The Development of a Filming Technique for the Eskimo Roll in Kayaking

By

Robert H. Nickel

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THE DEVELOPMENT OF A FILMING TECHNIQUE FOR THE ESKIMO ROLL IN KAYAKING

BY

ROBERT H. NICKEL

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

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ABSTRACT

The Development of a Filming Technique for the Eskimo Roll in Kayaking

The Eskimo roll is the most important safety maneuver that a kayaker must learn for righting a capsized kayak without having to exit from the kayak. A complete biomechanical film analysis of this skill required a method to simultaneously videotape all the movements above and below the water surface. The purpose of this study was to devise a method to accurately videotape the Eskimo roll, to obtain complete three dimensional kinematic descriptions of the Eskimo roll, and to calculate the paddle torques and forces required to complete the Eskimo roll. Data was collected on two skilled kayak instructors using a method that involved two plexiglass camera boxes attached to the pool wall and surrounded by wave guards. Cameras were placed in each box and positioned at the water level to film both the above water and below water movements. A transparent, spherical dome was placed between the water and the camera lens to correct for the refraction due to the water. Careful placement of the camera behind the dome minimized the refraction and allowed for the collection of kinematic data for the entire skill. Loss of accuracy was observed due to the wave action in the pool making it difficult to correctly position the cameras, and due to digitizing errors. The peak paddle torque for Subject 1 was -439 Nm and -356 Nm for Subject 2. The calculated forces on the paddle equaled -316.14 N and -259 N for Subject 1 and Subject 2 respectively.

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"THE DEVELOPMENT OF A FILMING TECHNIQUE FOR THE ESKIMO ROLL IN KAYAKING"

CHAPTER 1

INTRODUCTION

The Eskimo roll originated as a means to survive the capsizing of a kayak while seal hunting or fishing (Skilling, 1976). The quick roll could right the kayak without the kayaker having to leave the craft and enter the frigid water (see Figure 1-1).

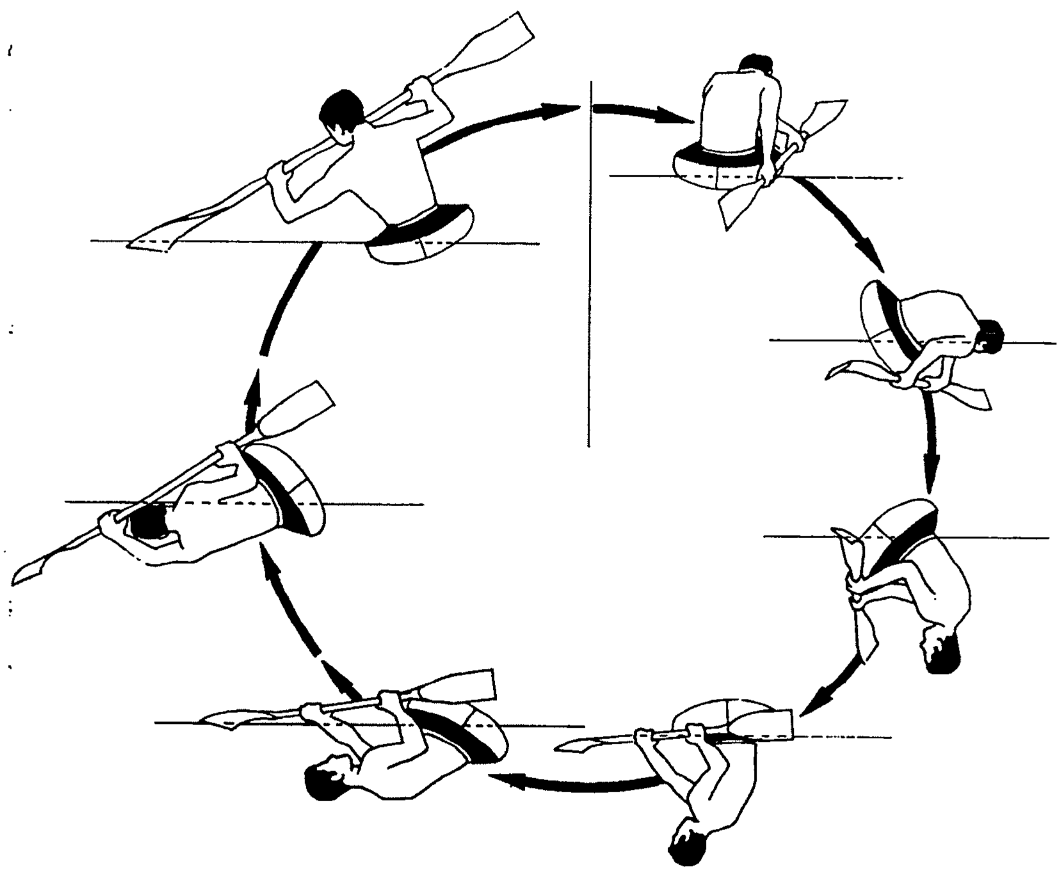


Figure 1-1. The body movements in the Eskimo Roll. (Michaelson & Ray, 1975, p. 141).

This maneuver was first developed by the Inuit of Greenland and Alaska. The earliest recorded description of an Eskimo roll was in 1767, by a European missionary named David Crantz, who had spent time in Greenland. Crantz listed ten methods of rolling that he observed used by the Inuit of Greenland (Skilling, 1976).

Hans Pawlata became the first European to complete an Eskimo roll on July 30, 1927 (Tejada-Flores, 1978). The attainment of this skill brought a new level of safety to the whitewater kayakers of the time who could now quickly right a capsized kayak. The roll was first used in a competition many years later during a slalom race in the late 1940's and has since become a common skill to master in kayaking.

Today the Eskimo roll is taught as the primary safety method to recover from an upset of a kayak (Bridge, 1978b). This basic skill is vital for the beginning kayaker to learn. The kayaker could quickly become exhausted if they had to leave the kayak and swim to shore to empty the kayak every time the unstable kayak capsized. Remaining in the water could become hazardous if the kayaker were a long way from shore or if the kayaker remained upside down in a rapidly flowing river.

The skill of the Eskimo Roll is difficult to learn and to instruct in the water environment. Many of the difficulties encountered result from the fact that the kayaker is under the water and has no direct communication with the instructor. The kayaker must hold their breath and will not be able to see the instructor. The skill begins from an unfamiliar inverted position and must be completed with little help from the instructor. The fear of not getting the body out of the water can prevent the kayaker from concentrating and performing the required sequences of movements (Bridge, 1978a).

This study was conducted to help analyze this complex skill and to facilitate the development of dry-land instruction methods for teaching the Eskimo roll. Previous biomechanical research on this skill has been very limited. This lack of research could be partly attributed to the many difficulties encountered when trying to film an underwater skill such as the Eskimo roll. The problems with filming any underwater skill include producing a clear view of the underwater movements without getting the camera wet. This filming had been accomplished by the use of underwater windows in the side of the pool walls (Hay & Thayer, 1989; Oka, Okamoto, Yoshizawa, Tokuyama, & Kumamoto, 1979), the submersing of cameras in water-tight housings (Maglischo, Maglischo, Higgins, Hinrichs, Luedtke, Schleihauf, et al., 1988; Schleihauf, Higgins, Hinrichs, Luedtke, Maglischo, Maglischo, et al., 1988; Wiegand, Wuensch, & Jaehnig, 1975) and the use of periscopes to view below the water (Hay, McIntyre, & Wilson, 1975; Hay & Thayer, 1989; Scheuchenzuber, 1979).

Each of the above filming methods had their advantages and disadvantages but all methods have a problem with the refraction, or bending, of the light. The light slows and bends as it passes from the air to the water environment because water is more optically dense than the air (McIntyre & Hay, 1975). The refraction became more of a problem when the skill occurred both above and below the water surface. The below water image was not aligned with the above water image and had to be corrected before kinematic values could be calculated.

The aim of this study was to investigate a videotaping technique which would enable the collection of accurate film data from a water and air environment. The video data would then be used in calculations to further describe Eskimo roll. These calculations included the drag torque due to movement through the water, the lift torque due to paddle movements, the weight torque due to body weight, and the buoyant torque due to the displacement of water. Once the required torques had been calculated, the information could be used to further modify an existing Eskimo roll simulator at the University of Manitoba. Currently, the simulator consists of the cockpit of a kayak, suspended above the ground surface by pins from a frame to allow for rotation, a paddle, and a semicircular reaction board for the subject to apply forces against via the paddle. The simulator needs to be modified in order that the production of torques and forces, equal in magnitude and timing to those found in the water situation, would right the kayak cockpit.

Purpose of the Study

The purposes of this study were:

1) To devise a method to videotape both the underwater and above water movements required to perform the Eskimo roll in kayaking that would produce accurate and reliable kinematics.
2) To produce three dimensional kinematics of experienced kayakers performing an Eskimo roll.

3) To calculate the torques produced about the long axis of the kayak that were required for the subject to complete the Eskimo roll.

Hypotheses

The following hypotheses were investigated:

1) It is possible to accurately measure the movements of the kayaker and kayak during the above water and underwater portions of the Eskimo roll.
2) The magnitude of the torques required by the kayaker could be calculated from the video data.

Rationale for the Study

The Eskimo roll has not been accurately analyzed using biomechanical analysis techniques. This study attempted to develop an accurate video analysis technique that could be used to describe in detail the joint movements required to complete the skill. The resulting torque calculations could then be used to assist in creating a dry-land Eskimo roll simulator which more accurately reflected the torques applied while underwater.

Limitations

1) The movements of the legs of the kayaker in the kayak were not visible. Thus, the positions of the leg segments had to be estimated for analysis purposes.
2) Each subject used their own paddle for performing the Eskimo roll but used the same kayak.

Delimitations

1) The data was collected only from experienced kayakers.
2) The subjects performed the roll starting from a stationary position in the pool so that they would remain in view of the cameras. This may have differed from the real-life situation when the kayak would be moving horizontally at the time of the execution of the roll.
3) The kayakers started the roll from a stationary, inverted position to eliminate the use of any momentum gained from rolling into the inverted position. A quick recovery in a real-life situation may not have a pause in the inverted position.

Definitions of Terms

Center of Buoyancy: The point through which the buoyant force acts and is also known as the center of volume of the displaced water (Hall, 1994).

Center of Mass: The single point, used to describe the motion of a mechanical system, which represents the average position of the system's mass about which all mass is equally distributed (Serway, 1990).

Coefficient of Drag: A unitless number assigned to an object to describe the ability to create drag based on the shape and orientation of a body relative to the fluid flow (Hay, 1985).

Coefficient of Lift: A unitless number which indicates the ability of an object to create lift forces and is based on the shape and orientation of a body relative to the fluid flow (Hay, 1985).

Direct Linear Transformation (DLT): A mathematical method to obtain three dimensional data from multiple two dimensional views by the use of a calibration frame (Abdel-Aziz & Karara, 1971)

Drag Force: A force that acts to slow the motion of an object moving through a fluid and is determined by the coefficient of drag for the object, the area of the object facing the flow, the density of the fluid and the relative velocity of the object (Hay, 1985).

Eskimo Roll: A maneuver performed in a kayak when the kayaker can right a capsized kayak while remaining in the kayak (Skilling, 1976).

Kinematics: The science of mechanics that deals with the description of motion (Hay & Reid, 1988).

Lift Force: A force acting perpendicular to the drag force on any object moving through a fluid and is determined by the coefficient of lift for the object, the surface area of the object against which lift can be created, the density of the fluid and the relative velocity of the object (Hay, 1985).

Moment of Inertia: The measure of the tendency of an object to resist angular motion and is determined by the mass of the object and the distribution of the mass relative to the axis of rotation (Hay, 1985).

Torque: The turning effect produced when a force is applied at some distance from the axis of rotation and is also known as a moment (Hay, 1985).

CHAPTER 2

REVIEW OF LITERATURE

Introduction

This chapter will examine the following topics: underwater videotaping, the use of cinematography as an analysis tool, the Eskimo roll maneuver, and the description of torques required to complete an Eskimo roll.

Underwater Videotaping

The videotaping of a sport skill for biomechanical analysis can be complicated when the skill occurs in a water environment. A thorough analysis of any water skill technique, such as those found in swimming strokes and the Eskimo roll, will necessitate the development of an accurate method to record the underwater movements.

Underwater Windows

The use of an underwater window is one of the simplest methods used to record the events occurring below the surface of the water. These windows are often built into the sides of pools and have been used when analyzing swimming techniques (Stoner & Luedtke, 1979). The window gives a good view of the underwater movements of a skill and eliminates the risk of water damage to the video cameras. Most windows are completely below the water and will only give a view of the underwater movements of a skill.

Windows have also been built so that they extend from below the water surface to above the water surface and will thus allow for a complete analysis of the athlete (Hay & Gerot, 1991).

There are some disadvantages with underwater windows in that they can only view a limited area in a pool and can be expensive to install (Hay & Gerot, 1991). The windows are fixed into the wall of the pool and cannot be moved to film different angles of a skill. Therefore, the skill can only be performed in an area where the window has viewing access. Pools will not always have an underwater window for viewing and any renovation to a pool to put in a window would be very expensive and often not practical.

A three dimensional videotaping session would require at least two windows and two cameras positioned to view two perpendicular planes of the same skill. If the pool did not have the multiple window set up, the videotaping would be limited to a single camera, two dimensional video analysis.

The use of underwater windows to obtain cinematographic data has been used to study how infants learn the skill of the flutter kick (Oka, et al., 1979). These films were used to describe the motions of the infants in different stages of learning. Filming has also been done through the glass side wall of a flume (Hay & Thayer, 1989). Swimmers were photographed while swimming in the flume so that tufts attached to their body could be observed to help describe the flow of water past the body during swimming. The windows in both of these studies successfully permitted the investigators to view the underwater movements performed by the subjects during the swimming strokes and made no mention of any problems with this method.

Video Tape Box

The use of a water-sealed box that can hold a camera underwater has been successfully used in water filming situations (Hoffman, 1976; Vertommen, Fauvart, & Clarys, 1982). This method involves the construction of a plexiglass box that can be attached to the edge of the pool and that extends down below the water surface. The camera must be placed in the bottom of the box so that filming below the water surface can occur (see Figure 2-1).

