conducted research using force analysis techniques that also compared the grab start with the conventional start. The subjects for this research were six male and five female university varsity swimmers. Shierman divided the starting motion into three phases: the initiation of takeoff, "gathering" for the start and the final thrust. Force data were taken using a Kistler force plate synchronized with a cinecamera. When the data were analyzed, it was found that the vertical and mediolateral (side-to-side) forces were minimal while the anteroposterior components of force most affected the performance of the swimmer. This demonstrates that the swimmers were directing themselves primarily in a horizontal forward direction at the start with negligible vertical forward effort.

The track start has been gaining popularity among athletes and coaches since 1980 (Councilman et al., 1988). This start is similar to the grab start except that the feet are placed in an anteroposterior staggered position. Researchers who have studied the track start have achieved similar results. When compared with the conventional start and the grab start the track start had a slower time "off the blocks" (Zatsiorsky et al., 1979; Ayalon et al. 1975), possibly because the athlete was only able to push off the surface firmly with one leg rather than two. Unlike the start in track and field the posterior foot is not supported by a wedge or block. The track start did allow the athlete to achieve a deeper angle of entry into the water (Councilman et al. 1988) because the swimmer must lift the back leg upward off the block causing it to redirect his or her centre of gravity vertically downward rather than in a horizontal direction.

In 1983 yet another starting method was proposed (Woebler, 1983). The "tuck start" was characterized by a low, compact body position, where the athlete can rotate extremely far forward over the forward edge of the block. The tuck start uses a position braced by the arms which grasp the side edges of the starting surface. At the command of the starter the athlete would spring forward off the block eliminating the need to redirect the centre of gravity from the vertical to the horizontal plane. No formal testing was performed on this starting technique. It was cautioned that the tuck start was developed and informally tested using only the KDI Paragon starting platform (other starting blocks might not be suitable for this technique). This starting method should be subject to further investigation, especially with extreme angles of starting block inclines (-30 degrees to -40 degrees).

Cinematographic techniques were used to analyze four different styles of swim starts (Zatsiorsky et al., 1979). Additional to the previously mentioned conventional, grab and track starts, a modified track start which supported the back leg is also tested in the study. In each case, the motion was timed from the sound of the starting gun until the point when a subject's hips reached a distance 5 metres from the starting platform. In this research the modified track start was the fastest, with the grab start second, still outranking the conventional start for speed. The track start was the slowest. The ability of the swimmer to minimize water resistance is also a factor that must be considered when start techniques are analyzed in this manner. This was not a consideration in this research. A swimmer who has a fast start "off the block" may also have a poor entry that will cause excessive water resistance, slowing the swimmer and skewing the results of the study. The study did go on to suggest that a better summation of forces for the conventional start could provide a faster start time, but exactly how this might be accomplished was not described. This was an important recommendation because the summation of forces principle (with respect to swim starting) had not been mentioned in the literature found before this time.

Starting block angles. The establishment of the ideal takeoff angle for a competitive swim start has also been studied. Heusner (1959) determined the ideal angle to be approximately -13 degrees. This value was analytically determined using a theoretical equation. Heusner was attempting to reduce the total swimming time with respect to the angle of takeoff. This logic applies only over a short sprint race when the speed of a start is of great consequence to the outcome of the race. The value of -13 degrees below horizontal was also reported by Groves and Roberts (1972) and Bowers et al. (1975). These researchers used a ratio of velocities, vertical to horizontal based on the movement of a swimmer's centre of gravity at takeoff.

Prior studies have also investigated starting block angles. It was reported that the use of a starting block set at any angle was of no advantage in the swim start (Stevenson and Morehouse, 1979; Elliot and Sinclair, 1970; Tuttle et al. 1939). Much of this research has been carried out using the conventional starting method. Since the grab start technique provides a more stable starting position for an athlete on an angular surface further research using, the grab start technique is necessary. Stevenson and Morehouse (1979) used cinematography and a strain gauged starting block to study the effects of starting block angles of 0, -10, -20 and -30 degrees below horizontal on swimming performance using the grab start technique. The differences in performances were analyzed biomechanically and it was concluded that the performance of the grab start was effected by a change in starting block angle. It was reported that the -20 degree block angle provided the most advantage to the athlete by reducing the time "on the blocks".

Force and work. The most important force acting on the body during the swim start is the ground reaction force. The ground reaction force acts through the feet during the support and thrust of the swimmer from the starting block. This force is a three-dimensional vector consisting of a normal component (Z) and two shear components (X and Y) which act against and along the supporting surface, respectively.

Little research has evaluated the swim start with respect to the reaction forces or muscular work. Such research has, however, been done on mechanically similar activities. To appreciate the mechanics of the swim better start the characteristics of other stationary takeoff actions will be reviewed. Jensen et al. (1983) stated that when a body is propelled from a stationary position, its projection depends on two factors—explosive power from leg extension and the ability to transfer momentum from other body parts. At takeoff, the momentum generated by swinging and/or lifting the limbs of the upper body (arms, shoulders and perhaps the head) provide a thrust to drive the body forward. The centre of gravity then shifts to a position where the forces of the legs are directed centrally. If an athlete is attempting to attain body projection for maximum horizontal distance, as in competitive swim starting and in broad jumping, it has been determined (Jensen et al., 1983) that leg extension must occur when the centre of gravity is well forward of the feet. Furthermore, the upper body thrust must be directed at least partially toward the horizontal so that anytime during leg extension a straight line could be drawn from the feet through the centre of gravity that would create an angle of, approximately, 45 degrees. The optimum angle for an object experiencing projectile motion has been prescribed as 45 degrees from horizontal if landing and takeoff are at the same level (Halliday and Resnick, 1982). This criterion is, however, impractical for an athlete to meet in many circumstances. For both the long jump and the swim start the athlete would have to exert tremendous physical effort to propel his or her body at an angle of 45 degrees. Much of the physical effort would be in propelling the body vertically rather than horizontally as is desirable. Moreover, with the swim start, the landing is always lower than the takeoff. For a "human projectile" when the athlete is attempting to achieve large horizontal distances, a more acute angle of takeoff is preferred.

The competitive swim start and broad jump can both be classified as double leg projection (thrust) actions, generally beginning from a crouched position. Research by Jensen et al. (1983) have determined that the optimum angle that the legs should flex to develop maximum force depends upon the strength of the extensor muscles. If a deep crouch position is used (where the angle of knee flexion is less than 90 degrees) forces can be applied over a greater distance to develop more acceleration. A deep crouch also demands that more work must be done to lift the body. Strong muscles (extensors of the hip) have been found to work more effectively when a deep crouch position is used, weaker muscles contribute best during a shallow crouch position when the joints are flexed to a lesser amount. In general, swimmers assume an optimum starting position with flexion at the hip is usually less than 90 degrees while that of the knee is 90 degrees or greater.

It should be noted that the competitive swim grab start differs from the broad or long jump in three ways. First, the centre of gravity is shifted much farther forward before extension of the lower limb occurs. Second, the toes are curled over the edge of the starting platform so that the final push is made nearly perpendicular to the resisting surface (if this situation did not exist there would be a reduced friction between the two surfaces (the feet and the starting block) which would significantly reduce the ability of the athlete to apply a horizontal thrust due to backward slippage). Third, the takeoff projects the swimmer to a prone position so the body is as straight and streamlined as possible and at entry to the water should be at an angle of 5 deg to 10 deg below horizontal (Jensen et al., 1983). Such an entry would be virtually impossible to perform if the takeoffs were at angles of 45 degrees, as previously suggested. A takeoff angle of 45 degrees would cause the swimmer to enter the water at a deeper angle than is desirable unless considerable arm motions were used in flight to reorient the body.

The primary driving forces for the standing broad jump takeoff are generated by the hip, knee, ankle and toe extension. The centre of gravity is kept forward of the feet at the moment of leg extension. The extensor muscles of the back, hip, knee ankle and toe contribute to projection of the athlete (Jensen et al., 1983). Research has shown that the ankle and hip muscles are the primary generators of energy during the long jump, while the knee muscles contribute very little work in the broad jump effort (Robertson and Fleming, 1987). In explanation it was stated that the muscles that cross the hip and ankle joints were net generators of energy, while the muscles of the knee are net energy absorbers. It is conceivable that similar characteristics should be found in the results of this research. In which case, the hip and ankle joints should have the greatest percentage contribution to the propulsion of the athlete.

Stewart et al. (1989) studied power contributions by the legs during the competitive swim grab start. Data were collected using a Kistler force platform mounted on a regulation starting block of -10 degree incline. Cinematographic data were collected on three male swimmers tested using a grab start. One trial from each was analyzed. Data were processed using inverse dynamics (Winter, 1979). No studies of this nature could be found for comparison so related jumping research was studied. Contrary to the results of jumping studies reported by Jensen (1983) the extensor muscles of the knee and ankle were the primary generators of energy, while the hip muscles did negative work and absorbed energy generated by the other muscles. It was concluded that the swimmers were forced to use the large muscles of the hip to position the trunk and to redirect the body's centre of gravity from a vertical to a horizonal plane, while the knee and ankle extensors were used to propel the athlete off the blocks. The results of this research suggested that the effect of the angle and height of the starting surface should be studied to discover if it were possible to create a positive work situation at the hip that should allow an athlete to perform a farther and more powerful start.

Methodology

Subjects. The subjects for this research were eight university female swimmers. All subjects were members of competitive swim clubs. Six of the athletes were members of the University of Ottawa varsity swim team. All of the swimmers had previous training and experience in the performance of the grab start from both the level starting block and a starting block incline at -10 degrees. All subjects were given instructions on the performance of the "toes back" start and were allowed to practice this skill until comfortable with it before the testing. All subjects were familiar with the Swim Canada rules and regulations under which each start was performed.

Table 1 Subject Data

Number of subjects	n=8
Subject gender	female
Age range	18-26 years
Mean age	20.6 years
Body mass range	59.6-75.6 kg
Mean body mass	65.7 kg

Experimental procedure. Swimmers were scheduled for one testing session. The swimmers were divided into two groups. One group of five swimmers was tested in the morning and the other group of three swimmers was tested in the afternoon. All swimmers performed under all of the test conditions so no distinction was made as to the group distribution. The subjects came at a time scheduled for their convenience. Each testing session lasted approximately 2.5 hours. All swimmers were tested at the University of Ottawa swimming pool. Upon arrival at the test site each subject was required to sign an informed consent form. Each swimmer was weighed and had anthropometric data measurements taken. Markers were placed on the left side of each subject at the centre of limb rotation for the shoulder, hip, knee, ankle, ball of foot, elbow and wrist. The markers were white and approximately 2.5 cm in diameter.