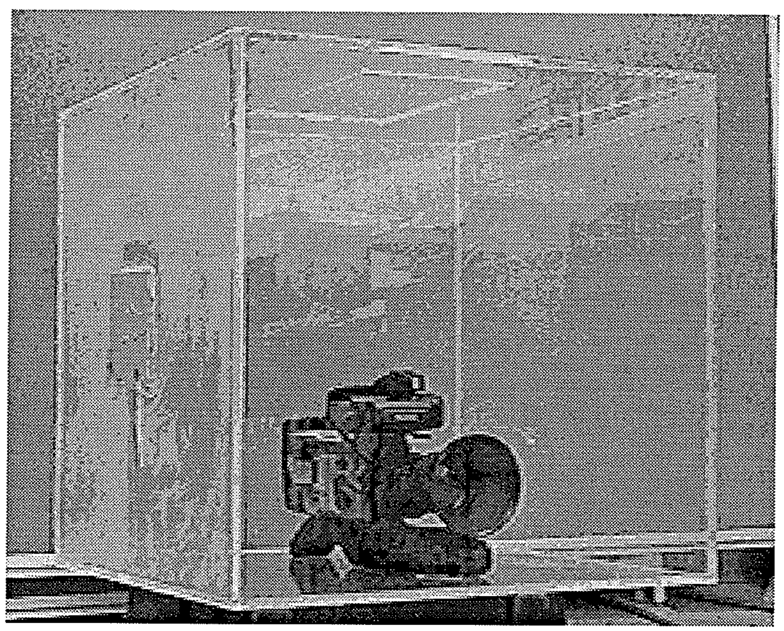


Figure 2-1. A plexiglass video box used to film underwater (Alexander, Giesbrecht, Boldt, & Nickel, 1994).

The main advantages to this system is that the box is portable and can be moved to any pool and moved to any position along the edge of the pool. The box can be built with a free-swinging ball-pin joint attached to the rear side of the box to allow the box to be rotated or tilted to get a better view of the skill (Hoffman, 1976; Vertommen, et al., 1982). The joint would connect from the rear of the box to a set of screw clamps that would be used to secure the box to the side of the pool. These type of boxes also have the advantage of being low cost, relatively easy to build, and easy to use. A counterweight will also be required to offset the buoyant force of the water acting on the box.

Disadvantages of this method include the fact that the camera must be placed below the water and if the box leaks the cameras are at risk from water damage (Hay & Gerot, 1991). Also, the cameras are often difficult to access once they are placed in the box so that no further focusing can be done below the water (Vertommen, et al., 1982). This requires that the subject must remain the same distance from the camera to remain in focus once the camera is submerged.

A slight modification to the box can allow the camera to be placed anywhere in the water and not just along the edge of the pool. The camera can be placed in a water-tight underwater housing made of plexiglass (Maglischo, et al., 1988; Schleihauf, Gray, & DeRose, 1983; Schleihauf, et al., 1988). These housings can be lowered into the water and secured where needed and are not limited to the side of the pool. These completely sealed boxes have been used to analyze the stroke patterns of swimmers. Three dimensional data has been collected to describe arm stroke patterns and velocities of freestyle swimmers (Maglischo, et al., 1988), and also to describe and calculate the forces due to hand propulsion in the front crawl stroke

(Schleihauf, et al., 1983). The underwater housings in these experiments allowed the investigators to digitize the film data for the underwater movements only and any problems encountered with this method were not listed or discussed.

Periscope Systems

Periscopes (McIntyre & Hay, 1975) or half-periscopes (Hay & Gerot, 1991) have been used as another method to capture underwater movements. The basic design of these periscope systems include a camera and support system, a wave guard, and a system of mirrors to reflect the image to the camera (Hay & Gerot, 1991). One mirror was placed at a 45 degree angle in the water to reflect the image of the subject either directly to the camera or to another mirror and then to the camera. The camera would never have to be placed below the water surface (see Figure 2-2).

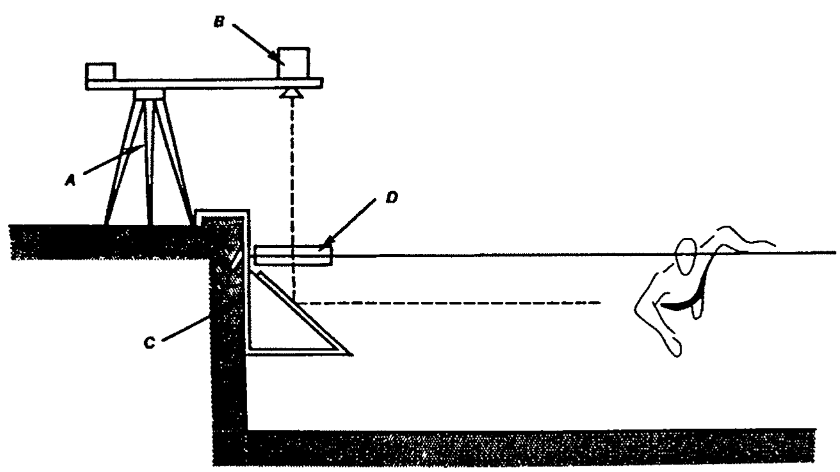


Figure 2-2. An example of a half periscope composed of a) camera support, b) camera, c) underwater reflecting mirror, and d) a wave guard. (Hay & Gerot, 1991, p.394).

The main advantage of this method is the fact that the cameras are not in the water and are at less risk from water damage (Hay & Gerot, 1991). The periscope could be moved where needed and made adjustable so that both movements above and below the water surface could be filmed simultaneously (McIntyre & Hay, 1975).

A disadvantage of this method is that the periscope frame may be large and cumbersome and the rippling of the water surface may distort the recorded image (McIntyre & Hay, 1975).

These periscope methods have been shown to yield good photos of the underwater movements of swimmers (Hay & Gerot, 1991). A movie camera or video camera can be substituted for the still camera in a periscope in any periscope to yield films of the swimmers if desired. Two dimensional kinematic descriptions of different lifesaving carrying techniques have also been studied using the periscope methods (Hay, et al., 1975). Film of the subjects performing the carrying techniques was recorded and digitized to yield X and Y position coordinates of points, and the time required to complete the skills. The investigators in this study had to correct the film data for the refractive effects of the water since this study involved movements occurring both above and below the water.

Underwater Cameras

The construction of water proof cameras makes it possible to take a camera into the water and film the movements. These cameras have the advantage of being moveable but are expensive and require someone to be in the water to operate the camera (Vertommen, et al., 1982). The construction of waterproof underwater housings for a normal camera is a less expensive method to get a camera underwater and has been used more often in the literature (Maglischo, et al., 1988; Schleihauf, et al., 1983; Schleihauf, et al., 1988).

Any camera under the water would be difficult to phase lock with an above water camera. This would require careful waterproofing of plug-ins and cords required for the cameras to be phase locked together. The phase locking would be necessary for a three dimensional digitized analysis to be completed.

Filming of Semisubmerged Activities

Semisubmerged skills such as the Eskimo roll and swimming occur simultaneously below and above the water and will often cross the boundary between the two different environments. An analysis of these types of skill would be complete only if a description of both the above and below water movements were included.

Often subjects were filmed below the water during one performance and then from above the water for a second performance so that a complete analysis could be completed (Scheuchenzuber, 1979). This would give a view of the total skill but for digitization purposes it would be better to film the above and below water motions simultaneously for one trial.

Some pools have been constructed with windows that extend above and below the water surface (Hay & Gerot, 1991). This method would allow the simultaneous filming of all movements but there are few pools that have been constructed in this manner.

The use of one camera filming the above water movements and another from the same angle filming below the water has been suggested as a possible solution (McIntyre & Hay, 1975; Scheuchenzuber, 1979). This method becomes complicated by the fact that the shutters of the two cameras must be accurately synchronized to expose the film at the same time. A three dimensional analysis using the minimum of two different views would therefore require four cameras for the analysis to be completed.

A single camera that can simultaneously record the above and below water movements would be ideal. This has been attempted by the use of a periscope with additional mirrors attached (Hay & Gerot, 1991). This method does give a simultaneous view of the skill but has the problem of wave distortion common to all periscopes, and the problem of combining two separate views that are at slightly different angles.

The split-image method has also been attempted by the construction of a split-image lens for a single camera (Scheuchenzuber, 1979). This method has two separate images reflected into the camera. The reflective mirrors are either completely below or above the water so no wave distortion would occur as in the periscope method. This method requires the construction of a multiple lens apparatus with multiple mirrors and a prism (see Figure 2-3). The construction of such a lens may make the method impractical for many investigators.

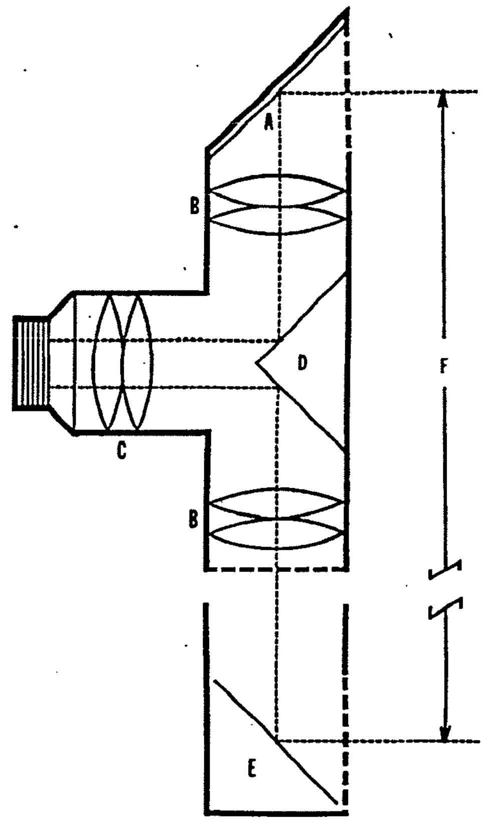


Figure 2-3. Split image lens: A. mirror, B. lens, C. macro lens, D. mirrored prism, E. periscope box and mirror, F. distance between mirrors. (Scheuchenzuber, 1979, p. 126).

Difficulties with Dual Media Videography

Any method for simultaneously filming a skill that occurs across two different density environments creates some unique problems not encountered in a single media environment. The filming of the skill can be hampered by the lighting conditions, camera alignment and wave action (McIntyre & Hay, 1975).

The lighting conditions below the water surface are often dimmer than above the surface which can cause problems when the camera is situated above the water as in the periscope methods (McIntyre & Hay, 1975). The problem can be solved by increasing the lighting under the water or to set the camera according to the lighting conditions under the water. The lighting problem can be easily corrected when using a split-image lens that can correct for the lighting differences by incorporating multiple lenses which can be individually adjusted to the lighting conditions (Scheuchenzuber, 1979).

The optical axis of any camera being used for the dual media videography must be aligned exactly with the water level (McIntyre & Hay, 1975). The camera's single lens must be level with the actual water line (or reflected mirror image of the water line) so that no part of the object will be obscured. If the camera was too low or too high, the video would show some surface reflection at the water-air interface which would block the view of the subject. If the camera lens is aligned correctly, the water-air interface will appear as a line running through the center of the image (see Figure 2-4).

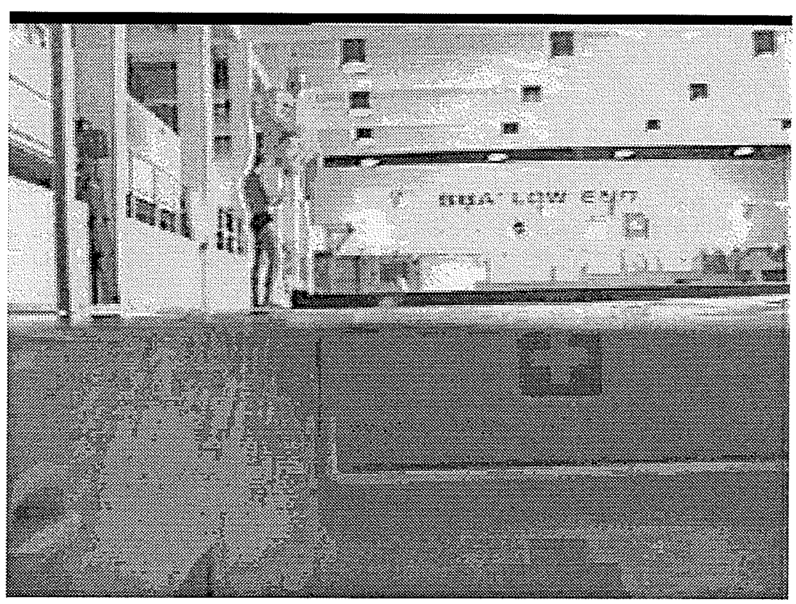


Figure 2-4. A correctly aligned camera with the water-air interface appearing as a thin line across the middle of the picture.

The presence of waves can cause the view of the subject to become distorted (Hay, et al., 1975; McIntyre & Hay, 1975). The waves cause varying water levels and varied light reflections that will be recorded by the camera. This problem can be eliminated by the use of baffles or wave guards around the submerged parts of the filming apparatus (Hay & Gerot, 1991) or by conducting the skill in a pool where the wave action was minimal (Scheuchenzuber, 1979).

Correction of Video Data for Refraction

The video of a skill showing both the above and below water views of a skill can not be used immediately for determining locations of points and locations of segments. The segments of the subject below the water will often appear dissociated from the segments above the water (McIntyre & Hay, 1975). This is caused by the refraction of the light (see Figure 2-5).

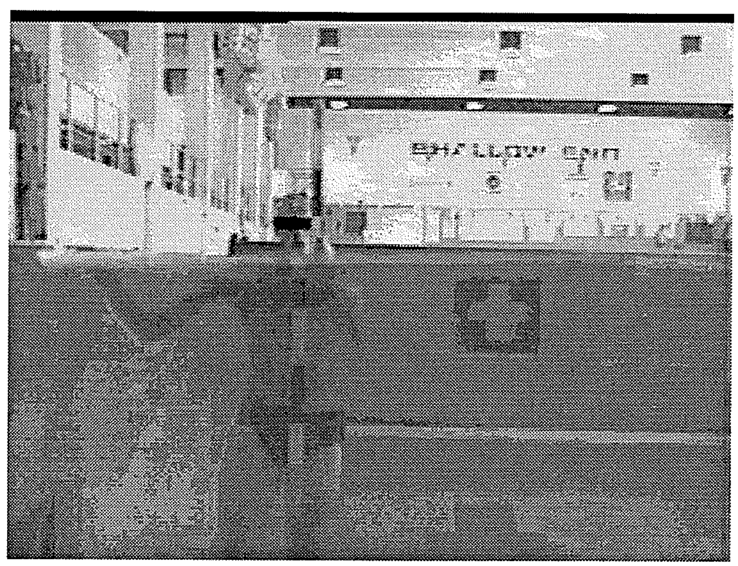


Figure 2-5. The dissociation of the above water position object from the below water object. Notice the misalignment of the hand held stick.