Before testing each group of swimmers, specific performance instructions were given. After listening to instructions the swimmers were provided with a warmup and practice time. When all swimmers in a group felt comfortable executing grab starts under the three experimental conditions, the testing began. The swim starts were performed from a Swim Canada regulation starting block, modified for the purposes of this research, into the deep-end of the swimming pool (depth approximately 5.25 m). The swimmers were instructed to start each time as if attempting a freestyle sprint race and were required to swim four or more strokes after each start. Subjects were started individually and were required to perform based on Swim Canada standards. All subjects performed three recorded trials at each of the three research conditions (level surface with the toes held over the forward edge of the starting surface, inclined surface with the toes held over the forward edge and inclined surface with the toes held back from the edge of the starting block). If a false start occurred, the trial was repeated. The swimmers were rotated so that all subjects were permitted to rest between the three conditions.

Instrumentation. A Kistler Multicomponent Measuring Platform (type 9281B) was used in the collection of force data. The force platform was securely mounted using flexible, nonstretch straps to the top of a swim starting block. The surface of the starting block was covered with a pliable material that would accommodate the lower surface of the force platform and reduce slippage and vibration of the instrument. The surface of the force platform was covered with a layer of course adhesive tape to reduce the chance of slippage. Wedges were inserted between the block and force plate to produce a level takeoff surface.

The motion of each subject was recorded by a 16-mm cinecamera (Locam) that was positioned perpendicular to the swimming lane at a position that could record both the takeoff and entry of each swimmer. The cinecamera was mounted on a tripod and levelled at a position approximately 10 m from the test area. The cinecamera remained stationary and the film was taken at a rate of 100 frames per second. The position of the camera and speed of the film remained consistent for all trials. Reaction forces for each trial were collected, simultaneously, with filming through the analogue-to-digital converters of a microcomputer. Synchronization of the cinecamera and the force plate was facilitated by a computer generated pulse. Data were collected for each swimmer from the time of the start until the subject entered the water.

Data processing. One trial from each subject under each condition was chosen from the data for processing. Criteria for selection of each trial were based upon the experimenter's judgement as to the quality of the start. The raw force data were low-pass, digitally filtered with a cutoff frequency of 10 Hz to reduce the effects of any vibrations occurring from the starting block. The directions of the forces were rotated 10 degrees for the two inclined conditions so that they ha d the same orientation as the cinefilm data.

The film was projected and digitized using an Hewlett-Packard (model HP9874) digitizer. A 3 x 5 grid was used to scale the data. The markers were digitized manually and the coordinates compared with their true grid loci to determine that accuracy of digitizing was 0.5 cm. The coordinate information for each recorded trial was digitally filtered with a fourth-order, zero-lag Butterworth low-pass filter at a cutoff frequency of 6 Hz, then further processed to compute segmental centres of mass, as well as, linear and angular velocities and accelerations (Winter, 1979).

The computer software package, BIOMECH (School of Human Kinetics, University of Ottawa), was used to calculate net forces and moments of force at the three lower limb joints and at the shoulder and elbow by inverse dynamics (Winter, 1979). The product of the net moments of force and their joint velocities were used to quantify the instantaneous powers. At a particular joint, the power generated by the net moment of force is the product of the net moment and the joint angular velocity (Winter, 1979). The general equation for calculating moment power was:

$$P_m = M_j \times \omega_j \qquad (1)$$

where, P_m is the power produced by the net moment of force (W),

M_j is the net moment (N.m) and

ω_j is the joint angular velocity (rad/s).

The mechanical work done at each joint was calculated using trapezoidal integration of the power histories beginning at the lowest displacement of the centre of gravity until the point of takeoff (Robertson and Fleming, 1987). The equation used for calculating work is:

$$W_m = \int P_m \, dt \qquad (2)$$

where, W_m is mechanical work in joules (J) and

P_m is moment power in watts (W)

The takeoff velocities in metres per second were calculated from the horizontal and vertical velocities of the path of the centre of gravity for each swimmer at takeoff. The angles of takeoff for each swimmer were derived by finding the least squares parabola that best fits the total body centre of gravity trajectories. These values were calculated from the subject's kinematic data using a polynomial least squares curve fitting technique (appendix 1). The values for the takeoff velocities and takeoff angles are located in Table II.

Statistical treatment. The data were analyzed statistically using analysis of variance (ANOVA) procedures. Three analyses were performed. The analyses that compared the distance of the dive for the swimmers across the three conditions and that for the angle of takeoff of the swimmers under the three conditions were performed using a one-way repeated measures ANOVA procedures with a univariate application using a mixed model. The velocity of start and power generated by the hip were considered proportional and therefore a one-way doubly multiple repeated measures ANOVA procedure with averaged multivariate tests of significance was used to analyze these values. The statistics were compiled on the mainframe computer of the University of Ottawa using the SPSSx software package. All statistical data were evaluated at the 0.05 level of significance.

Results and Discussion

The movement pattern for the swimmers executing the grab start for each of the three research conditions was essentially the same. Subjects were required to perform each start based on *Swimming/Natation Canada* standards. All swimmers used the same technique with modifications due to personal style being minimal. The greatest possible difference between the subjects was the timing factor for the start. More experienced swimmers tended to have a more evenly timed series of movements for their starts. A model of a grab start using a stick-figure diagram is found in Figure 1.

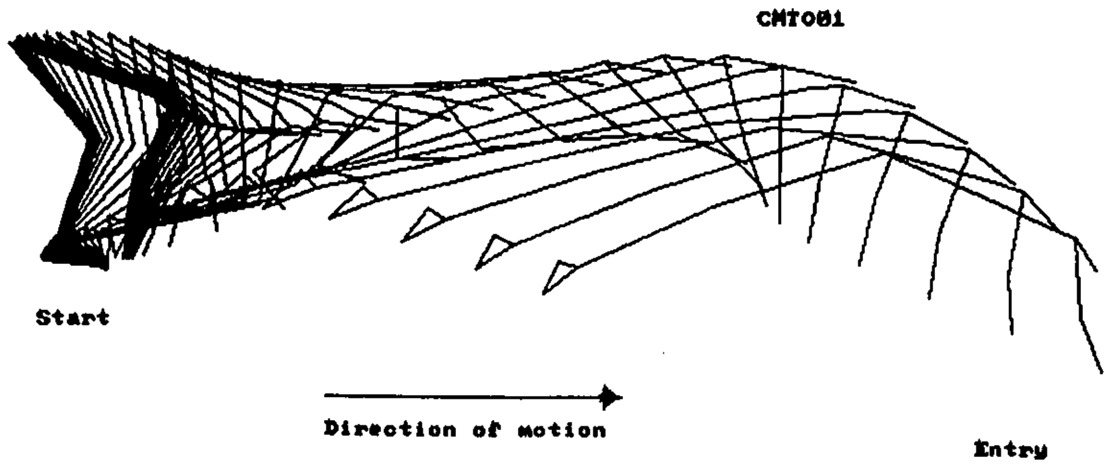

Figure 1 Stick-figures of a subject performing a Toes-Over, grab start

Average moment powers. The powers produced by the three net moments of force were normalized to percent of thrust and ensemble averaged for each research condition. Figures 2, 3 and 4 show the powers produced by the hip, knee and ankle moments for each of the three types of starts. The solid line in each figure represents the mean power while the broken lines show plus or minus one standard deviation. In Figure 2 the minus one standard

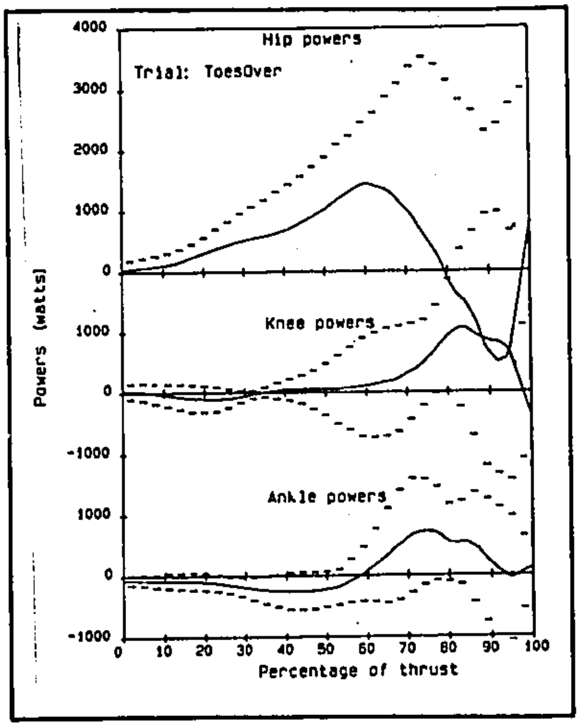

Figure 2 Average powers of the hip, knee and ankle moments for the Toes-Over grab start

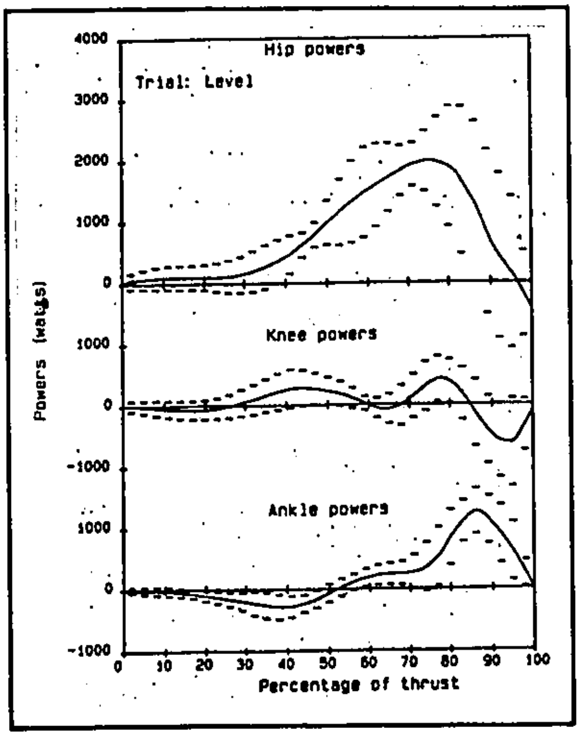

Figure 3 Average powers of the hip, knee and ankle moments for the Level grab start

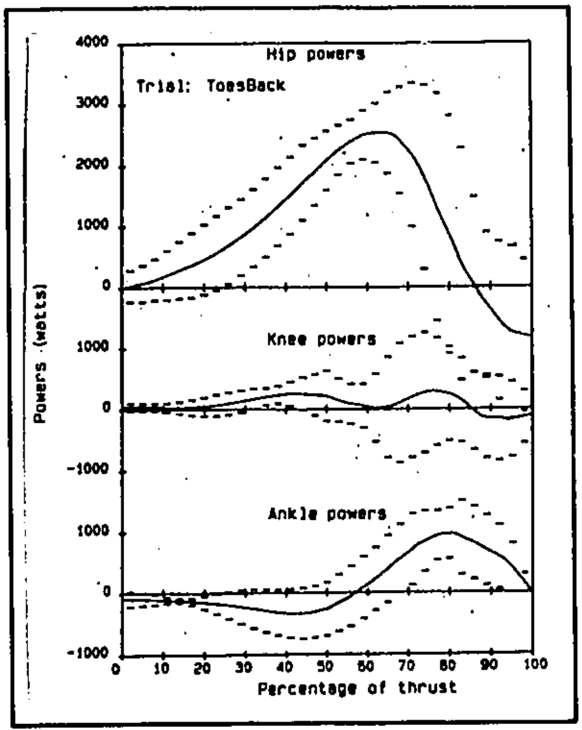

Figure 4 Average powers of the hip, knee and ankle moments for the Toes-Back grab start

deviation for the hip moment powers was not plotted due to its overlap with the knee powers.

The power data from the Level trials (Figure 3) and the Toes-Back trials (Figure 4) were very similar at each of the three joints. The power curves for both research conditions show that the hip experienced a large concentric extensor moment as the swimmer extended the hip to thrust her body from the starting block. The sizes of the average powers for the hip for both the Level and Toes-Back conditions were generally more than 2000 W. These results reveal that the extensor muscles of the hip joint provided the largest amount of positive work of the three joints in thrusting the swimmers from the starting block.

Much less power was generated by the knee joint. In both the Level and Toes-Back styles the average peak powers did not exceed, approximately, 300 W. This result suggests that the knee joint played a less important role in producing the work done to thrust the swimmer from the starting blocks. The ensemble averaged power curves show that the patterns of power production were essentially the same for both the Level and Toes-Back starts (Figures 3 and 4, respectively). They also show that the hip and the ankle moments were the principal generators of power to thrust the swimmer from the starting blocks for these two conditions, while the knee moment contributed relatively little power. This is in agreement with the findings in the jumping research of Robertson and Fleming (1987). This does not mean that the knee is unimportant in the starting process. It likely has an important stabilizing action for the swimmer, however, in terms of power production the knee moments were small contributors.

Power analyses for the Level and Toes-Back grab starts. Figures 5, 6 and 7 show the angular velocities, moments of force and powers produced by the moments of force for the hip, knee and ankle joints, respectively, for a typical subject's Level grab start. Similarly, Figures 8, 9 and 10 show the same subject's results for the Toes-Back grab start. Note, that the discussion of the moments of force and their associated powers will only be considered between the start of the thrust (indicated by the code, STRT) and the takeoff point (indicated by the code, OFF) when the toes left the starting platform.

The patterns of power produced by the knee for the Level and Toes-Back conditions were similar. The knee moments first provided a concentric flexor moment (Figures 6 and 9, respectively). These produced a prestretching at the beginning of the start and prior to the large thrust generated by the hip muscles. This was followed by an extensor moment of approximately the same magnitude occurred at approximately the same time as peak power was reached by the hip moment of force. This extensor moment was followed by an eccentric flexor moment. This flexor moment occurred at the same time as the ankle reached its maximum power output.

The ankle moments (Figures 7 and 10) begin with eccentric, plantar flexor contractions, simultaneous, with the flexor moments at the knee. The actions of the ankle moments were to produce prestretching in preparation for the following concentric contraction. This following large concentric plantar flexor moment occurred just after the peak thrust from hip moments. Coincidently, the average maximum powers for the ankle moment of force were approximately 1000 W for both the Level and Toes-Back conditions.

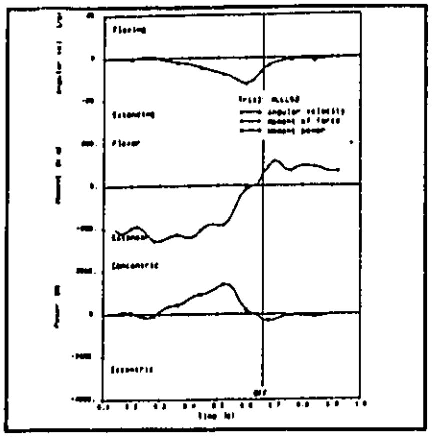

Figure 5 Angular velocity, moment and power at the hip for a Level grab start

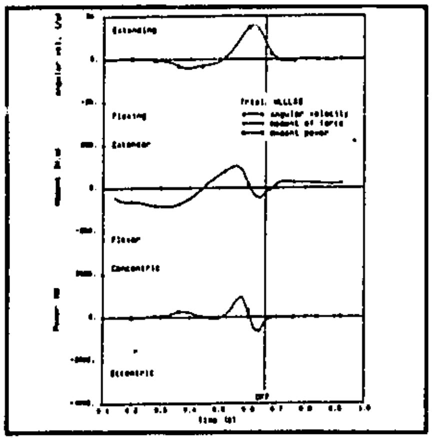

Figure 6 Angular velocity, moment and power at the knee for a Level grab start

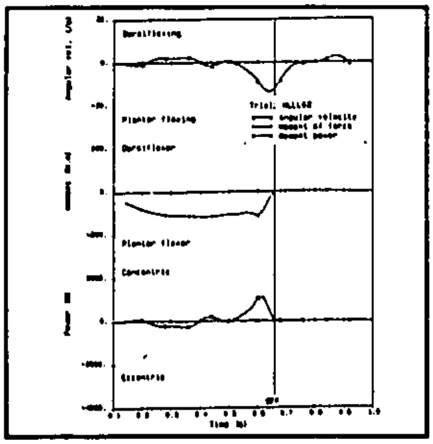

Figure 7 Angular velocity, moment and power at the ankle for a Level grab start

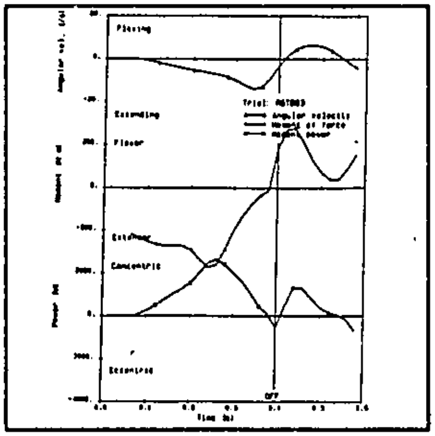

Figure 8 Angular velocity, moment and power at the hip for a Toes-Back grab start

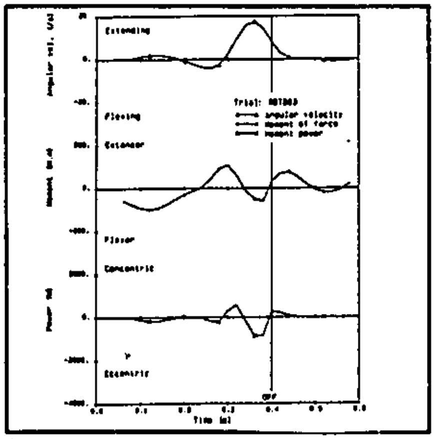

Figure 9 Angular velocity, moment and power at the knee for a Toes-Back grab start

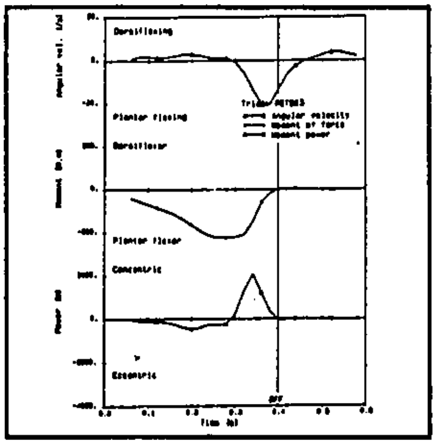

Figure 10 Angular velocity, moment and power at the ankle for a Toes-Back grab start

Power analyses the Toes-Over grab start. The patterns of power of the hip, knee and ankle moments of force were different for the Toes-Over research condition. Figures 2 and 11 illustrate that the hip moment produced a concentric extensor contraction similar to those produced with the other two conditions, however, the peak power produced was much less than either the Toes-Back or Level conditions. The peak power production at the

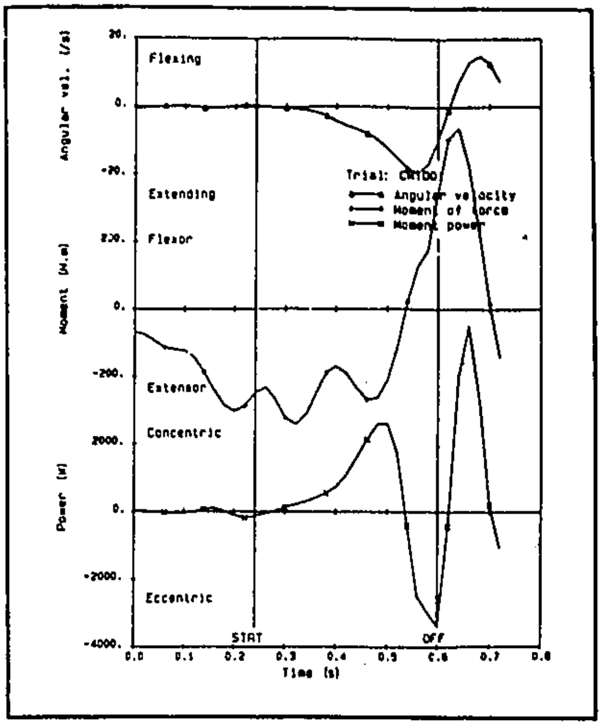

Figure 11 Angular velocity, moment and power at the hip for a Toes-Over grab start

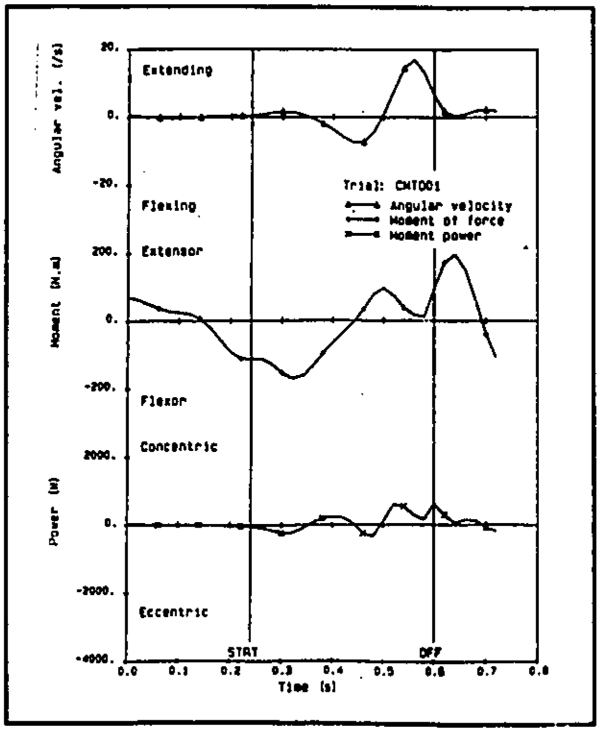

Figure 12 Angular velocity, moment and power at the knee for a Toes-Over grab start