The refraction is the result of the bending of the light as it passes from one medium to another such as across the air-water interface (see Figure 2-6) (Miller, 1982). This occurs because the water is more optically dense and causes the speed of light to be less in the water than in the air. This would also occur across the air-plexiglass or water-plexiglass boundary. The relationship between the angle of refraction in water and the angle of incidence for light in the air can be described by Snell's law (McIntyre & Hay, 1975).

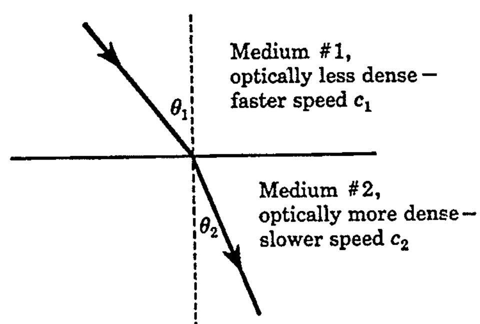


Figure 2-6. The bending of the light as it passes from one medium to another as viewed from above. Angle one is the angle of incidence and angle two is the angle of refraction. (Miller, 1982, p.427).

Snell's law is most commonly written as:

$$n_1 \sin\varnothing_1 = n_2 \sin\varnothing_2$$

where n_1 is the index of refraction for material one, n_2 is the index of refraction for material two, $\varnothing_1$ is the angle of incidence measured from the normal, and $\varnothing_2$ is the angle of refraction measured from the normal (Serway, 1990). This law describes the effect that the properties of the two materials and the angle of incidence have on the path of a ray of light.

The index of refraction is a dimensionless number used to describe the speed of light in a material. The index of refraction can be calculated by dividing the speed of light in a vacuum by the speed of light in the desired type of material. This value has been calculated to be 1.333 for water and 1.000 for air. This would indicate that the water is more optically dense and will cause the light ray to bend towards the normal as the light passes from the air to the water (Miller, 1982).

The lens of the video cameras have been constructed to correct for the refraction of the light as it passes from the air to the glass interface at the outermost part of the lens. The problem is that the introduction of the water environment and the additional plexiglass components in front of the lens results in the light rays being bent more than the lens was designed to deal with. The additional bending of the light will cause the image in the video camera to distorted and the underwater image will be misaligned.

Light rays passing from one optical environment to another, at right angles to the interface between the two environments, will not be bent (Walton, 1988). These light rays will pass through the interface in a straight line and show no refraction . Camera views of any object placed directly in front of the camera will show no refraction on the portions of the object that appear in the center of the field of view. The refraction will be observed to increase from the center of the field of view to the outside edges. The greatest distortion and misalignment of the object will be observed at these extreme edges of the field of view where image forming rays strike the interface at the greatest angle from the normal (see Figure 2-7).

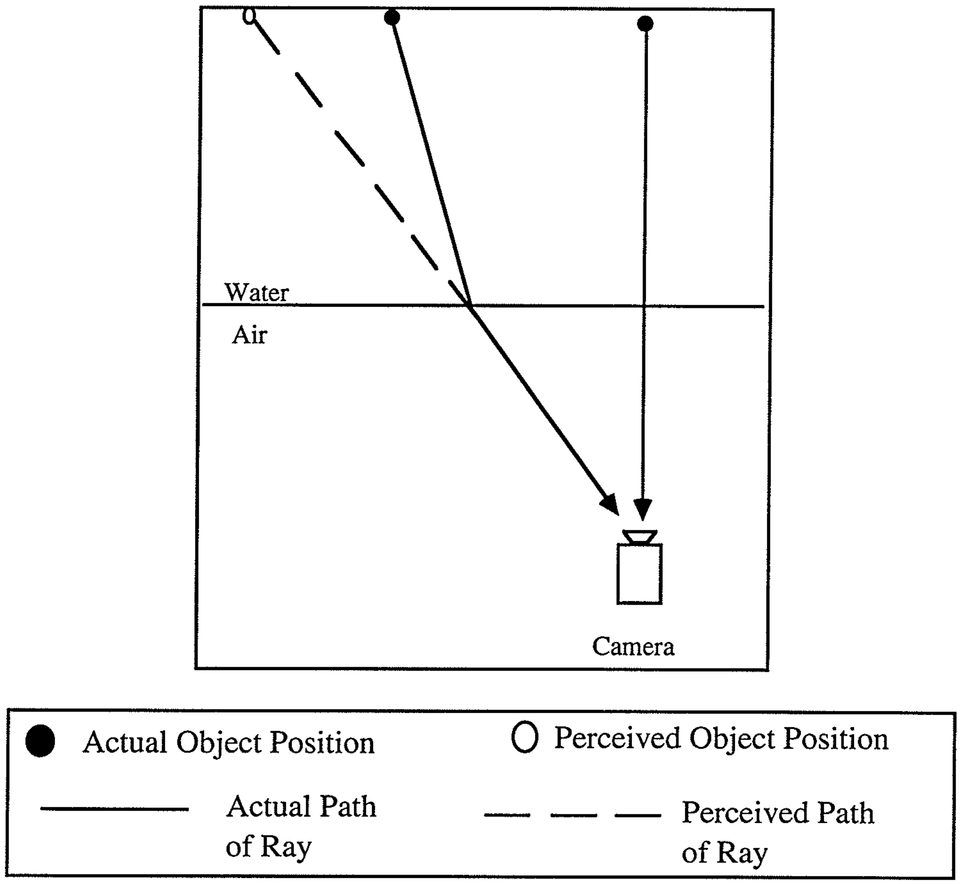


Figure 2-7. Top view of the bending of light rays as they pass from a water to an air environment. Note that only the rays passing at right angles to the water/air interface do not bend. All other rays will bend and the object will then be perceived to be in a position other than it's true position.

The dissociation of the above water segments from the segments below the water due to refraction can be corrected prior to filming if one uses the split-image method (Scheuchenzuber, 1979). The mirrors and lenses can be adjusted so that the two images align correctly before the filming session is to begin.

The errors due to refraction can also be corrected after the filming is complete if split-image methods were not used (McIntyre & Hay, 1975). The point coordinates can be converted to a common reference point which will correctly align all points. This will create a data set of point coordinates that have been corrected for the refraction and can now be further analyzed to produce basic kinematic variables.

Dome Technique

The careful placement of a transparent, spherical dome in front of the camera lens can be used to eliminate the refraction and result in videotape data that can be immediately analyzed. This dome solution has been used successfully with three dimensional video motion analysis systems to analyze the movements of swimmers (Walton, 1988), and the range of motion of spacesuits that were being tested in a water environment (Reinhardt & Walton, 1988).

The dome must be placed between the lens of the camera and the subject so that light rays that form the image in the camera will pass through this dome. The lens system of this set up includes the camera lens and any other plexiglass placed between the subject and camera. The dome is also a part of this lens system and must be placed at the air/water interface between the camera lens and the pool water. The camera position or dome position must be adjusted to align the optical axis of the dome with the optical axis of the camera lens to eliminate the refraction. The distance between the camera lens and the dome must also be adjusted so that the center of curvature of the dome coincides with the focal point of the lens.

The key to the dome system is that no refraction will occur if the light rays hit the dome surface at right angles and continues through the dome in a straight line. All light rays converging on the center of a sphere or radiating out from the center of a sphere will strike the surface of the sphere at right angles and will not be bent (see Figure 2-8). The correct alignment of the camera with the dome will result in the camera image being formed only by these straight light rays. The recorded camera image will then show no refraction problems. This lens set up will then work correctly in the water or air environments (Walton, 1988).

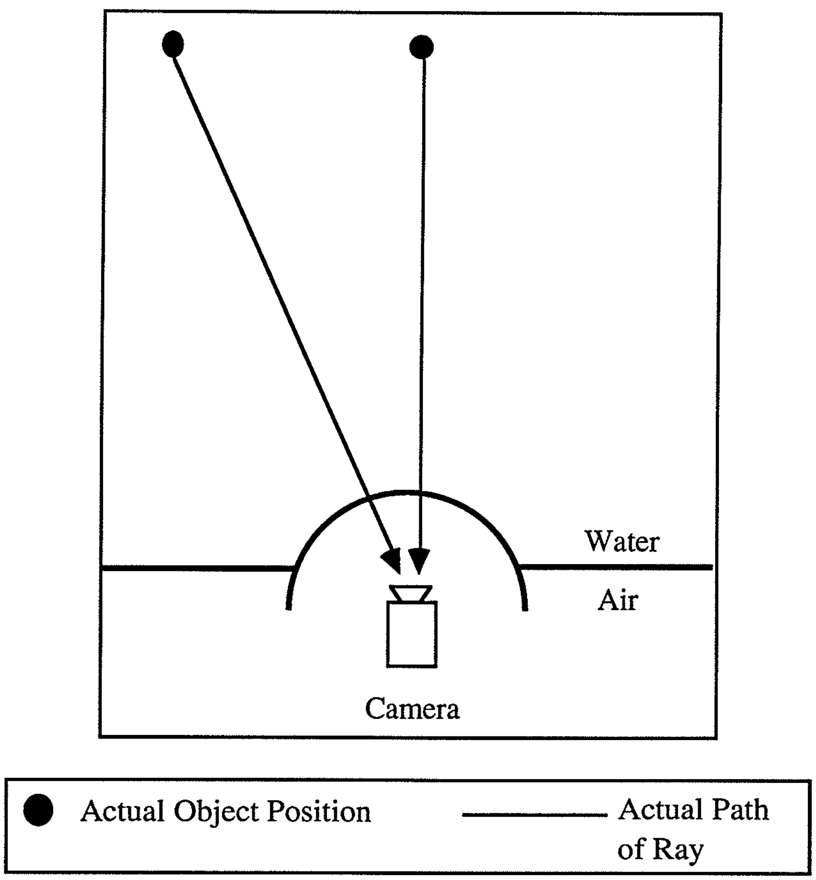


Figure 2-8. Top view of the bending of light rays as they pass from a water to an air environment through a curved interface. Note that all the rays pass at right angles to the curved water/air interface and do not bend. The perceived object position will then be the true object position.

The correct positioning of the camera can easily be determined by filming any object with vertical lines on it's surface (Walton, 1988). The camera and dome system should be placed in the water so that the dome is half below the water level and half above the water level and the camera will record an image of both below and above the water. The object with the vertical lines must be placed in the field of view of the camera with the vertical lines visible above and below the water line. The camera position behind the dome must be adjusted until the vertical lines are aligned above and below the water. These lines will remain aligned for a correctly positioned camera even if the camera housing with the dome is rotated.

Video Analysis

The use of video cameras instead of the formerly used film cameras (Hoffman, 1976) can be justified if it can be shown that both methods will yield similar results. Video cameras and video tapes are advantageous because of the lower cost involved (Abraham, 1987; Kennedy, Wright, & Smith, 1989), easier use and a shorter processing time (Kennedy, et al., 1989). The resolution of the video image produced was found to be acceptable but limited by the numbers of pixels of the video monitor (Angulo & Dapena, 1992).

The main drawback to the video taping methods is that standard video cameras can only film at a rate of 60 frames per second (Angulo & Dapena, 1992; Kennedy, et al., 1989). The 60 frames per second may be too slow to capture very quick movements of body parts.

The accuracy of video analysis has also been shown to be less than the high speed film method (Angulo & Dapena, 1992; Kennedy, et al., 1989). Kennedy et al., (1989) calculated error values for known positional coordinates to be 4.8 millimeters for film data and 5.8 millimeters for video data. The difference of 1 millimeter was found to be statistically significant ($p<.05$) but this larger video error (5.8 millimeters) only represented .29% of the entire field of view. The error in the film data represented .24% of the field of view. The 0.05% increase in the error of the entire field of view with the video system was statistically significant but represented such a small percent of the total field of view that the two systems were deemed to be equally accurate from a practical standpoint. The field of view used for this comparison experiment was 2 x 2 x 2 meters. The field of view for this Eskimo Roll study was comparable so similar accuracy could be expected

The decreased accuracy of the video taping method was also shown by Angulo and Dapena (1992). This study used the Peak Performance Technologies Inc. video analysis system to collect the positional coordinates of objects in a large field of view (8 meters) and a smaller field of view (approximately 2.4 meters). These video values were compared to the similar data obtained with a film system. The error values for the small field of view positional coordinates was 10 millimeters for the video and 4 millimeters from the film method. The larger field of view resulted in a resultant postional error of 39 millimeters for the video and 29 millimeters for the film data. The video system error result represented a 0.3% and 1.3% error of the total surveyed area for the small field of view and large field of view respectively. The film system error result represented a 0.1% and 1.0% error of the total surveyed area for the small field of view and large field of view respectively.

This indicated that the film system was more accurate than the video system under both conditions (Angulo & Dapena, 1992). The larger the field of view studied, the less accurate the video system. This was partially attributed to the lack of resolution with the video system. The larger field of view resulted in each video pixel covering a larger real-life distance and any video analysis could not be more exact than one pixel in any direction. Even at the large field of view, the error was only 1.3% of the total area. This value was small enough to conclude that the video system was precise enough for practical purposes and could be even more precise (0.3%) when a smaller field of view was used as is planned in the Eskimo Roll study.

The Peak Performance Technologies video analysis system was evaluated on the ability to measure angles of a moving object (Scholz & Millford, 1993). A moving bar was videotaped and the angular position was determined from the video system and compared to trigonometrically calculated angles obtained from hand measured distances. The study found that the video system was accurate and precise when used to measure angles during an object's motion. The within-trial standard deviations ranged from 0.05 -0.8° (indicating high precision) and the angle measurement deviations from the actual angle ranged from 0.0-0.8° (indicating high accuracy).

Eskimo Roll

There are said to be over two dozen variations in how to perform an Eskimo roll to right a capsized kayak (Michaelson & Ray, 1975). The term Eskimo roll has been used to describe any method used by an Eskimo to right a capsized kayak (Trewiler & Smith, 1978). This would include rolling with or without the aid of a paddle, and rolling with the aid of any other object (such as the floating ice flow). The method that will be used in this study will be the Screw Roll type. This method has the advantage over other types in that the hands remain in the normal paddling position on the paddle (Skilling, 1976). The Screw Roll stroke starts near the bow of the kayak and arcs toward the stern (Trewiler & Smith, 1978). The paddle blade must be kept at a climbing angle relative to the water surface during this arc and not in a position parallel to the water surface. The Screw Roll is the primary roll used to recover from surprise upsets because time can be saved as no special shifting of the hands on the paddle is required (Bridge, 1978b).

The skill of the Eskimo Roll is difficult to learn but does not require great physical strength to execute (Bridge, 1978a; Diehl, 1982). The difficulties encountered in learning the skill can be grouped as being intellectual, psychological, and physical.

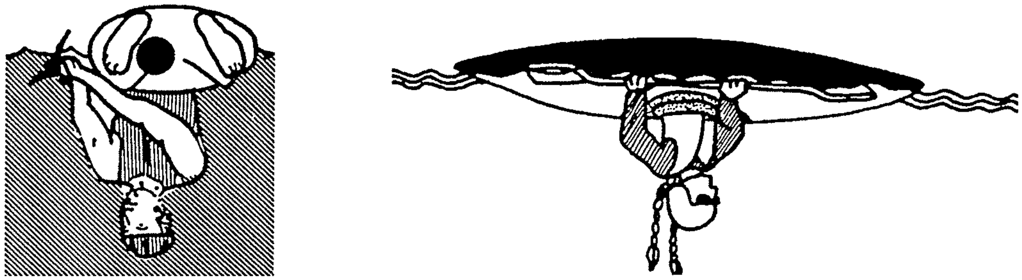
The intellectual difficulties result from the fact that the skill is performed starting with the body in an inverted position (Bridge, 1978a). The beginning kayaker can easily confuse the directions and orientations of the paddle and kayak since the skill begins in the unfamiliar inverted position. This confusion can be increased since the subject will often first view someone doing the roll from an above water angle. In addition, the kayaker will not be able to communicate with the instructor during the skill since they are underwater. The water will also prevent the instructor from giving visual feedback to the kayaker during the performance of the role.

The psychological difficulties arise from the fact that the kayaker is inverted and under the water (Bridge, 1978a). The kayaker must hold their breath until they complete the roll. The beginner may panic if they cannot roll the kayak since a failed roll will mean that the subject remains underwater and unable to breathe. The fear can prevent the kayaker from concentrating on performing the required sequence of movements.

The physical challenge to the Eskimo Roll is not absolute physical strength but the correct sequencing of the required muscles (Bridge, 1978a). This complex motor skill must be divided into the different elements and practiced so that the sequencing of movements becomes well learned and can be performed with little conscious thought (Tejada-Flores, 1978). The correct sequencing should result in a roll that requires only minimal physical strength.

Eskimo Roll Sequence

The Eskimo roll has been described using four different stages (Tejada-Flores, 1978). These stages were the set up, the sweep, the hip snap and the recovery. The phases will blend together and should appear as a single, smooth motion taking from 2 to 4 seconds to rotate the kayak about it's longitudinal axis (Stuart, 1976). The following description will be for a roll to the kayakers left side.



a b

Figure 2-9. The set up position for the Eskimo Roll. View from a) the front of the kayak and b) from the side of the kayak. (a) (Stuart, 1976, p.16); b) (Trewiler & Smith, 1978, p.34).

Set Up: The set up position must be assumed when the kayak is in the inverted position but may also be assumed prior to rolling into the water (see Figure 2-9). If this position is adopted while the kayak is still upright, it must be maintained as the kayaker rolls the kayak into the inverted position (Williams, 1967).

The roll begins with the trunk flexing forward over the hull of the kayak and the paddle held along the left side of the kayak which will roll under the water first. The trunk and shoulders of the kayaker should also be rotated 90 degrees towards the left side to allow for the paddle to be placed along this side of the kayak with the right hand reaching towards the bow and the left hand reaching towards the stern. The flexing of the trunk serves to move the center of mass of the kayaker nearer to the longitudinal axis of the kayak to decrease the resistance of the body to rotation and thus make rotating easier (Steidle, 1976).

The resulting rotations of the body and kayak to the inverted position, due to the weight of the body and kayak, will be accelerated because the moment of inertia of the system about the long axis of the kayak has been reduced. This relationship between the moment of inertia, the moment, and the angular acceleration can be mathematically stated as follows:

$$\Sigma T = I\alpha$$

(Serway, 1990).

The T represents the total torque about the long axis of the kayak, the I represents the moment of inertia of the system (the kayak and kayaker) about the long axis of the kayak, and the α represents the angular acceleration of the system about this same axis. This relationship indicates that if the total torque is constant, the angular acceleration of the system may increase if the moment of inertia of the system were decreased.

The moment inertia of the system is reduced when the kayaker flexes or extends their trunk and brings the center of mass of their upper body closer to the long axis of the kayak (Steidle, 1976). The effect of this movement on the moment of inertia can be described using the formula to calculate the moment of inertia. The moment of inertia, or resistance of an object to changes in angular motion, can be calculated with the following formula:

$$I = \Sigma mr^2$$

(Hay, 1985).

The I represents the moment of inertia of the object about the axis of rotation, the m represents the mass of the object, and the r represents the distance of the mass from the axis of rotation. If the kayaker were to flex or extend their trunk, this would decrease the r distance about the long axis of the kayak in the frontal plane. This would result in a corresponding decrease in the moment of inertia (I) to make the resistance to rotation decrease.

The paddle should be held parallel and near the water surface with the right arm extended and reaching the farthest forward. The paddle blade will be resting against the side of the kayak. The kayak paddle is constructed so that the blades are set at right angles to each other (Skilling, 1976). It is very important to flex the wrists so that the leading edge of this forward (right) paddle blade is tilted upwards when in the inverted position. This paddle position will put the forward blade at a climbing angle during the sweep phase (Williams, 1967). The climbing angle is important to keep the blade near the surface of the water during the sweep phase. A paddle that remains near the surface during the sweep phase indicates that the lift force of the paddle is in the correct direction to create torques to aid in the completion of the roll. A paddle that is diving deeper into the water indicates that the lift force is not in the correct direction to create the torques necessary to roll into the upright position.

The lift created by the paddle is due to the water passing around the blade. The water passing around the paddle blade will move quicker over one side of the paddle blade than the other due to the orientation of the paddle. This difference in relative velocities between the sides of the blade will result in a high velocity/low pressure side being created relative to the lower velocity/higher pressure side. This relationship between the velocity of the water and the pressure is called the Bernoulli principle. The resulting lift force will be in a direction from the high pressure region to the low pressure region and will also be perpendicular to the flow of the fluid about the blade (Hall, 1994).

The positive attack angle created by tilting the leading edge of the blade upwards will result in a great enough pressure difference between the two sides of the blade to create an upward lift force (see Figure 2-10). The direction of this lift force must be upwards in the direction that the kayaker wants to roll. A downward directed lift force could be created by tilting the leading edge of the blade downward but the lift force would not be in the correct direction to help in completing the roll.

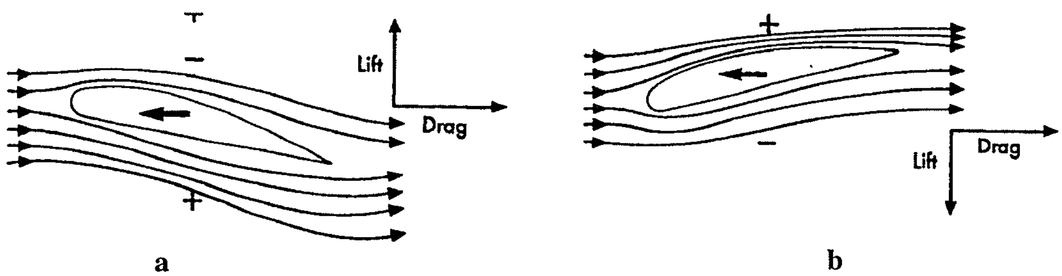


Figure 2-10. Lift force direction as the result of a foil shaped object with a) a positive attack angle resulting in a lift force directed upwards, and b) a negative attack angle resulting in the lift force being directed downwards. (Hall, 1994, p. 483).

The Sweep: The kayaker begins to roll upright by sweeping the forward (right) paddle blade backwards in a large arc from the left bow side of the kayak to the right stern side of the kayak (see Figure 2-11). The leading edge of the forward paddle blade must remain tilted upwards which will keep the blade near the surface of the water and create the lift forces. The rear (left) paddle blade is raised out of the water along the bottom of the kayak as the sweep progresses by extending the rear arm to push the blade upwards (Stuart, 1976).

The right arm will be abducted and flexed at the shoulder as the body rotates to face the opposite direction during the sweep of the blade (Steidle, 1976; Williams, 1967). The trunk will also be extending during this motion. The arms should be fully extended at the elbow and the trunk flexed to the right side so that the paddle blade sweeps outward in the largest arc possible. The larger arc of the paddle will serve to increase the moment arm length from the paddle blade to the long axis of the kayak (Stuart, 1976). This will help to increase the torque producing capability of any force being applied at the paddle blade.

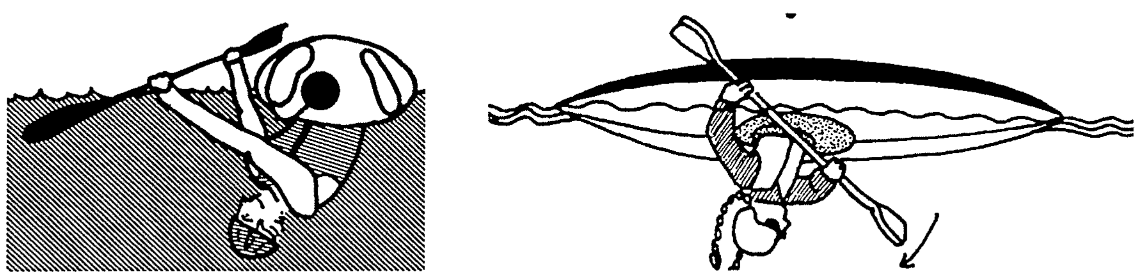


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Figure 2-11. View of the paddle arc during the sweep phase as viewed from a) the front of the kayak and b) the side of the kayak. (a) (Stuart, 1976, p.17); b) (Trewiler & Smith, 1978, p.34).

The sculling action of the sweep brings the kayaker towards the surface of the water and helps the kayak to turn upright. The sweep phase continues until the paddle is perpendicular to the long axis of the kayak.

The Hip Snap: The hip snap begins near the end of the sweep phase and will result in the kayak being rotated to an upright position (Tejada-Flores, 1978) (See Figure 2-12). The timing and completion of the hip snap is suggested to be the crucial movement required to get the kayak upright (Diehl, 1982; Steidle, 1976). This snap should occur as the paddle is perpendicular to the long axis of the kayak (Trewiler & Smith, 1978).

The kayaker will laterally flex the trunk to cause the kayak hull to rotate under their hips and closer to the upright position (Tejada-Flores, 1978). This is accomplished by the contraction of the right lateral abdominal muscles and can be aided by an action-reaction torque created by pulling the blade of the paddle in towards the kayak. The action torque would result from adducting the shoulder joint and bringing the right paddle blade toward the side of the kayak. The reaction torque of the paddle on the kayaker would result in the kayak and kayaker rotating to the upright position. This action-reaction relationship is commonly known as Newton's third law (Hall, 1994). The kayak and hips must exit the water first, followed by the trunk and the head (Tejada-Flores, 1978). An attempt to rotate the kayak and upper body at the same time will result in an unsuccessful roll since not enough torque can be produced to rotate the system with this body position with it's greater moment of inertia.

The paddle will also be used as a stabilizer at this point as the trunk will be hyperextending to further decrease the moment of inertia for rotation about the long axis of the kayak (Steidle, 1976).

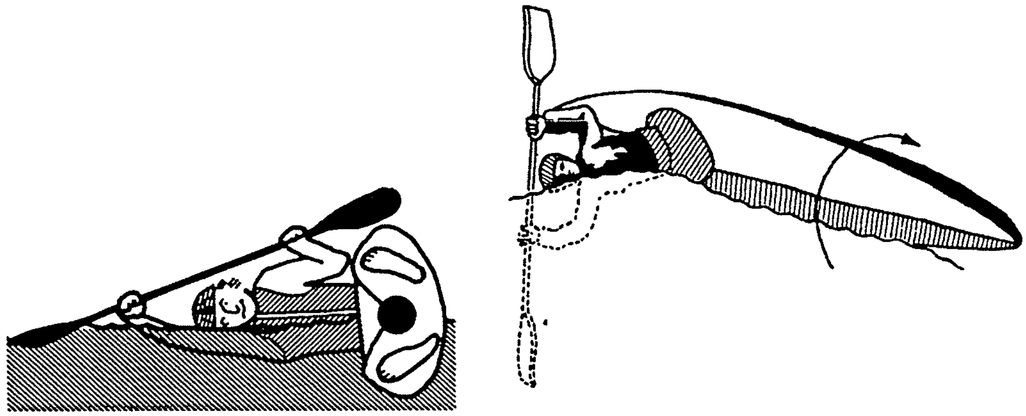

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Figure 2-12. The hip snap phase a) starting position and b) the head and body remaining low in the water as the kayak rotates. (a) (Stuart, 1976, p. 17); b) (Tejada-Flores, 1978, p. 97).

Recovery: The right paddle blade that is in the water is pulled downward to act as a brace to create resistance to help lift the body upright. This blade should finish near the surface of the water with the opposite blade held higher in the air (see figure 2-13) (Bridge, 1978b).