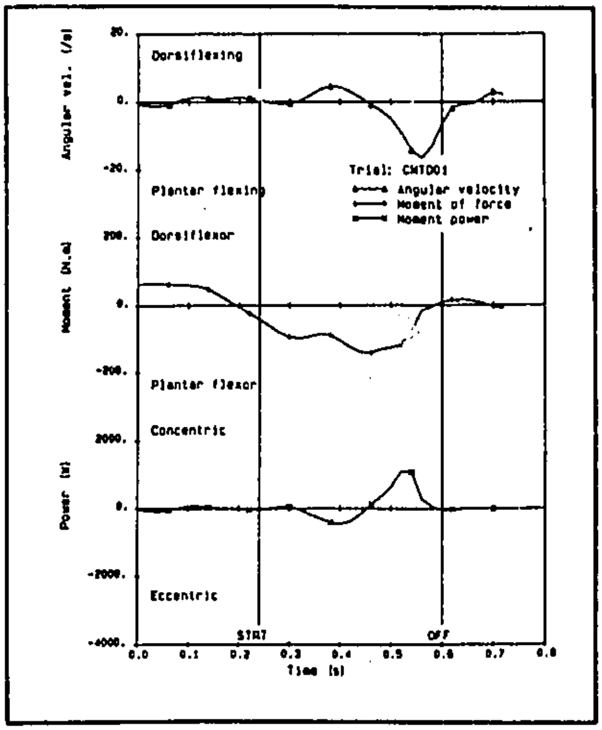

Figure 13 Angular velocity, moment and power at the ankle for a Toes-Over grab start

hip was, approximately, 2500 W for the subject illustrated in Figure 11 but averaged only 1250 W for all subjects combined. In general, the hip moment of force generated less power and therefore performed less work during the Toes-Over start.

The knee (Figures 2 and 12) experienced a very small eccentric, flexor moment, followed by a relatively large concentric extensor contraction. The peak power generated by the knee joint was reached after the hip had experienced peak power and was approximately 1000 W on average but only 500 W for the subject depicted in Figure 12. The knee moment for the Toes-Over condition generated much more power than for the other two types of starts.

The ankle (Figures 2 and 13) provided an eccentric plantar flexor moment as it did for the other conditions. This was followed by a concentric plantar flexor moment as the swimmer thrust from the starting block. The power, approximately 750 W, generated by the ankle was slightly less than that generated by the knee or the hip. This indicated that during the grab start for the Toes-Over condition the hip, knee and ankle contributed almost equally to the amount of power generated by the legs at the start.

The Toes-Over condition was the method which is commonly used by competitive swimmers and the starting method with which they are most experienced. Their experience may have enabled the swimmers to execute a more efficient start using the Toes-Over method.

Movement sequencing. Movement sequencing did occur to a certain extent during each of the starts. This is illustrated by the ensemble averaged power curves found in Figures 2, 3 and 4. When the swimmers performed the grab start under the Level and Toes-Back condition peak power for the hip was reached prior to, or simultaneously with, peak power from the knee. Both the hip and the knee reached peak power production before the ankle. This indicated that the extensor muscles of the hip were acting slightly prior to, or simultaneously with, the knee but always before the ankle. With the Toes-Over start peak power for the hip occurred first, but were followed by peak power from the ankle and then the knee. In the ideal situation an athlete would recruit the muscles of the hip, then the knee and finally the ankle to execute the dive. This result is supported by Dyson (1962) who stated that for jumping activities, contraction of the leg muscles should be simultaneous to produce the maximum impulse, but that in practice there will be sequencing from proximal to distal muscles. Previous research by Stewart et al. (1989) found that during the swim start there was simultaneous contraction of all moments of force of the leg. The sample size in this study, however, was very small (n=3).

The results of this research show that under all three research conditions the hip extensor muscles reached their maximum power earlier than the ankle plantar flexors. The hip also experienced a large positive concentric contraction under all three research conditions. The action of the knee, however, was relatively inconsistent in terms of maximum power. The actions of the hip and ankle appeared to be responsible for generating the most power during the grab start in the Level and Toes-Back conditions. This is consistent with findings in the broad jump research by Robertson and Fleming (1987). The results from the grab starts performed under Toes-Over condition were different from the other two research conditions. As this was the most common method of starting, swimmers may be trained to have a more efficient and uniform start with this method.

The pattern of peak power generation was the factor which most clearly distinguished the Toes-Over condition from the others. In terms of horizontal distance achieved and the other performance variables this condition does not appear to be different from the other two takeoff conditions.

The summation of forces principle was supported under the Level and Toes-Back research conditions. The summation of forces principle states that to produce the most powerful movement possible all muscles which affect the active joints must be utilized to their fullest extent (Dyson, 1964; Robertson and Fleming, 1987). When the results of this research were compared to those for the standing broad jump (Robertson and Fleming, 1987) the findings were similar. The aforementioned broad jump research demonstrated that the hip and ankle moments were the primary generators of energy, while the knee moment contributed very little to the work in the jump. While the knee in the Toes-Over trials did generate more power than under the other two research conditions, the statistical analysis showed that the results for the Toes-Over condition were not significantly different from the other two types of starts.

In terms of comparing the swim start to the broad jump it would seem that when performing under the Level and Toes-Back conditions swimmers execute the start much like the execution of a broad jump, however, when performing the start with the Toes-Over method swimmers utilize the moments of force differently. The novel nature of the Level and Toes-Back conditions may cause the swimmers to perform differently, more like a broad jump than a swim start. The more efficient movement which occurred with the Toes-Over condition might be developed by swimmers with the other two techniques if they were given extensive training and practice with these skills. In turn, it would also be interesting to see whether the performance variables (takeoff angles, horizontal distances of dive etc.) would be enhanced with the Level or Toes-Back techniques when the swimmers were experienced and practiced at each of these skills.

The results of the present study are much different from the results obtained in previous swim start research by Stewart et al. (1989). The previous study demonstrated that the hip muscles were performing negative work during the start and that the ankle and knee were the primary generators of energy. As previously mentioned the sample size used by Stewart et al. (1989) was very small and it is possible that the angle of the starting block was not correctly accommodated during the data processing. The results of the present study indicate that during the grab start when the starting block is level or at a -10 degree incline the extensor moments of force at the hip and ankle are the primary generators of energy during motion. It is these moments of force which are responsible for the net work done during the start.

Table 2 Takeoff characteristics of each subject for the three start conditions

	Takeoff velocity (m/s)	Takeoff angle (deg)	Distance to entry (metres)	Max. hip moment power (watts)
Level				
S1	4.6	1.59	2.0	2281.9
S2	4.7	2.40	2.0	2531.5
S3	6.4	1.08	2.2	1377.3
S4	4.7	0.58	2.2	1626.9
S5	3.9	9.20	2.0	2688.2
S6	4.4	1.80	2.0	1824.9
S7	5.3	3.34	2.3	3829.6
S8	4.8	1.42	2.2	2199.4
mean	4.9	2.68	2.1	2295.0
s.d.	0.7	2.59	0.1	714.5
Toes-Over				
S1	7.3	2.10	2.2	2597.5
S2	3.3	0.86	2.0	2968.7
S3	6.6	0.78	2.0	157.9
S4	6.7	0.07	2.0	1966.7
S5	6.1	0.30	1.8	3972.5
S6	6.1	2.54	2.0	2278.4
S7	6.5	1.29	2.3	2747.5
S8	5.4	2.69	2.0	2602.5
mean	6.0	1.24	2.0	2474.1
s.d.	1.1	0.94	0.1	1014.0
Toes-Back				
S1	6.0	0.50	2.1	2391.5
S2	7.2	4.33	2.0	3364.2
S3	6.0	4.70	1.9	1906.9
S4	6.6	1.74	2.0	2232.1
S5	6.1	7.34	1.9	3120.3
S6	5.7	1.54	2.1	2856.9
S7	5.7	7.30	2.0	2627.4
S8	6.8	5.32	2.0	2841.4
mean	6.3	4.09	2.0	2409.1
s.d.	0.5	2.44	0.1	945.1

Table 3 Maximum powers (W) produced by the extensor hip, knee and ankle moments of force for the three types of starts

	Hip	Knee	Ankle
Level			
S1	2281.9	23.6	1309.5
S2	2531.5	736.5	1389.2
S3	1377.3	947.7	1077.9
S4	1626.9	199.7	1270.2
S5	2688.2	1262.1	1692.6
S6	1824.9	639.5	1293.2
S7	3829.6	407.8	2142.9
S8	2199.4	412.3	1298.4
mean	2295.0	591.2	1434.5
s.d.	714.5	360.2	311.9
Toes-Over			
S1	2597.5	591.0	1100.3
S2	2968.7	356.6	1062.0
S3	157.9	-417.7	35.6
S4	1966.7	379.5	1370.4
S5	3972.5	517.0	1894.7
S6	2278.4	1811.0	1951.4
S7	2747.5	1233.6	2253.3
S8	2602.5	610.4	1221.6
mean	2474.1	635.2	1361.2
s.d.	1014.0	613.3	648.4
Toes-Back			
S1	2391.5	922.7	1087.8
S2	3364.2	198.3	1232.2
S3	1906.9	853.0	1218.2
S4	2232.1	342.1	1410.0
S5	3120.3	566.8	1283.9
S6	2856.9	1803.5	2215.5
S7	2627.4	562.1	2052.5
S8	2841.4	859.3	1107.4
mean	2667.6	763.5	1450.9
s.d.	945.1	465.7	574.0

Force signatures. Force vector diagrams for the three research conditions are illustrated in Figures 14, 15 and 16. The magnitude and direction of the ground reaction forces during each of the dives are represented by the length and direction of the force vectors in each diagram. During each dive the largest forces were applied by the balls of the feet in the direction of travel (off the blocks) of the swimmer. The force vectors were longest and most concentrated at the edge of the starting surface which is located under the balls of the feet, indicating that the forces are being applied most powerfully and rapidly at this point. The patter of the force vectors in all diagrams indicates that the swimmer did not move solely in the forward direction. The sagittal movements of the swimmers were, however, minimal and were likely due to a slight slippage of the swimmer on the starting surface, or to the slight influence of a dominant side in terms of lower limb strength.