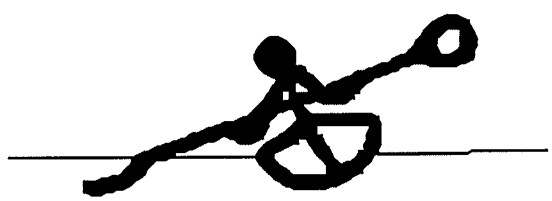


Figure 2-13. The recovery position at the completion of the roll. (Williams, 1967, p.83).

The body should exit the water with the trunk extended and with the kayaker facing the sky (Stuart, 1976; Trewiler & Smith, 1978). This position aids in decreasing the moment of inertia about the long axis of the kayak and decreases the height to which the center of gravity of the kayaker must be lifted (Steidle, 1976).

The whole roll ends with the kayaker finishing the paddle sweep and pulling the blade out of the water while sitting upright (Stuart, 1976).

Net Torque

The kayak must be rotated upright about an axis of rotation that can be approximated by the axis extending from the bow to the stern of the kayak. The rotation is the result of a net torque being applied in the direction of the desired rotation. The torque is the result of forces being applied at some distance from the longitudinal axis of the kayak (Hay & Reid, 1988). The formula to calculate the torque is:

$$T=Fd$$

(Serway, 1990).

The T represents the torque created, the F represents the force used to create the torque, and the d represents the perpendicular distance from the line of force application to the axis of rotation for the movement, which is the long axis from the bow to the stern of the kayak.

The net torque can be calculated by using Newton's Laws of Motion and the equations developed for analyzing dynamic situations (Serway, 1990). The net torque is equal to the angular acceleration of the kayak and kayaker multiplied by the moment of inertia of the system:

Torque = (moment of inertia) * (angular acceleration)

or

$$T= I\alpha.$$

This torque is composed of four known terms: 1) the lift force created by the movement of the paddle and 2) the buoyant force of the water act to create torques in the direction of the required rotation. A portion of 3) the weight of the body and 4) the force of drag on the body from the water creates torques in the direction opposite to the desired motion (Alexander, et al., 1994). The buoyant force and the paddle lift force must be large enough to create sufficient torque to rotate the kayak against the opposing torques of the weight and drag.

The torque equation including all known terms can then be written as:

Lift Torque + Buoyant Torque + Drag Torque + Weight Torque = $I\alpha$

or

$$(1) \quad T_{lift} + T_{Buoyant} + T_{Drag} + T_{Weight} = I\alpha$$

Lift Torque

The lift torque results from the movement of the paddle blade. The blade of the paddle should be swept through the water at a climbing angle so that lift forces can be created (Stuart, 1976) (as in Figure 2-10). This lift force applied at some distance from the axis of rotation of the system will create a torque. This torque must be directed in direction of righting the kayak.

The magnitude of the lift force is determined by four different factors (Hall, 1994). These include: 1) the coefficient of lift for the object, 2) the fluid density, 3) the surface area against which lift is generated, and 4) the relative velocity of the moving object. The coefficient of lift is a number which describes the body's ability to create lift based on the shape of the object. The best shape would be a foil shape similar to the shape of an airplane wing. The kayak paddles are constructed in a shape that exhibits some foil-like qualities to aid in the creation of lift. The denser the fluid the greater the amount of lift force that can be created, but the kayaker would not have any control over this factor which would remain at a constant value. A larger area against which lift forces can be created will result in greater lift forces, but there is a constant surface area of the paddle blade used. The faster the object moves in relation to the speed of the fluid the greater the lift forces. The greater lift forces would be generated if the kayaker swept the paddle blade in a high velocity motion.

The angle between the long axis of the paddle blade and the water flow direction, the angle of attack, will also affect the lift forces (Hall, 1994). The angle of the moving paddle blade must be one at which the lift is in the correct direction and the ratio between the blade lift and the blade drag is at a maximum. The optimal angle of attack is difficult to measure but a study done with a discus found that the most effective angle was near 10 degrees (Hay, 1985). This angle should be similar for other objects that possess foil-like qualities. The optimal angle would be the angle at which the lift forces created have been maximized and the drag forces on the paddle minimized.

The kayaker will also sweep the paddle outward in as large an arc as possible. This tends to move the paddle blade farther away from the long axis of the kayak. This type of sweep will increase the lever arm (or moment arm) for the paddle since the lift force acting on the paddle blade is now farther from the kayak (Steidle, 1976). The larger moment arm, combined with the lift force at the paddle blade, will result in a larger lift torque.

Buoyant Torque

The buoyant force is the result of the water pushing upwards against the kayak and kayaker. The magnitude of this buoyant force can be determined by applying Archimedes' principle. Archimedes' principle states that the magnitude of the buoyant force would be equal to the weight of the water that the kayaker displaced when placed in the water (Hay, 1985). This buoyant force, when applied at a distance from the axis of rotation for the system, can create a torque to help right the kayak. This buoyant torque would be in the same direction as the lift torque and would aid in the righting of the kayak.

The buoyant force is determined by the specific weight of the fluid and the volume of displaced fluid (Hall, 1994). The specific weight of the water would remain constant but the amount of water displaced by the kayaker and the kayak would change. The buoyant force would therefore vary depending on how much of the body and kayak were under the water. Since the kayaker and kayak do not sink, the total buoyant force would be less than the weight of a volume of water equal to the combined volumes of the kayaker and kayak.

The ability of this buoyant force to create a torque will also depend on the position the kayaker. The buoyant force can be considered to act at the center of buoyancy of the system (Hay, 1985). The farther that the line of force acting through the center of buoyancy is from the long axis of the kayak, the greater the moment arm for the buoyant force, and the greater the buoyant torque becomes. The moment arm distance will vary for different body positions but should be maximal when the kayaker has swept the paddle outwards 90 degrees and is starting the hip snap.

Drag Torque

The drag torque would be the result of the drag force acting on the kayaker and kayak as they move through the water. This torque would resist the righting motion of the Eskimo roll and would tend to make rolling more difficult.

The drag force is the result of three forms of resistance: 1) surface drag, 2) form drag, and 3) wave drag (Hall, 1994). The surface drag is the result of the friction between the layers of water moving near the surfaces of the kayaker and kayak as they move through the water. The form drag is the result of pressure differences between the lead and rear sides of the kayaker and kayak moving through the body. This would be large for the kayaker since their body position under the water is not very streamlined and will not slice easily through the water. The third and final source of drag would be the wave drag created at the boundary of the air and water. This drag is only a factor when the kayaker and kayak move across this boundary and would not be a factor when the kayak or kayaker are completely above or below the water.

The drag force is dependent on 1) the coefficient of drag for the object, 2) the density of the fluid, 3) the surface area of the object facing the fluid flow, and 4) the velocity of the moving object (Hall, 1994). The coefficient of drag is a number to describe the shape and orientation of the object and the resulting ability to create drag. The density of the water would remain constant and a greater density would result in greater drag. The surface area perpendicular to the motion of the fluid would change for different body positions of the kayaker. The drag force would therefore vary also, as the area increased, the drag forces would increase. The velocity of the kayaker and kayak moving through the water would also affect the drag, as the faster the kayaker moved, the greater the drag force.

Weight Torque

The weight torque results from the force of gravity acting on the mass of the kayaker and kayak. This force is directed towards the center of the earth and would cause a torque that would resist the righting direction of the roll. The weight of the kayaker and kayak would remain constant but the distance from the axis of rotation to the application of this force would vary depending on the body position.

The weight force can be considered to be applied at the center of gravity of the kayaker and kayak (Hay, 1985). If the kayaker flexed or hyperextended their trunk so that their center of gravity were moved closer to the long axis of the kayak, the moment arm for the weight torque would be decreased. These positions with the shorter moment arm would result in a smaller weight torque to resist the Eskimo roll and should result in the easier completion of the roll.

Required Torque

Sufficient net torque in the direction of the intended Eskimo roll will result in the kayak rotating to an upright position. This net torque is the sum total of all created torques. These torques include known torques stated previously and any unknown torques that may be required to summate to the net torque values. Torques in the clockwise direction can be assigned a negative value and torques in the counter-clockwise direction would be assigned a positive value before summing all the torques. A term for any unknown torque can be added to formula (1). Formula (1) can then be rearranged to solve for the unknown torque required to create the total net torque necessary to right the kayak and could then be written as:

$$T_{unknown} = I\alpha + T_{lift} + T_{Buoyant} - T_{Drag} - T_{Weight}$$

The kayaker must perform the correct movements in the correct sequence to create the net torque required to complete an Eskimo roll. The net torque must be in the desired direction of the roll. Failure to perform a roll will be the result of insufficient torque generation to overcome the magnitude of the resistive torques.

Previous Biomechanical Studies

The previous biomechanical research literature on the Eskimo roll has been very limited. Only one study has attempted to analyze the torques required in the Eskimo roll (Alexander, et al., 1994).

This study calculated the weight torque, lift torque, drag torque, and buoyant torque required for the roll. The variables required to calculate these torques were either estimated or collected from a video analysis of the skill (see Figure 2-14).

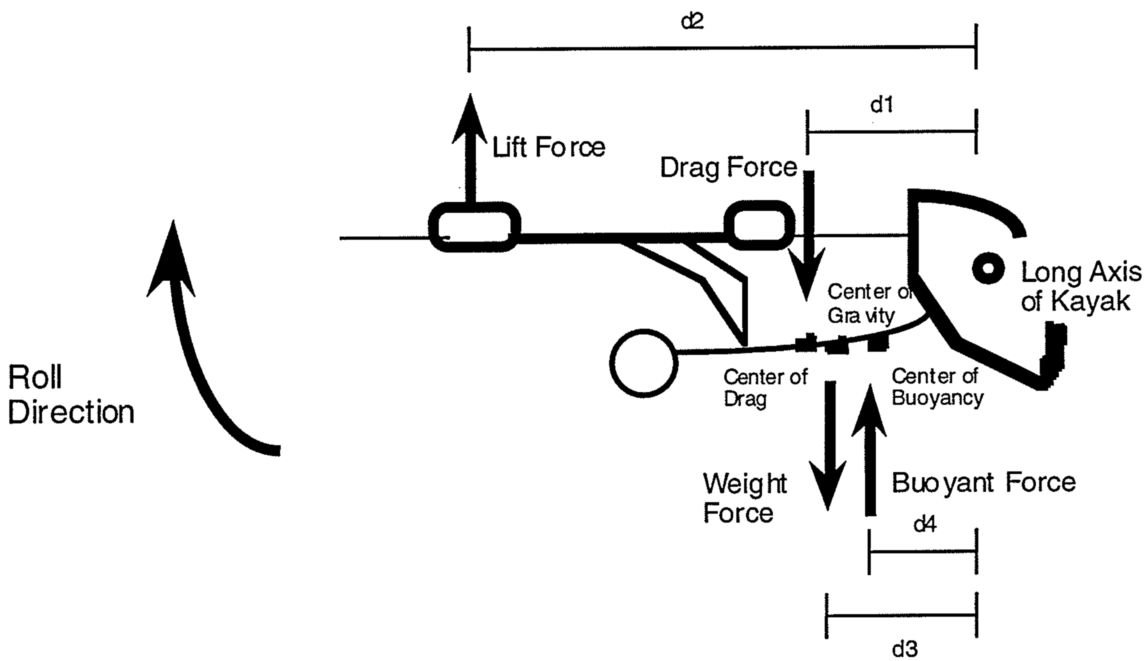


Figure 2-14. The forces and moment arms (d1, d2, d3, d4) used in the study by Alexander, Giesbrecht, Boldt and Nickel (1994).

The drag torque due to the movement through the water was calculated by multiplying the drag force by the distance from the center of pressure of the drag force to the long axis of the kayak (d1). This distance (d1) was estimated to be half the distance from the hips to the top of the head. The drag force was calculated by determining the values for the coefficient of drag, area of athlete perpendicular to the flow of the fluid, the velocity of the kayaker moving through the fluid, and the density of the fluid. These variables were either estimated, obtained from tables, or calculated from the film data (Alexander, et al., 1994).

The lift torque was calculated by multiplying the lift force by the distance from the end of the paddle blade to the long axis of the kayak (d2). The moment arm distance (d2) was calculated from the film data. The force of lift was determined from the determination or estimation of the velocity of the paddle, area of the paddle blade, density of the water, and the coefficient of lift (Alexander, et al., 1994).

The weight torque was determined by multiplying the weight force by the moment arm for the force (d3) (Alexander, et al., 1994). This moment arm distance (d3) was determined from the video data and was estimated as the horizontal distance from the center of gravity of the kayaker to the long axis of the kayak. The weight force was determined by multiplying the weight of the kayaker and kayak by the acceleration of gravity.

The buoyant torque was calculated by multiplying the buoyant force by the moment arm for the force (d4) (Alexander, et al., 1994). The moment arm for the buoyant force (d4) was estimated to be half the distance from the hips to the shoulders. The buoyant force was estimated to be equal to the weight of the water displaced by the kayaker.

One of the main limitations to the previous study was the accuracy of the video data (Alexander, et al., 1994). The difficulty in filming the Eskimo roll resulted in video data that lacked accuracy. Data points to be digitized were often obscured due to the movements across the air-water boundary and the difficulty in filming underwater. Errors at this stage of the analysis then affected the positional data, velocity data, and acceleration data that was obtained from the film.

There was a need for future studies to improve the technique used to videotape the Eskimo roll and to collect more accurate video data. Two gen-locked cameras filming both the underwater and above-water movements through a domed surface are needed to obtain a better video record of the skill and aid in the computer analysis of the roll. This improved video analysis could then be used to recalculate the torques for the Eskimo roll. This analysis and skill description could then provide a more complete and accurate understanding of the Eskimo roll.

A better understanding of the Eskimo roll can then be used to facilitate the construction of a dry-land simulator. The simulator could be constructed so that only the production of a torque profile similar to the calculated torque profile would result in the righting of the simulator. The individual torque profiles would have to be incorporated in some way into the simulator to maintain a realistic situation.

CHAPTER 3

METHODS

Subjects

The subjects used in this study were two kayak instructors from the University of Manitoba in Winnipeg, Manitoba, Canada. These subjects were selected for their experience and ability to perform the Eskimo Roll in a kayak on a consistent basis.

One subject was contacted by the investigator at the University of Manitoba and was informed of the filming date and time. This subject then notified another skilled subject of the test date and time. The testing took place indoors at the pool in the Frank Kennedy Center at the University of Manitoba. The experimental procedures were first explained to the subjects and then an informed consent form was completed by the subjects before participating in the study (Appendix A). The kayakers used the same fiberglass kayak but their personal paddles to perform the Eskimo Rolls.

There was a total of two male subjects used in this experiment with each subject agreeing to perform at least five Eskimo Rolls. This would provide at least ten possible Eskimo Rolls for analysis. The subjects were required to wear only swimsuits so that clothing would not interfere with the view of their body. The body mass, in kilograms, of each subject was also recorded. The mass of the kayak was also recorded.

Data Collection Procedures

Pilot Study One

The first pilot study was a single camera two dimensional videotaping session conducted on November 2, 1994 to test the videotaping method. The study involved placing a Panasonic Camcorder (PV-460-K) in a plexiglass box and filming a single subject. The plexiglass box (the same as the one pictured in Figure 2-1), containing the video camera, was held exactly at water level by the investigator so that the camera simultaneously recorded a view including both above the water and below the water surface. The subject in the pool held a straight wooden stick half above the water and half below the water and moved the stick left and right in the field of view.

The goal of the pilot study was: 1) to determine if the camera and plexiglass box could simultaneously record the above and below water views, 2) to identify any possible problems with this method, and 3) to investigate a method to correct for the water refraction.

The videotape of the subject was viewed to identify any difficulties or problems with the method. Aligned points on the stick were digitized to determine the influence of the refraction on the recorded view. The videotape of the subject illustrated that simultaneous views of the above and below water movements could be obtained. The major problem identified when filming was the difficulty of waves obscuring the subject (see Figure 3-1). A wave crest in front of the camera lens resulted in the above water view being blocked and a wave trough in front of the camera lens resulted in the below water view being completely blocked. This problem could be partially overcome by ensuring the water was as calm as possible before videotaping a skill, and by constructing a wave guard around the plexiglass box to keep the wave interference to a minimum.

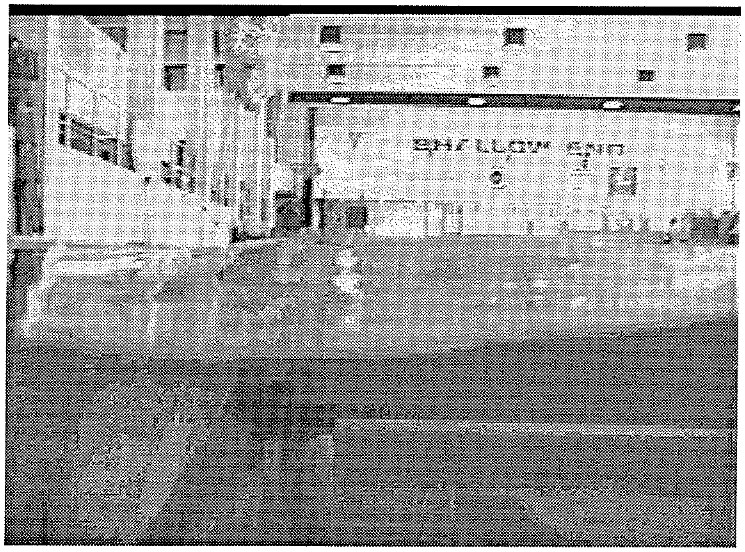


Figure 3-1. A view of the subject being partially obscured by wave action in the pool.

An additional problem encountered was that the plexiglass box had to be firmly attached to the pool to prevent movement of the camera. The wave action tended to cause the plexiglass box to bob up and down in the water and made it impossible to keep the camera aligned at the water surface. Any fine adjustments to the alignment of the camera could be best accomplished by adjusting the position of the camera in the box instead of adjusting the box position.

Digitization of the video film indicated that the view below the water was magnified and misaligned due to the refraction of the water. The magnification caused by the water was also shown to cause errors in the true position data for each point. The true length of a portion of the stick below the water was measured to be 0.539 meters but the length measured from the film data was calculated to be 0.738 meters. This represented a difference of 0.199 meters or 36.9 percent of the true length. It is critical that this type of error is corrected in order to produce an accurate biomechanical analysis.

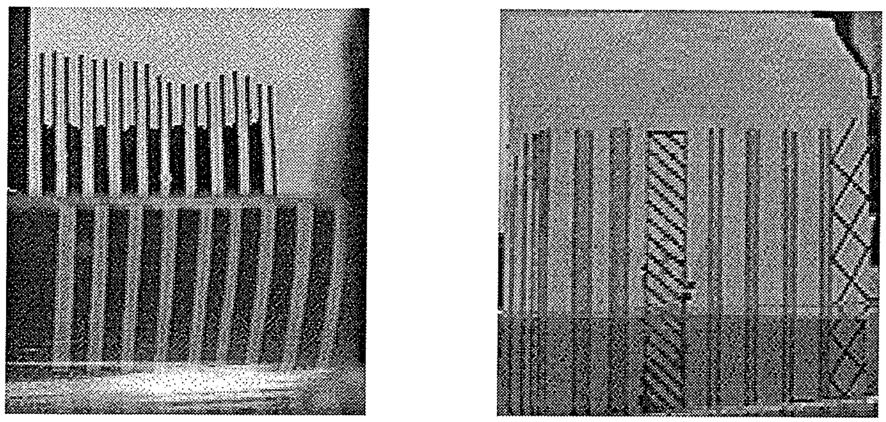
The use of a separate scaling factor for the above water view and the below water view would eliminate the magnification problem but it was not possible to eliminate the misalignment problem in this manner. The calculation of a single misalignment correction value that could be applied to all values below the water was not shown to be a valid method to correct the misalignment problem. This single correction value was inaccurate because the amount of refraction misalignment increased in magnitude as the object moved from the center of the field of view to the outer edges of the field of view. One solution would be to calculate the rate of change of the correction factor from the center to the edges of the field of view and then use the variable correction factor to correct the image based on the objects position in the field of view.

Laboratory Trials

Experimental trials were completed in the Biomechanics Lab at the University of Manitoba to evaluate the use of plastic domes attached to the plexiglass box to eliminate the refraction. A plastic dome, obtained from a local handicraft store, was fitted to the inside wall of one plexiglass box. The dome was part of a spherical, clear plastic container with a portion of this sphere cut off to create the dome shaped lens that was attached to the plexiglass box (see Figure 3-2). A piece of paper with vertical and diagonal marked lines was placed on the side of the box opposite of the dome and was used to observe the refraction caused by the water.

Figure 3-2. The camera box with the attached plastic dome.

Water was placed in the box until the dome was half submerged. This water level also half submerged the lined paper and allowed a simultaneous view of the above and below portions of the paper when viewed through the dome from the outside of the box. A video camera was then held in a position behind the dome and filmed the lined paper through the plastic dome. Careful alignment of the camera behind the plastic dome allowed for the magnification and misalignment due to the refraction to be eliminated (see Figure 3-3). The correct camera position occurred when the focal point of the camera lens was aligned with the center of the dome. The correct position was easily distinguished by viewing the lined paper through the viewfinder. Only the correct camera position produced an image in which the lines on the paper were aligned.



a b

Figure 3-3. The view of lined paper half below the water surface when a) the dome was not used, and b) when viewing through the dome.

Pilot Study Two

A second pilot study was conducted in the pool, in February 1996, with the purposes of evaluating 1) the effectiveness of newly constructed wave guards, 2) the effectiveness of clamps to hold the plexiglass boxes stationary, 3) the floats on the calibration tree, and 4) the ability of plexiglass domes to eliminate the refraction due to the water.

Two sets of wave guards were constructed with each wave guard consisting of two wooden-board arms that would be placed on the pool deck (See Figure 3-4). The dimensions of each arm in centimeters was 245 x 5.1 x 10.2. These wooden arms were placed on the pool deck and allowed to extend 122.5 centimeters out over the water in the pool.

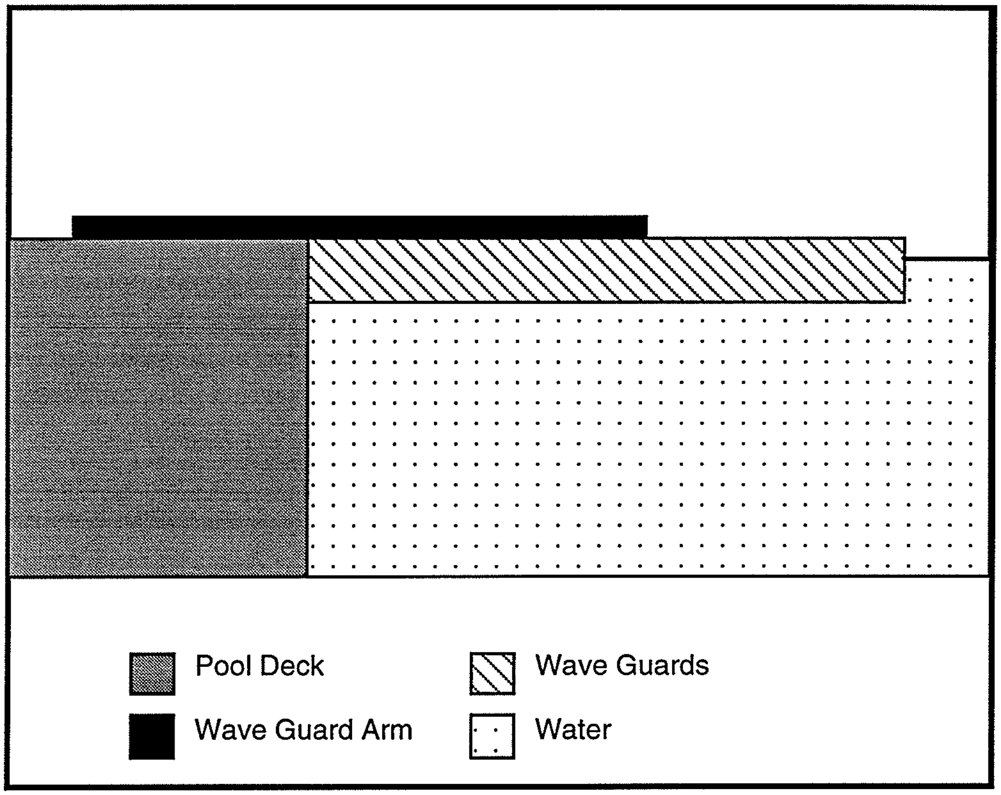


Figure 3-4. Side view of the wave guard in the pool.

A wooden plank was attached to each arm for the purpose of stopping the waves. The plank measured 2.54 x 20.32 x 182.88 centimeters and was attached in a vertical position on the arms (See Figure 3-5). The arms were connected by a plexiglass sheet measuring 111.76 x 33 x 0.33 centimeters. The plexiglass sheet was reinforced with a metal rod attached by wire along the top of the entire length of the sheet. The purpose of this reinforcement was to prevent the plexiglass from bending when struck by a wave. The clear plexiglass sheet was necessary so that the video camera could film through the front of the wave guard and record the skill. The wave guards were held onto the pool deck by iron weights which fitted over the arms of the wave guards. One weight was fitted over each arm of the wave guard and each weight weighed approximately 32 kilograms.

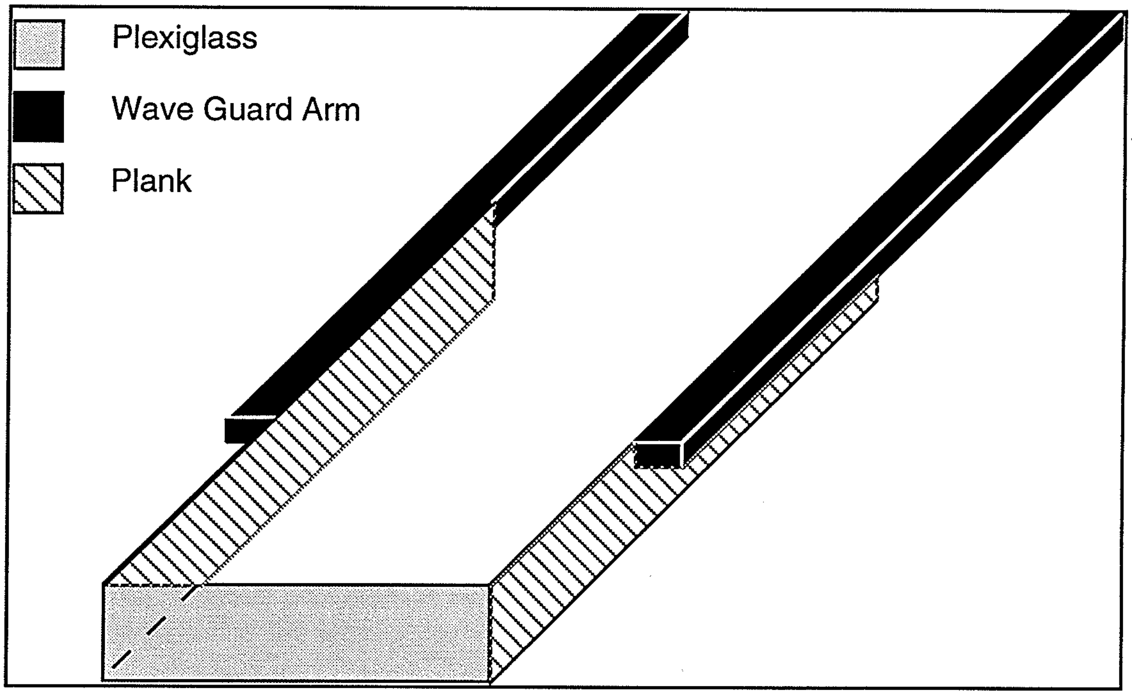


Figure 3-5. Illustration of the construction of the wave guard.

Each plexiglass box was clamped to the lip of the pool by two bar clamps (see Figure 3-6). The plexiglass box was positioned inside the wave guard at an equal distance from each arm of the wave guard (see Figure 3-7). The depth of the box in the water was adjusted so that the dome attached to the outside edge of the box was now half submerged and facing the plexiglass wall of the wave guard. The video camera was then placed in the box and the camera filmed the center of the pool through the plexiglass sheet of the wave guard. The camera position was adjusted by the addition or removal of cardboard spacers placed under the camera body.