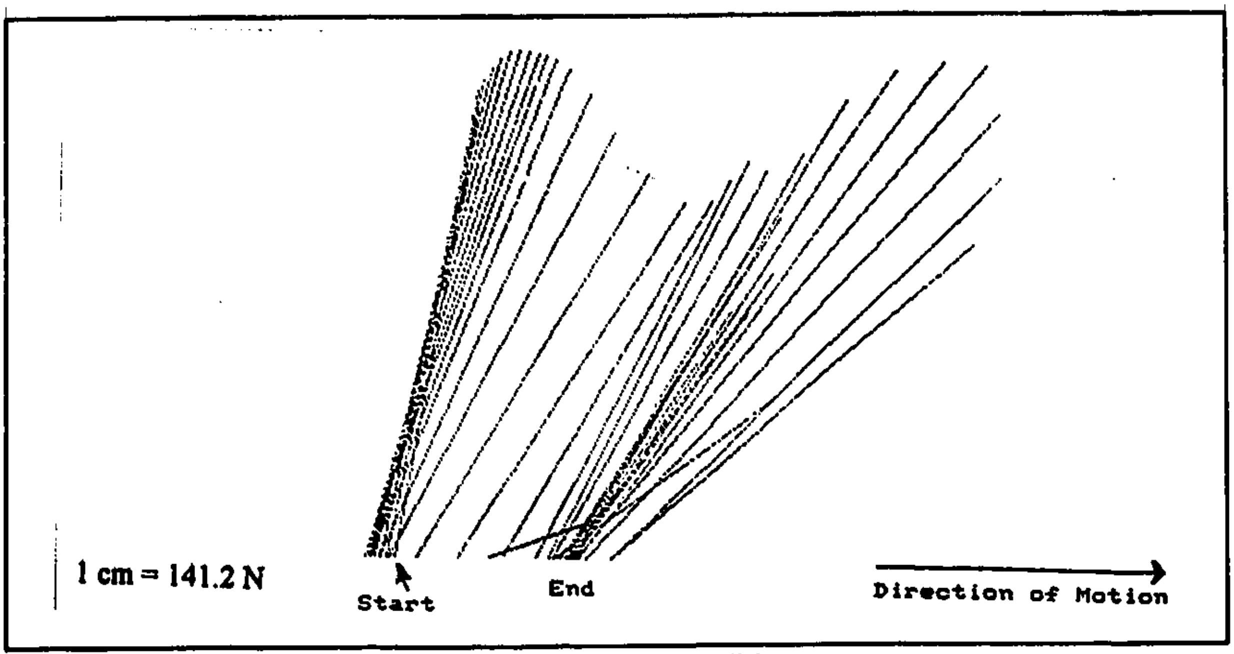

Figure 14 Diagram of force vectors for the Level condition

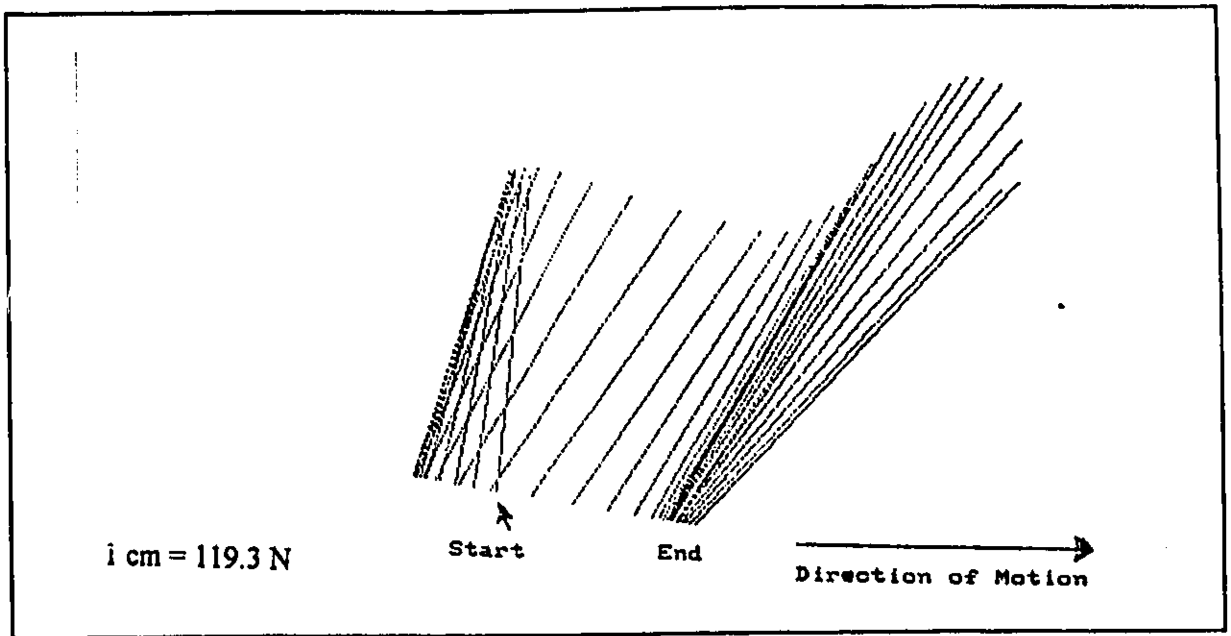

Figure 15 Diagram of force vectors for the Toes-Back condition

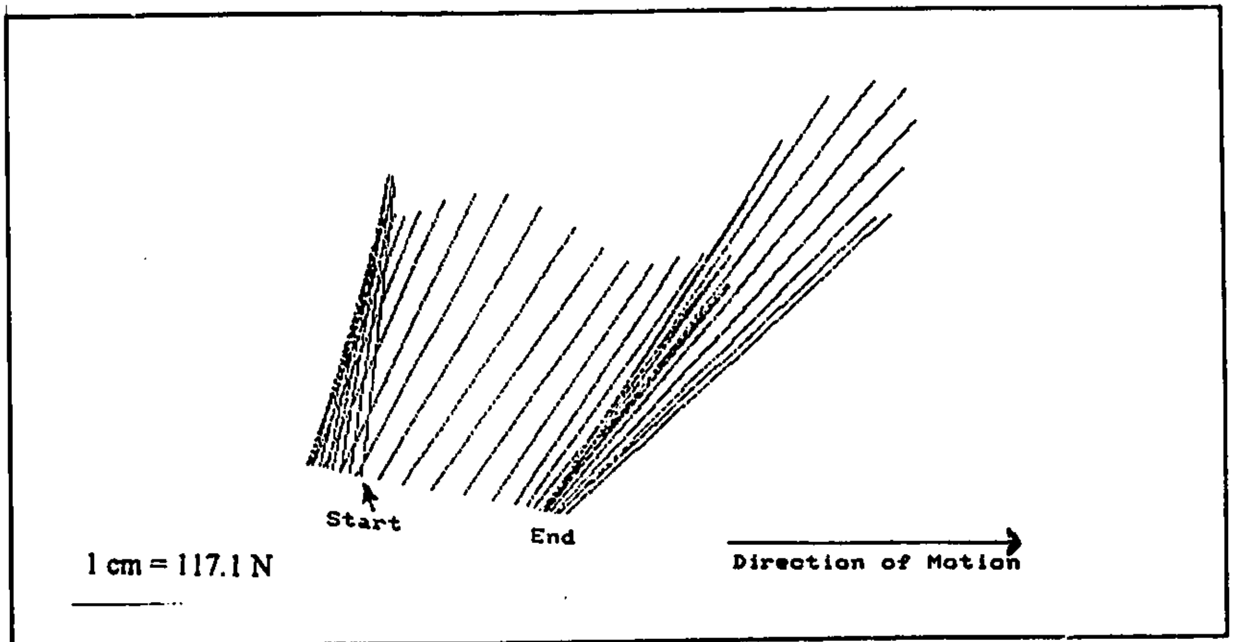

Figure 16 Diagram of force vectors for the Toes-Over condition

Statistical analyses. The angle of the starting block did not have a significant effect on the horizontal distance of the dive in this study (Table 4). When the swimmers started from a level surface they were not able to travel further than when the start was performed for an inclined surface. An athlete who achieves a long flight phase for a swim start should have an advantage during a short (sprint) race. The research also indicates that the performances of the swimmers were not improved significantly when the grab start was performed under the Toes-Back condition. The swimmers did not show significant differences in their ability to perform the grab start whether or not they were permitted to curl their toes over the edge of the starting surface. The hypothesis that a swimmer who dives from a level surface would travel farther than one who leaves from an incline plane due to the improved projection distance which should be achieved was not supported. The distance for each dive was measured based on the position of the centre of gravity at the first water entry point. Mean values for distance indicate

Table 4 ANOVA summary table for horizontal distance of dive across the three conditions

Univariate Application using a Mixed Model

Source of Variance	***df***$^+$	**SS**	**MS**	**F**
Condition	14.00	0.20	0.01	3.00^{++}
Error	2.00	0.05	0.03	
Total	16.00	0.25		

$^+$*df* corrected using Huynh-Feldt Epsilon = 1.0000
$^{++}p > 0.05$

that when swimmers started from a level surface, they did not achieve a greater horizontal distance for their dives than when starting from the inclined surface.

These results are contradictory to previous research. Heusner (1959) recommended that a starting surface of -13 degrees was optimal for swimmers, however, this was before the grab start was widely used by athletes. Groves and Roberts (1972) and Bowers et al. (1975) also recommended the -13 degree starting block angle. These results were obtained using a ratio of velocities, vertical to horizontal, based on the swimmer's centre of gravity much similar to the present research. It is difficult to compare previous studies directly to this research as an angle of -13 degree was not studied and researchers can only extrapolate the data from the -10 degree results. Still other researchers (Tuttle et al., 1939; Elliot and Sinclair, 1979) stated that starting block angle was not a significant factor in the start. Based on this research for female swimmers using the grab start technique there is not a significant difference in performance whether using a level starting block of a starting block which is at a -10 degree incline.

The greatest power production at the hip also facilitated the greatest takeoff velocity. This is logical as it is the extensor muscles of the hip (gluteus maximus, semimembranosus, semitendinosus and biceps femoris) which are used to thrust the swimmer's body forward from the blocks. There were no significant differences in either of these values across the three starting conditions (see Table 5).

Table 5 ANOVA summary table for velocity and power values across the three conditions

Multivariate Tests of Significance (S=1, M=1, N=1)

Test	**Value**	**Exact F**	**Hypoth.DF**	**Error DF**	**Sig. of F**
Pillais	0.78444	3.63902	4.00	4.00	0.119
Hotellings	3.63902	3.63902	4.00	4.00	0.119
Wilks	0.21556	3.63902	4.00	4.00	0.119
Roys	0.73444				

The forward velocity of a swimmer at the start is the physical factor which most affects the speed of the start. A swimmer who has a rapid takeoff velocity will have a quick start and a speedy entry into the water provided that her body position is streamlined. The reaction time of the swimmer to the start command is the only other principle factor which can affect the timing of a start. Reaction time is a psychomotor rather than a physically (biomechanically) controlled factor. The swimmer who is able to achieve a rapid takeoff velocity will theoretically have the fastest start, all other factors being equal. The athlete must strive to achieve a rapid takeoff velocity while also correctly positioning his or her body to create the longest flight phase for the dive. In terms of maximum power of the hip muscles during takeoff (Table 3), the results of this research indicate that there is no significant difference across the three research conditions. Power production remained essentially constant across the changes in the starting surface angle. The intent of this research was to establish a condition, whereby, maximum power at the hip was achieved along with increased takeoff velocity and increased horizontal distance. Based on the results of this study alteration of the angle of the starting surface from level to -10 degrees is not sufficient to facilitate maximum power production at the hip or increase a swimmer's takeoff velocity. Most competitive swim starting blocks are positioned at a -10 degree angle. This does not appear to be more advantageous to a swimmer than starting from a level surface of the same height. Further investigation which examines more extreme angles of incline (-15 degrees etc.) should be undertaken to determine the optimum angle for the starting surface. Altering the stance of the swimmer on the starting surface from a Toes-Over to a Toes-Back position is also not sufficient to significantly alter the power production of the hip during the grab start. The idea put forward by Stewart et al. (1989) that it was possible that a certain amount of power was absorbed in the reorienting of the trunk from a vertical to a horizontal position in preparation for the swimmer to enter that water in a dive was not supported nor rejected by this research.

The takeoff angle for the swimmer was not significantly affected by altering the angle of the starting surface or by the foot position of the swimmer (Table 6). No previous research was found which discussed the angle of takeoff of the swimmer with respect to the angle of the starting surface. Most literature was concerned solely with the angle of the starting block. The swimmers who started from an inclined plane in this study had takeoff angle values which were variable when compared to swimmers who started from a level surface, perhaps an ideal condition exists between the angle of takeoff of the swimmer and the distance of the dive based on the original angle of the starting block. Clearly further research should be performed which

Table 6 ANOVA summary table for takeoff angle across the three conditions

Univariate Application using a Mixed Model

Source of Variance	*df*$^{+}$	**SS**	**MS**	**F**
Condition	12.77	51.71	3.69	2.01^{++}
Error	1.82	14.87	7.43	
Total	14.59	66.58		

$^{+}$*df* corrected using Huynh-Feldt Epsilon = 0.9121
$^{++}p > 0.05$

will investigate the ideal takeoff angle for a competitive swimmer under various conditions.

Conclusions

Based on the results obtained by this study the following statements are warranted.

1. The extensor muscles of the hip joint are the major thrusters of the body when performing a grab start.

2. There were no significant differences in the performances of the grab start with respect to distance of the horizontal flight phase of the dive whether starting from a level surface or a surface on a -10 degree incline.

3. There were no significant differences in the performances of the grab start with respect to angle of takeoff of the dive whether starting from a level surface or a surface on a -10 degree incline.

4. There were no significant differences in the performances of the grab start with respect to velocity of takeoff or power generation by the hip whether starting from a level surface or a surface on a -10 degree incline.

5. The position of the feet (whether or not the toes were curled over the edge of the starting block) had a significant effect on the grab start technique in terms of takeoff velocity, power production at the hip, takeoff angle and horizontal distance of the dive when starts were performed from an inclined starting block (-10 degrees).

6. The female swimmers in this study used a different starting technique when executing the grab start in the Toes-Over position from an inclined starting surface than they did when in the Toes-Back or Level positions. The difference in technique may be a function of experience and practice.

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Appendix I. Program for least-squares curve fitting of centres of gravity.

```
      IMPLICIT REAL*8(A-H,O-Z),LOGICAL($)
C
      REAL*8 T(1001),X(1001),Y(1001),WORK(21,21),COEFSX(21),COEFSY(21),S(41)
      LOGICAL LX*1,LY*1
      DATA LX/'X'/,LY/'Y'/
C
    1 WRITE(6,100)
      NPTS=0
      DO 2 I=1,1001
      READ(5,200,END=300) T(I),X(I),Y(I)
    2 NPTS=NPTS+1
200   FORMAT(10X,F8.0,2F11.0)
C
300   N2=NCOEFF*2-1
      CALL GEPLSD (2,COEFSX,3,S,NPTS,T,X,DEVNX,IER,WORK)
      IF(IER.NE.0) GO TO 6
      CALL GEPLSD (3,COEFSY,5,S,NPTS,T,Y,DEVNY,IER,WORK)
      IF(IER.NE.0) GO TO 6
C
      WRITE(6,102)
      WRITE(6,101) (COEFSX(I),I=1,2)
      WRITE(6,101) (COEFSY(I),I=1,3)
C
      WRITE(6,109) LX
      DO 3 I=1,NPTS
      E=COEFSX(1)
      DO 5 J=2,2
    5 E=E*T(I)+COEFSX(J)
    3 WRITE(6,103) T(I),X(I),E
      RMS=DSQRT(DEVNX/NPTS)
      WRITE(6,104) DEVNX,RMS
      WRITE(6,109) LY
      DO 8 I=1,NPTS
      E=COEFSY(1)
      DO 9 J=2,3
    9 E=E*T(I)+COEFSY(J)
    8 WRITE(6,103) T(I),Y(I),E
C
      RMS=DSQRT(DEVNY/NPTS)
      WRITE(6,104) DEVNY,RMS
      VX=COEFSX(1)
      VY=(2*COEFSY(1)*T(1) + COEFSY(2))*T(1)
      V=DSQRT(VX*VX+VY*VY)
      ANGLE=DATAN2(VY,VX) * 57.2958
      WRITE(6,110) VX,VY,V,ANGLE
C
    6 WRITE(6,107)
      STOP
C
   12 FORMAT(2I5)
   11 FORMAT(F10.1,G14.7)
  100 FORMAT(' POLYNOMIAL LEAST-SQUARES CURVE FITTING.'/)
  101 FORMAT(T15,3G14.7)
  102 FORMAT('         Fitting coefficients (highest power to lowest)')
  103 FORMAT(3F10.4)
  104 FORMAT(/10X,'Sum of squared deviations = ',G13.5/
     +      /8X,'ROOT-MEAN-SQUARE DEVIATIONS = ',G13.5/)
  105 FORMAT(' Number of coefficients of polynomial= ',I5/
     +       ' Number of fitting points            = ',I5/)
  107 FORMAT(' No fit was possible.')
```

```
108 FORMAT(' Not enough data or data not arranged in two columns.')
109 FORMAT(/' ',T7,'Time',T17,A1,T26,'Est.')
110 FORMAT(/8X,'HORIZONTAL TAKEOFF VELOCITY = ',G13.4/
   +       /8X,'  VERTICAL TAKEOFF VELOCITY = ',G13.4/
   +       /8X,'     TOTAL TAKEOFF VELOCITY = ',G13.4/
   +       /8X,'            AND ANGLE (DEG)  = ',G13.4)
    END
```