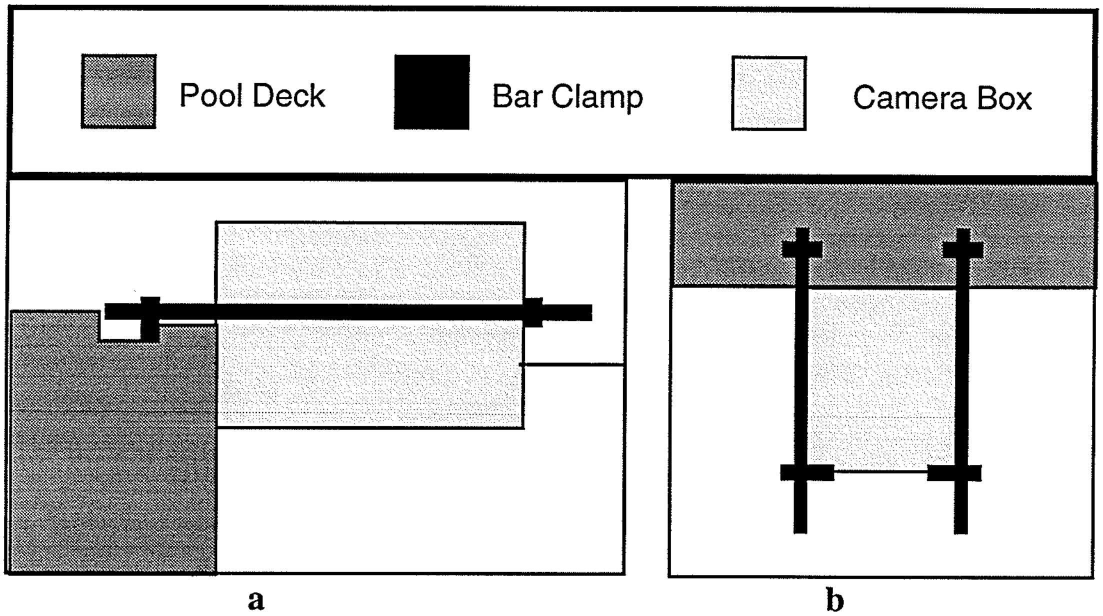


Figure 3-6. Position of the bar clamps to hold the camera box onto the side of the pool. The view from a) the side and b) the top of the camera box.

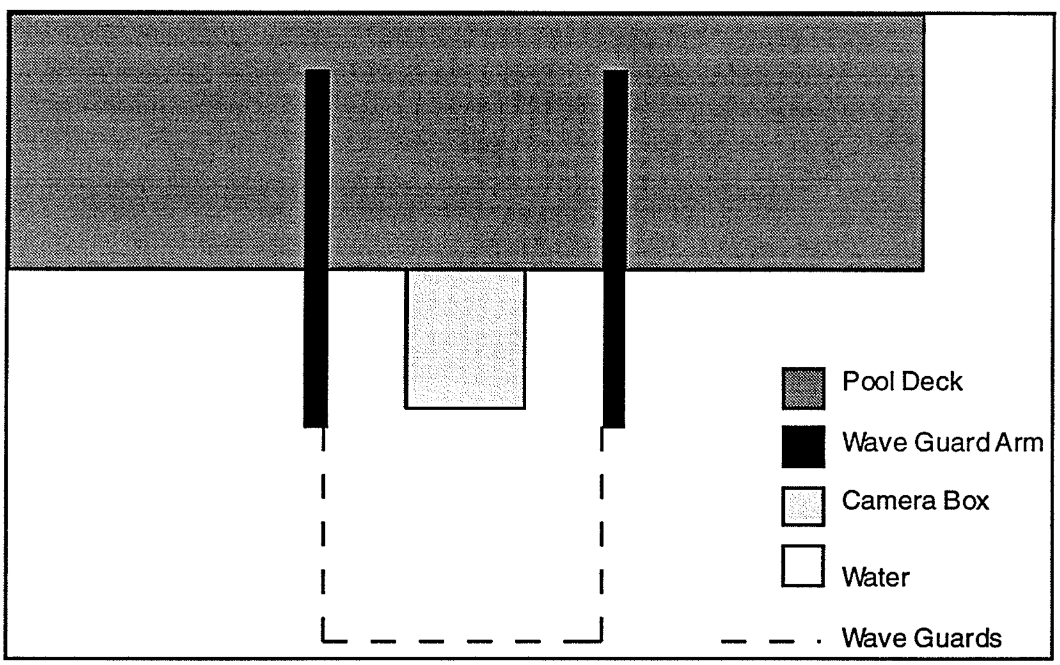


Figure 3-7. Top view of the wave guard location in the pool with camera box in position.

The cameras were focused on a lined sheet of arborite that was held half submerged in the pool in front of each wave guard. This lined sheet of arborite was necessary so that the refraction could be studied. This refraction tool measured 59 x 122 x 0.1 centimeters. The arborite had a white background with strips of black tape attached to create vertical and diagonal lines of varying thickness (see Figure 3-8). This refraction tool was viewed through the viewfinder of each camera. The cameras were focused and adjusted in position to eliminate the refraction using the same technique in the lab experiments conducted previously.

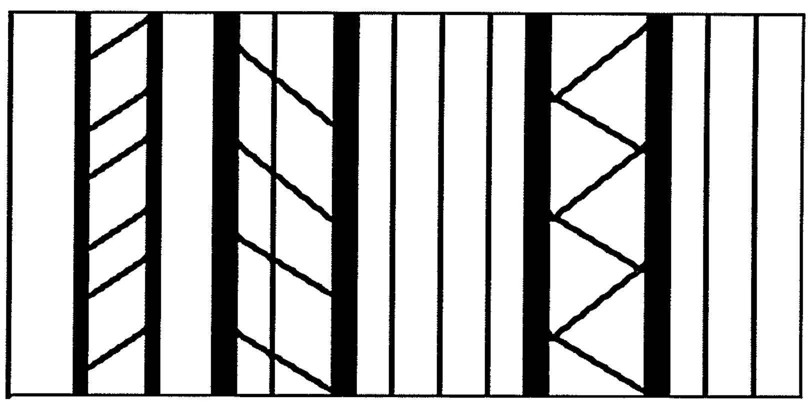


Figure 3-8. The refraction tool design. Black tape lines on a white background used to observe any misalignment due to the refraction.

Calibration Tool

A float system was also tested to ensure that a calibration tool necessary for three dimensional videotaping could be kept floating in the water. The floats consisted of four liter plastic jugs which were tied onto the calibration tool to enable it to float. Three of these floats were used. The floats for the three dimensional calibration tree were successful but it was determined that one more such float would be helpful to keep the calibration tree floating high enough in the water.

This pilot study illustrated that the refraction correction achieved with the domes in the lab trials could be repeated in the pool situation. It was noted that it was very difficult to correctly position the camera based solely on the view through the viewfinder because the viewfinder of each camera was not easily accessible once the camera was placed in the box. In addition, the cardboard spacers proved difficult to use and did not allow for the camera to be easily adjusted.

A minor adjustment in the length of two of the clamps was also required to make the camera positioning faster and more secure.

The wave guards were found not to be successful in stopping the waves in front of the dome of the plexiglass box. The guards did not extend far enough down into the water and therefore allowed waves to come under the guards and disrupt the water around the camera boxes.

Pilot Study Three

A third pilot study was conducted on April 10, 1996, with the purpose to test the entire three dimensional filming system. This new setup incorporated new wave guards, clamps, and camera adjustment system using a television monitor.

The new wave guards were similar to the guards used in the previous pilot study but had some additional attachments. The addition of 1 centimeter thick plywood sheets to the guard resulted in a completely enclosed area in which the camera box could be placed (see Figure 3-9). This was done to prevent the waves from moving under the wave guards. This enclosed area measured 122 x 122 x 61 centimeters. The increase in the size of the wave guard also required that the plexiglass sheet used to connect the two arms together be increased to 111.76 x 61 x 0.33 centimeters.

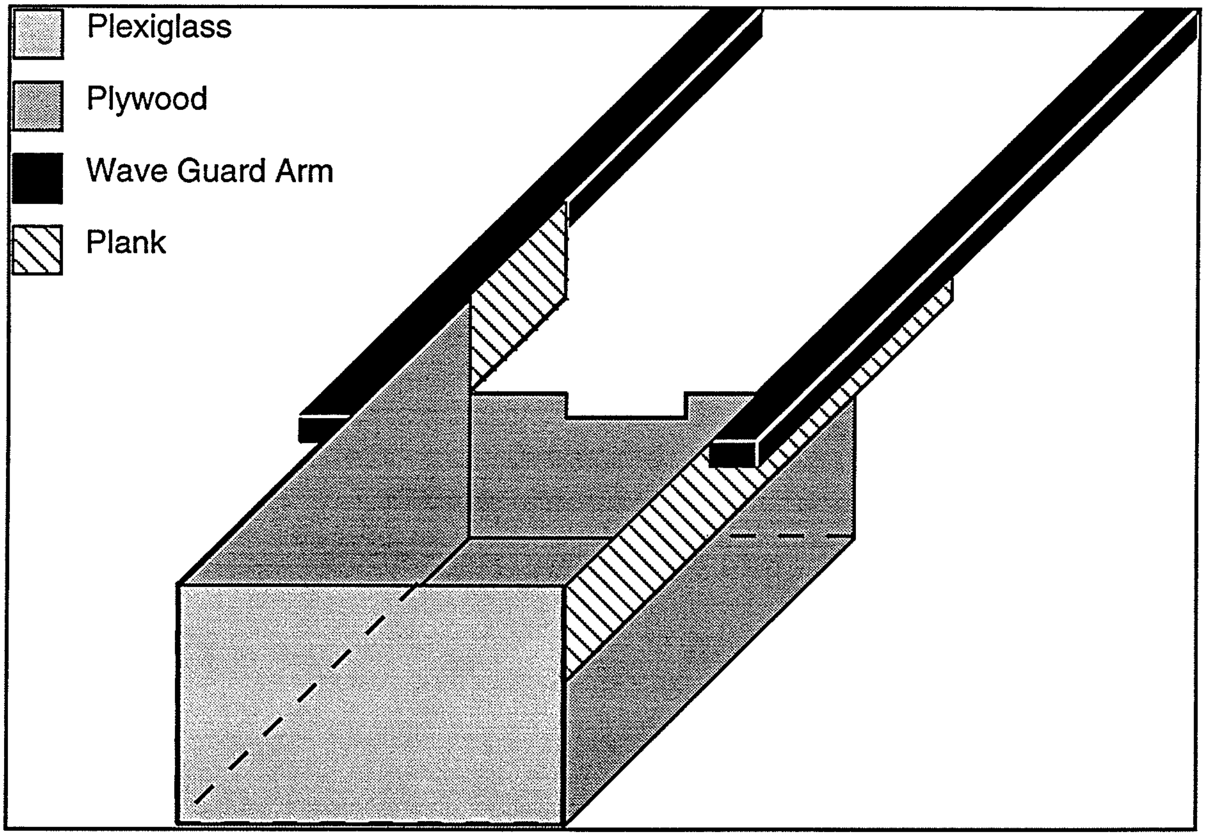


Figure 3-9. The wave guard design with the completely enclosed space to prevent waves around the camera box.

The wave guards were placed on the pool deck (see Figure 3-10) and a camera box was clamped to the edge of the pool inside each of the wave guards as had been done previously. The wave guards were not made water tight so that the water could enter the enclosed area and reach a level equal to that of the water in the pool. The camera boxes were clamped so that the plastic dome on each box was half submerged.

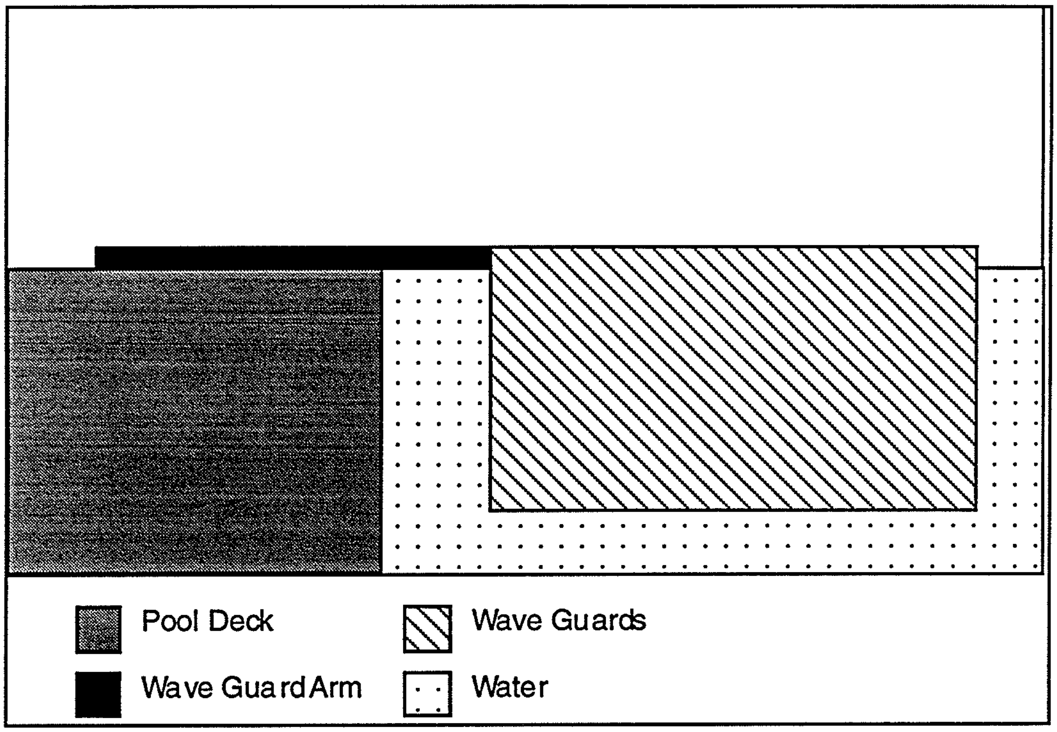


Figure 3-10. The side view of the wave guard in position in the pool.