Appendix I. Subroutine for rotating force platform data.

```
C           Subprogram: ROT3D

      SUBROUTINE ROT3D (X,Y,Z,THETA,PHI,ZETA)

C This routine rotates a 3-D position vector through an ordered set of 3-D
C rotation angles.  Rotations are assusmed to be in the order: THETA
C then PHI then ZETA.  Where,
C     THETA is the X rotation in degrees,
C     PHI   is the Y rotation in degrees and
C     ZETA  is the Z rotation in degrees.

      REAL X,Y,Z,RT,RP,RZ,THETA,PHI,ZETA,XT,YT,ZT,ROT(3)

      ROT(1)=THETA/57.2958
      ROT(2)=PHI/57.2958
      ROT(3)=ZETA/57.2958

      DO 10 I=1,3

      IF(ROT(I).EQ.0.) GO TO 10

      RT=0.
      RP=0.
      RZ=0.
      IF(I.EQ.1) THEN
            RT=ROT(1)
      ELSE IF(I.EQ.2) THEN
            RP=ROT(2)
      ELSE
            RZ=ROT(3)
      ENDIF

         XT=X* COS(RZ)*COS(RP) -
     1      Y*(SIN(RZ)*COS(RT) - COS(RZ)*SIN(RP)*SIN(RT)) +
     2      Z*(SIN(RZ)*SIN(RT) - COS(RZ)*SIN(RP)*COS(RT))

         YT=X* SIN(RZ)*COS(RP) +
     1      Y*(COS(RZ)*COS(RT) - SIN(RZ)*SIN(RP)*SIN(RT)) -
     2      Z*(SIN(RT)*COS(RZ) - SIN(RZ)*SIN(RP)*COS(RT))

         ZT=X*SIN(RP) + Y*COS(RP)*SIN(RT) + Z*COS(RP)*COS(RT)

       X=XT
       Y=YT
       Z=ZT

 10    CONTINUE
       RETURN
       END
```

```
FILE: RM3      SPSS      •                VM/SP CONVERSATIONAL MONITOR SYSTEM                PAGE 0

TITLE  EXAMPLE OF DOUBLY RM data  - velocity and power
FILE HANDLE MARC NAME='velocity data a'
DATA LIST FILE=MARC RECORDS=1/
 vel1 vel2 vel3 power1 power2 power3
 (T10,f3.1,T20,f3.1,t30,f3.1,t40,f6.1,t50,f5.1,t60,f6.1)
MANOVA vel1 vel2 vel3 power1 power2 power3 /
 WSFACTORS = pos(3)/
 MEASURE = velocity power /
 WSDESIGN = pos/
 PRINT=CELLINFO(MEANS, COV) SIGNIF(HYPOTH AVERF,UNIV) /
 ANALYSIS(REPEATED)/design /
EXECUTE
FINISH
```

```
12-May-94   EXAMPLE OF DOUBLY RM data  - velocity and power
13:32:33    UNIVERSITY of OTTAWA             AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * *

        8 cases accepted.
        0 cases rejected because of out-of-range factor values.
        0 cases rejected because of missing data.
        1 non-empty cell.

        1 design will be processed.
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
               CELL NUMBER
                  1
Variable
  DUMMYFAC        1

Cell Means and Standard Deviations
Variable .. VEL1
                                            Mean  Std. Dev.          N  95 percent Conf. Interval

For entire sample                          4.850       .739          8     4.232       5.468
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Variable .. VEL2
                                            Mean  Std. Dev.          N  95 percent Conf. Interval

For entire sample                          6.000      1.222          8     4.978       7.022
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Variable .. VEL3
                                            Mean  Std. Dev.          N  95 percent Conf. Interval

For entire sample                          6.262       .545          8     5.807       6.718
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Variable .. POWER1
                                            Mean  Std. Dev.          N  95 percent Conf. Interval

For entire sample                       2294.962    763.860          8  1656.361    2933.564
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Variable .. POWER2
                                            Mean  Std. Dev.          N  95 percent Conf. Interval

For entire sample                       2411.462   1084.003          8  1505.215    3317.710
Variable .. POWER3
                                            Mean  Std. Dev.          N  95 percent Conf. Interval

For entire sample                       2409.087   1010.348          8  1564.417    3253.758
```

```
12-May-94   EXAMPLE OF DOUBLY RM data   - velocity and power
13:32:33    UNIVERSITY of OTTAWA              AMDAHL 5880 DP    VM/HPO 5

* * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * *
Tests involving Between-Subjects Effects.

 EFFECT .. CONSTANT
 Adjusted Hypothesis Sum-of-Squares and Cross-Products

                         T1                T4

 T1            780.90042
 T4         324704.55375  135014715.03375

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Multivariate Tests of Significance (S = 1, M = 0, N = 2 )

 Test Name             Value          Exact F       Hypoth. DF         Error DF        Sig. of F

 Pillais              .99592        732.55421             2.00             6.00             .000
 Hotellings        244.18474        732.55421             2.00             6.00             .000
 Wilks                .00408        732.55421             2.00             6.00             .000
 Roys                 .99592
 Note.. F statistics are exact.

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 EFFECT .. CONSTANT (Cont.)
 Univariate F-tests with (1,7) D. F.

 Variable         Hypoth. SS         Error SS       Hypoth. MS          Error MS                F          Sig. of F

 T1                780.90042          3.54958        780.90042            .50708       1539.98439               .000
 T4          135014715.03375    8510962.41625  135014715.03375     1215851.77375        111.04537               .000
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   EXAMPLE OF DOUBLY RM data  - velocity and power
13:32:33    UNIVERSITY of OTTAWA          AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * * *
Tests involving 'POS' Within-Subject Effect.

 Mauchly sphericity test, W = 5.66544E-12
 Chi-square approx. =           140.27344 with 9 D. F.
 Significance =                      .000

 Greenhouse-Geisser Epsilon =       .40243
 Huynh-Feldt Epsilon =              .50451
 Lower-bound Epsilon =              .25000

AVERAGED Tests of Significance that follow multivariate tests are equivalent to
univariate or split-plot or mixed-model approach to repeated measures.
Epsilons may be used to adjust d.f. for the AVERAGED results.
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   EXAMPLE OF DOUBLY RM data  - velocity and power
13:32:33    UNIVERSITY of OTTAWA             AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

 EFFECT .. POS
 Adjusted Hypothesis Sum-of-Squares and Cross-Products

                        T2            T3             T5             T6

 T2              7.98062
 T3             -2.89505       1.05021
 T5            644.80625    -233.90985    52098.06250
 T6           -387.77370     140.66875   -31330.74230    18841.68750

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Multivariate Tests of Significance (S = 1, M = 1 , N = 1 )

 Test Name            Value        Exact F     Hypoth. DF      Error DF       Sig. of F

 Pillais             .78444        3.63902           4.00          4.00            .119
 Hotellings         3.63902        3.63902           4.00          4.00            .119
 Wilks               .21556        3.63902           4.00          4.00            .119
 Roys                .78444
 Note.. F statistics are exact.
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 EFFECT .. POS (Cont.)
 Univariate F-tests with (1,7) D. F.

 Variable       Hypoth. SS        Error SS     Hypoth. MS        Error MS            F        Sig. of F

 T2              7.98062         3.35437        7.98062          .47920     16.65418             .005
 T3              1.05021         9.45479        1.05021         1.35068       .77754             .407
 T5          52098.06250   4455266.18750    52098.06250    636466.59821       .08186             .783
 T6          18841.68750   6489208.42250    18841.68750    927029.77464       .02032             .891

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
-May-94   EXAMPLE OF DOUBLY RM data  - velocity and power
:32:33    UNIVERSITY of OTTAWA             AMDAHL 5980 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * *

sts involving 'POS' Within-Subject Effect.

FFECT .. POS
djusted Hypothesis Sum-of-Squares and Cross-Products

                   VELOCITY          POWER

ELOCITY             9.03083
OWER              795.47500     70939.75000

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
VERAGED Multivariate Tests of Significance (S = 2, M = -1/2, N = 5 1/2)

est_Name              Value        Approx. F      Hypoth. DF       Error DF        Sig. of F

illais               .42974         1.91575          4.00           28.00            .136
otellings            .75307         2.25922          4.00           24.00            .093
ilks                 .57036         2.10671          4.00           26.00            .109
oys                  .42949
ote.. F statistic for WILK'S Lambda is exact.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
FFECT .. POS (Cont.)
nivariate F-tests with (2,14) D. F.

ariable          Hypoth. SS        Error SS      Hypoth. MS       Error MS             F        Sig. of F

ELOCITY             9.03083        12.80917         4.51542         .91494       4.93520          .024
OWER            70939.75000   10944474.61000    35469.87500    781748.18643      .04537          .956

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

576 bytes of memory are needed for MANOVA execution.
```

```
FILE: RM1      SPSS     *                   VM/SP CONVERSATIONAL MONITOR SYSTEM

TITLE  RM OF DISTANCE DATAM
FILE HANDLE MARC NAME='DISTANCE DATA A'
DATA LIST FILE=MARC RECORDS=1/
 LEVEL OVER BACK (T10,F3.1,T20,F3.0,T30,F3.0)
MANOVA LEVEL OVER BACK /
 WSFACTORS = POS(3)/
 MEASURE = DIST /
 WSDESIGN = POS/
 PRINT=CELLINFO(MEANS, COV) SIGNIF( AVERF) /
 ANALYSIS(REPEATED)/DESIGN /
EXECUTE
FINISH
```

```
FILE: RM2      SPSS     *                VM/SP CONVERSATIONAL MONITOR SYSTEM

TITLE  RM OF angle DATA
FILE HANDLE MARC NAME='angle DATA A'
DATA LIST FILE=MARC RECORDS=1/
 LEVEL OVER BACK (T10,F3.1,T20,F3.0,T30,F3.0)
MANOVA LEVEL OVER BACK /
 WSFACTORS = POS(3)/
 MEASURE = DIST /
 WSDESIGN = POS/
 PRINT=CELLINFO(MEANS, COV) SIGNIF( AVERF) /
 ANALYSIS(REPEATED)/DESIGN /
EXECUTE
FINISH
```

```
12-May-94   SPSS RELEASE 4.1 FOR IBM VM/CMS
13:26:51    UNIVERSITY of OTTAWA             AMDAHL 5890 DP   VM/HPO 5

For VM/HPO 5              UNIVERSITY of OTTAWA             License Number 1001
This software is functional through July 31, 1997.

Try the new SPSS Release 4 features:

* LOGISTIC REGRESSION procedure                  *
* EXAMINE procedure to explore data              *
* FLIP to transpose data files                   *
* MATRIX Transformations Language                *
*                                                *

See the new SPSS documentation for more information on these new features.

   1  0  TITLE  RM OF DISTANCE DATAM
   2  0  FILE HANDLE MARC NAME='DISTANCE DATA A'
   3  0  DATA LIST FILE=MARC RECORDS=1/
   4  0   LEVEL OVER BACK (T10,F3.1,T20,F3.0,T30,F3.0)

This command will read 1 records from DISTANCE DATA A1

Variable   Rec   Start      End         Format

LEVEL        1      10       12         F3.1
OVER         1      20       22         F3.0
BACK         1      30       32         F3.0

   5  0  MANOVA LEVEL OVER BACK /
   6  0   WSFACTORS = POS(3)/
   7  0   MEASURE = DIST /
   8  0   WSDESIGN = POS/
   9  0   PRINT=CELLINFO(MEANS, COV) SIGNIF( AVERF) /
  10  0   ANALYSIS(REPEATED)/DESIGN /
```

```
12-May-94   RM OF DISTANCE DATAM
13:26:52    UNIVERSITY of OTTAWA          AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * *

         8 cases accepted.
         0 cases rejected because of out-of-range factor values.
         0 cases rejected because of missing data.
         1 non-empty cell.

         1 design will be processed.

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
               CELL NUMBER
                    1
 Variable
   DUMMYFAC         1

 Cell Means and Standard Deviations
 Variable .. LEVEL
                                            Mean   Std. Dev.           N   95 percent Conf. Interval

 For entire sample                         2.112        .125           8       2.008       2.217
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Variable .. OVER
                                            Mean   Std. Dev.           N   95 percent Conf. Interval

 For entire sample                         2.037        .151           8       1.912       2.163
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Variable .. BACK
                                            Mean   Std. Dev.           N   95 percent Conf. Interval

 For entire sample                         2.000        .076           8       1.937       2.063
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

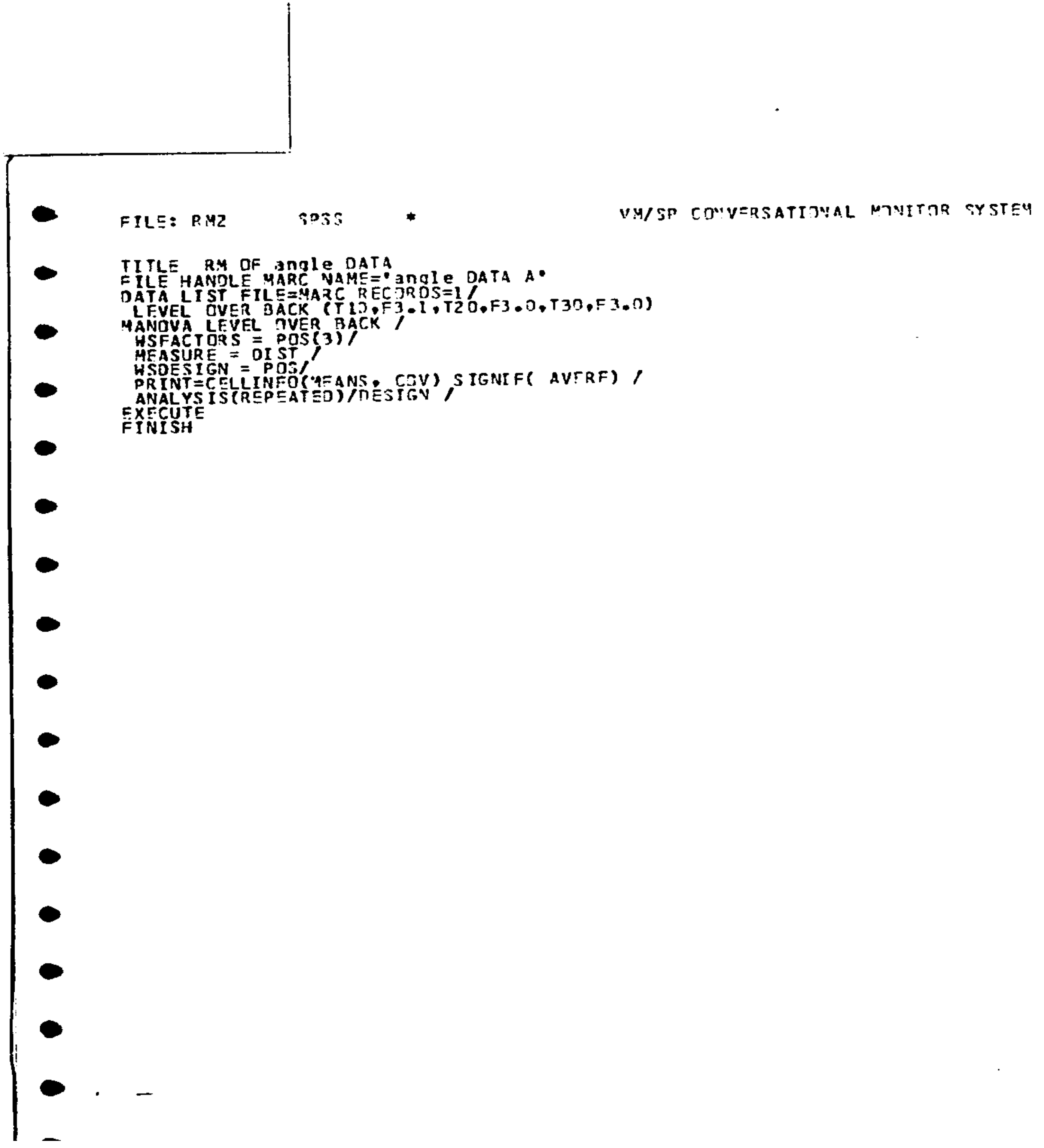
```
12-May-94   RM OF DISTANCE DATAM
13:26:52    UNIVERSITY of OTTAWA            AMDAHL 5890 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

Tests of Between-Subjects Effects.

 Tests of Significance for T1 using UNIQUE sums of squares
 Source of Variation          SS      DF        MS         F  Sig of F

 WITHIN CELLS                .11       7       .02
 CONSTANT                 100.86       1    100.86   5619.94      .000
```

```
12-May-94   RM OF DISTANCE DATAM                       AMDAHL 5890 DP   VM/HPO 5
13:26:52    UNIVERSITY of OTTAWA

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

Tests involving 'POS' Within-Subject Effect.

 Mauchly sphericity test, W =        .99420
 Chi-square approx. =                .03491 with 2 D. F.
 Significance =                        .983

 Greenhouse-Geisser Epsilon =        .99423
 Huynh-Feldt Epsilon =              1.00000
 Lower-bound Epsilon =               .50000

AVERAGED Tests of Significance that follow multivariate tests are equivalent to
univariate or split-plot or mixed-model approach to repeated measures.
Epsilons may be used to adjust d.f. for the AVERAGED results.
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   RM OF DISTANCE DATAM                      AMDAHL 5880 DP   VM/HPO 5
13:26:52    UNIVERSITY of OTTAWA

* * * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

 EFFECT .. POS
 Multivariate Tests of Significance (S = 1, M = 0, N = 2 )

 Test Name             Value        Exact F      Hypoth. DF       Error DF       Sig. of F

 Pillais              .35323        1.63840            2.00           6.00            .271
 Hotellings           .54613        1.63840            2.00           6.00            .271
 Wilks                .64677        1.63840            2.00           6.00            .271
 Roys                 .35323
 Note.. F statistics are exact.

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   RM OF DISTANCE DATAM
13:26:52    UNIVERSITY of OTTAWA                 AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * *

Tests involving 'POS' Within-Subject Effect.

 AVERAGED Tests of Significance for DIST using UNIQUE sums of squares
 Source of Variation          SS       DF        MS          F  Sig of F

 WITHIN CELLS                .20       14       .01
 POS                         .05        2       .03       1.33      .197

5192 bytes of memory are needed for MANOVA execution.
```

```
12-May-94   RM OF DISTANCE DATAM
13:26:52    UNIVERSITY of OTTAWA             AMDAHL 5880 DP   VM/HPO 5

Preceding task required .03 seconds CPU time;  1.23 seconds elapsed.

   11  0  EXECUTE

Preceding task required .00 seconds CPU time;  .04 seconds elapsed.

   12  0  FINISH

     12 command lines read.
      0 errors detected.
      0 warnings issued.
      0 seconds CPU time.
      2 seconds elapsed time.
        End of job.
```



```
FILE: RM2        SPSS      *                VM/SP CONVERSATIONAL MONITOR SYSTEM

TITLE  RM OF angle DATA
FILE HANDLE MARC NAME='angle DATA A'
DATA LIST FILE=MARC RECORDS=1/
 LEVEL OVER BACK (T10,F3.1,T20,F3.0,T30,F3.0)
MANOVA LEVEL OVER BACK /
  WSFACTORS = POS(3)/
  MEASURE = DIST /
  WSDESIGN = POS/
  PRINT=CELLINFO(MEANS, COV) SIGNIF( AVERF) /
  ANALYSIS(REPEATED)/DESIGN /
EXECUTE
FINISH
```

```
12-May-94   SPSS RELEASE 4.1 FOR IBM VM/CMS
13:28:45    UNIVERSITY of OTTAWA              AMDAHL 5980 DP   VM/HPO 5

For VM/HPO 5            UNIVERSITY of OTTAWA            License Number 1001
This software is functional through July 31, 1994.

Try the new SPSS Release 4 features:

* LOGISTIC REGRESSION procedure                                  *
* EXAMINE procedure to explore data                              *
* FLIP to transpose data files                                   *
* MATRIX Transformations Language                                *
*                                                                *

See the new SPSS documentation for more information on these new features.

   1  0  TITLE  RM OF angle DATA
   2  0  FILE HANDLE MARC NAME='angle DATA A'
   3  0  DATA LIST FILE=MARC RECORDS=1/
   4  0   LEVEL OVER BACK (T10,F3.1,T20,F3.0,T30,F3.0)

This command will read 1 records from ANGLE DATA A1

Variable   Rec   Start     End          Format

LEVEL        1      10      12          F3.1
OVER         1      20      22          F3.0
BACK         1      30      32          F3.0

   5  0  MANOVA LEVEL OVER BACK /
   6  0   WSFACTORS = POS(3)/
   7  0   MEASURE = DIST /
   8  0   WSDESIGN = POS/
   9  0   PRINT=CELLINFO(MEANS, COV) SIGNIF( AVERF) /
  10  0   ANALYSIS(REPEATED)/DESIGN /
```

```
12-May-94    RM OF angle DATA
13:28:46     UNIVERSITY of OTTAWA            AMDAHL 5880 DP    VM/HPO 5

* * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * *

         8 cases accepted.
         0 cases rejected because of out-of-range factor values.
         0 cases rejected because of missing data.
         1 non-empty cell.

         1 design will be processed.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                 CELL NUMBER
                   1
Variable
  DUMMYFAC         1

Cell Means and Standard Deviations
Variable .. LEVEL
                                             Mean  Std. Dev.          N   95 percent Conf. Interval

For entire sample                           2.637      2.786          8       .308      4.967
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Variable .. OVER
                                             Mean  Std. Dev.          N   95 percent Conf. Interval

For entire sample                           1.275      1.005          8       .435      2.115
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Variable .. BACK
                                             Mean  Std. Dev.          N   95 percent Conf. Interval

For entire sample                           3.137      2.188          8      1.308      4.967
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   RM OF angle DATA
13:28:46    UNIVERSITY of OTTAWA            AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

Tests of Between-Subjects Effects.

 Tests of Significance for T1 using UNIQUE sums of squares
 Source of Variation          SS       DF        MS          F   Sig of F

 WITHIN CELLS               43.23       7       6.18
 CONSTANT                  132.54       1     132.54     21.46      .002
```

```
12-May-94   R4 DF angle DATA
13:28:46    UNIVERSITY of OTTAWA           AMDAHL 5880 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

Tests involving 'POS' Within-Subject Effect.

 Mauchly sphericity test, W =        .66964
 Chi-square approx. =               2.40611 with 2 D. F.
 Significance =                        .300

 Greenhouse-Geisser Epsilon =        .75167
 Huynh-Feldt Epsilon =               .91208
 Lower-bound Epsilon =               .50000

AVERAGED Tests of Significance that follow multivariate tests are equivalent to
univariate or split-plot or mixed-model approach to repeated measures.
Epsilons may be used to adjust d.f. for the AVERAGED results.

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   RM OF angle DATA
13:28:46    UNIVERSITY of OTTAWA              AMDAHL 5880 OP   VM/HPO 5
```

Manova

```
* * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * *

 EFFECT .. POS
 Multivariate Tests of Significance (S = 1, M = 0, N = 2 )

 Test Name            Value        Exact F       Hypoth. DF        Error DF         Sig. of F

 Pillais             .34727       1.59606             2.00             6.00             .278
 Hotellings          .53202       1.59606             2.00             6.00             .278
 Wilks               .65273       1.59606             2.00             6.00             .278
 Roys                .34727
 Note.. F statistics are exact.

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
12-May-94   RM OF angle DATA
13:28:46    UNIVERSITY of OTTAWA            AMDAHL 5890 DP   VM/HPO 5

* * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E -- DESIGN   1 * * * * * * * * * * * * * * * * * *

Tests involving 'POS' Within-Subject Effect.

 AVERAGED Tests of Significance for DIST using UNIQUE sums of squares
 Source of Variation          SS      DF        MS          F   Sig of F

 WITHIN CELLS              51.71      14      3.69
 POS                       14.87       2      7.43       2.01      .170

5192 bytes of memory are needed for MANOVA execution.
```

```
12-May-94   RM OF angle DATA
13:28:46    UNIVERSITY of OTTAWA              AMDAHL 5880 DP   VM/HPO 5

Preceding task required .03 seconds CPU time;  1.13 seconds elapsed.

  11  0  EXECUTE

Preceding task required .00 seconds CPU time;  .00 seconds elapsed.

  12  0  FINISH

    12 command lines read.
     0 errors detected.
     0 warnings issued.
     0 seconds CPU time.
     1 seconds elapsed time.
       End of job.
```