The cameras were placed inside each camera box and positioned on a thick piece of a putty-like substance. This dough-like substance was made of flour, water, salt and tartar mixed together and heated until the mixture became firm and putty-like. This homemade putty was chosen to act as the system to adjust the camera position in the box since the thickness and shape of the putty could be easily manipulated to alter the position of the camera that had been placed on the putty. This allowed for the camera position to be easily adjusted with only slight pressure being applied to the putty.

A television monitor was connected to the cameras so that the refraction adjustments could be performed. This made the camera view of the refraction tool easier to see and would make the effects of the camera position changes easier to observe. The television monitor eliminated the difficulty of accessing the viewfinder to adjust the camera once the camera had been placed in the box.

This pilot study determined that the new wave guards were more successful in eliminating the waves around the camera box. The securing of these wave guards proved difficult and time consuming since a back wall for the guard had to be attached after the camera box had been secured to the side of the pool. The clamps held the box firmly against the pool edge without moving and the playdough allowed ease of adjustment of the cameras. The television monitor made the refraction correction tool easier to view but it was found that a backlighting problem occurred due to the windows in the pool area. The lighting problem resulted in only one camera recording a good view of the pool. The backlighting problem could be best corrected by positioning one of the camera boxes directly in front of the windows and facing away from the windows so the window light was behind the camera.

Final Data Collection

The wave guards were the same as the wave guards used in the third pilot study but additional sheets of the 1 centimeter thick plywood were attached to the original guards. The additional sheets of plywood were attached to the rear end of the wave guards and increased the area enclosed by the guard to 122 x 183 x 61 centimeters (see Figure 3-11).

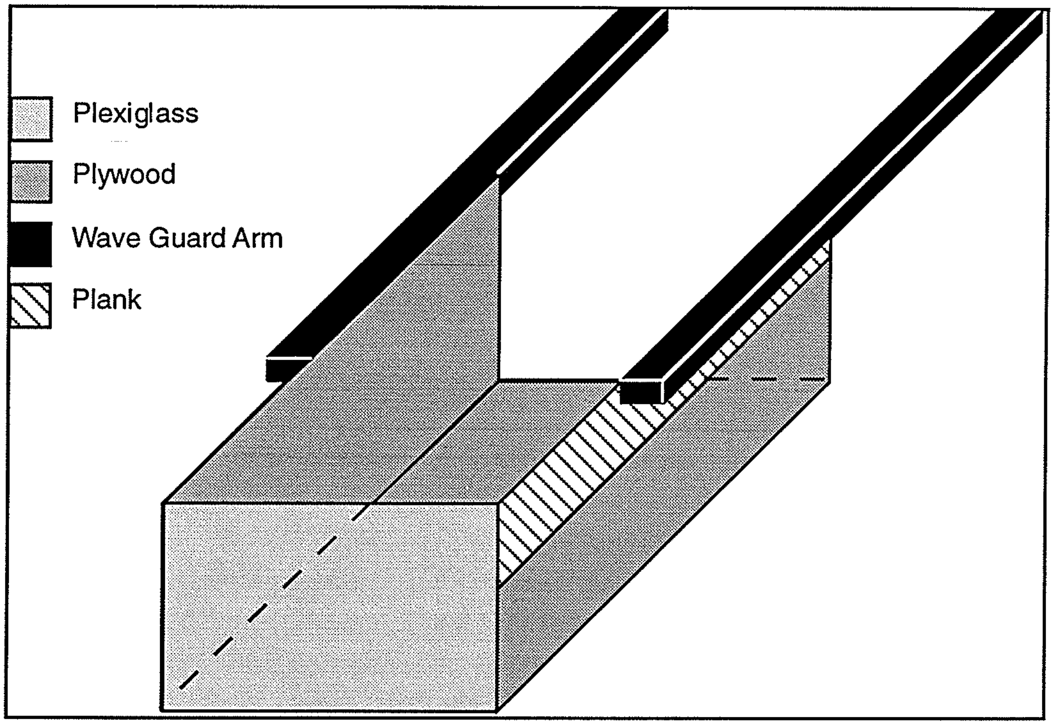


Figure 3-11. The wave guard design with the larger enclosed area for the camera box.

The additional plywood allowed for the rear end of the guard to rest against the edge of the pool. This made setup faster since a back wall to the enclosed area did not need to be attached. This design also made the wave guard more stable since additional counter weights could be placed on the bottom of the guard to ensure that the edge of the guard rested against the pool and did not float freely in the water (see Figure 3-12).

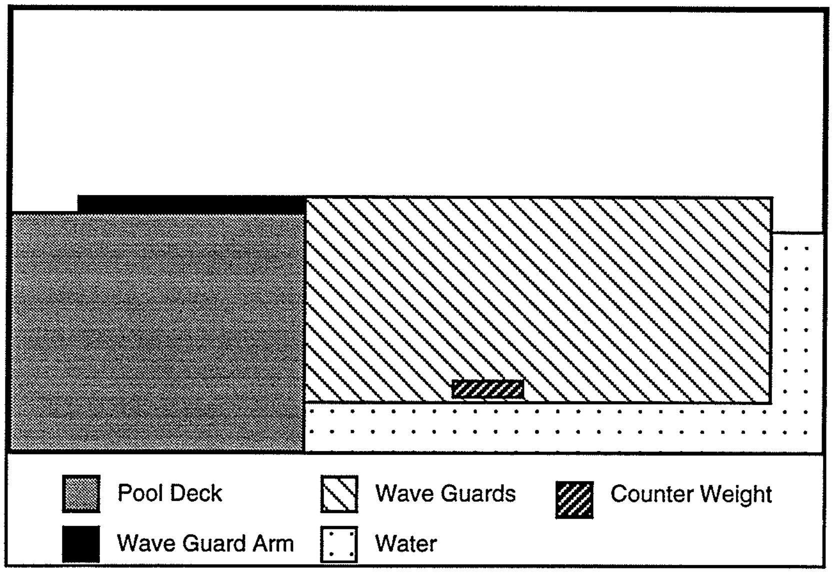


Figure 3-12. The side view of the wave guard showing the plywood sides extending backwards to the pool edge and the position of the additional counter weight.

One set of wave guards were used with each camera box and setup as in Figure 3-13.

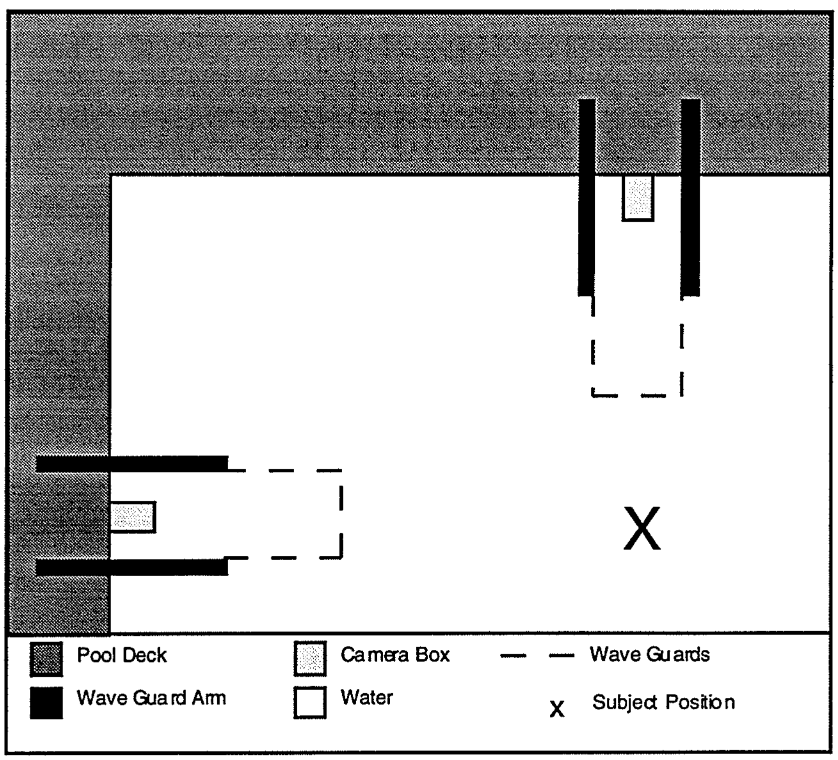


Figure 3-13. The top view of the pool setup with both camera boxes and wave guards included.

The camera boxes were attached to the lip of the pool on adjacent sides of the pool. The camera boxes were positioned with the plastic dome facing the position where the subject was to complete the skill. The camera boxes were attached inside the area enclosed by the wave guards and were both approximately 6.5 meters from where the subject would be performing the skill. Water was allowed to enter the area enclosed by the wave guards until it equaled the water level outside of the guards. The depth of the camera boxes in the water was such that the plastic domes were half submerged. This required that the bottom side of the boxes were submerged only approximately 8 centimeters below the water surface. The domes of the camera boxes were 122 centimeters from the plexiglass front of the wave guard.

Camera Boxes

There were two camera boxes used. Each box was made entirely of clear plexiglass with a 40 x 21 centimeter hole cut in the top to allow for the cameras to be placed inside. The two boxes used were different sizes because the larger box was obtained from another previous study and the smaller box was constructed specifically for this study. The larger box was found to be more difficult to submerge in the water since it displaced more water so the second box was constructed with the smaller dimensions to make the submersion of this box easier.

The larger camera box was made with plexiglass that was 1 centimeter in thickness. The dimensions of this box were 61 x 61 x

61 centimeters and had an attached dome that was 7.5 centimeters in diameter.

The smaller box was made with plexiglass that was only 0.6 centimeters in diameter. The dimensions of this box were 32 x 62 x 50 centimeters and had a plastic dome of diameter 9 centimeters.

Each camera box was attached to the side of the pool by two bar clamps. One end of each clamp was placed on the lip of the pool and the other end of the clamp was placed on the edge of the box with the dome on it (edge nearest the pool center). The tightening of the clamps resulted in the camera box being tightened against the side of the pool. Two cement bricks were placed in each camera box to help counteract the buoyant force of the water and to aid in keeping the box partially submerged in the water.

Video Camera Placement

The subjects were filmed using two video cameras positioned at approximately right angles to each other. A Panasonic OmniMovie PV-S770A-K camcorder was placed in the large camera box and set up in front of the subject to film the frontal view of the skill. A Panasonic Digital 5100 video camera was placed in the smaller camera box and placed approximately 90 degrees from the first camera to film the sagittal view of the skill. The cameras were focused in so that the lens would capture the entire skill with minimal extra area included. The cameras recorded at a film speed of 60 frames per second and a shutter speed of 1/250 per second. Each camera was mounted on the playdough that had been placed in the bottom of the boxes

The Panasonic Digital 5100 video camera was connected to a Panasonic AG-7400-K portable video cassette recorder and was powered by a 12 volt car battery. The PV-S770A-K camcorder and the portable video cassette recorder were powered by their own individual internal battery packs.

The two cameras were gen-locked together with connecting wires to synchronize each frame of film. A time code generator (Comprehensive Video Supply Corporation, Model TCG-1000) was also connected to each camera and powered by the 12 volt car battery. The time code generator numbered each frame of film so that the same instant in time could be identified on each separate video tape.

The camera connection setup was as illustrated in Figure 3-14.

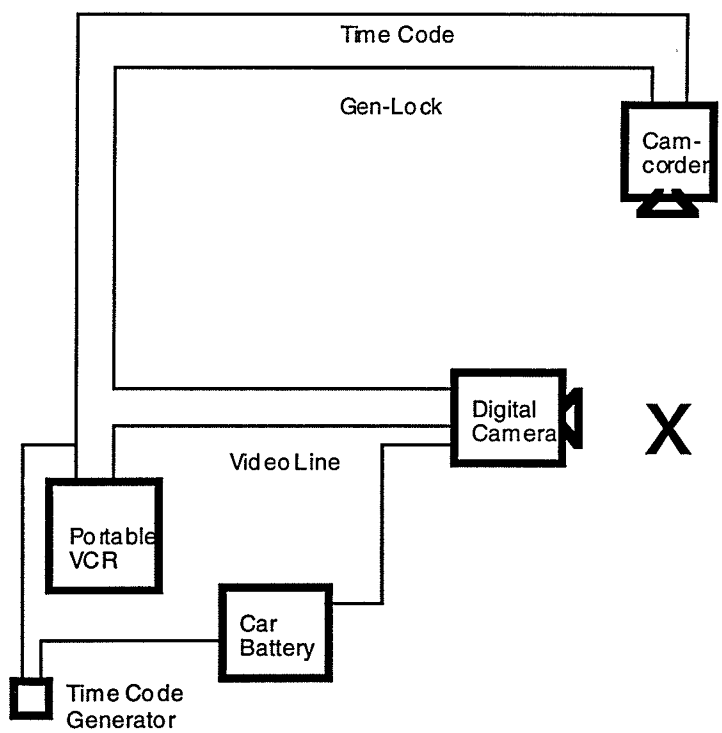


Figure 3-14. The video camera setup and connections.

Data Collection Procedure

The wave guards and the camera boxes were set up as described previously and each camera was turned on and placed in a waterproof camera box. The cameras were zoomed in on the area where the kayaker was to perform the skill so that the entire skill was captured without any movements occurring outside of the field of view. The cameras were connected, one at a time, to the television monitor to correct for refraction.

The refraction correction was done separately for each camera. The video out cable from the camera was attached to the video in on the television monitor. The lined refraction correction tool was held in front of the camera in the approximate position where the kayaker would be performing the skill and the camera was focused on this plane. The lined refraction correction tool was held half submerged in the water so that the camera would record an under water and an above water view simultaneously. The camera was adjusted by manipulating the shape of the playdough base until the lines were aligned on the refraction tool. This was accomplished by moving the camera in any direction until a satisfactory view was observed on the television monitor. The optical axis of the camera was simultaneously aligned with the water level so that the air and water boundary appeared as a narrow band in the camera field of view. This procedure was completed for each camera.

The next step was to film the calibration frame to calibrate the space for the three dimensional analysis. The calibration tree consisted of a block with eight attached metal arms (see Figure 3-15). The arms each had three precisely placed plastic balls that were at known distances from each other. The calibration frame was necessary when using the DLT method to calibrate the space and determine three dimensional positional coordinates from two planar camera views. This would allow for the video distances to be converted to real-life distances (Peak Performance Technologies, 1994).

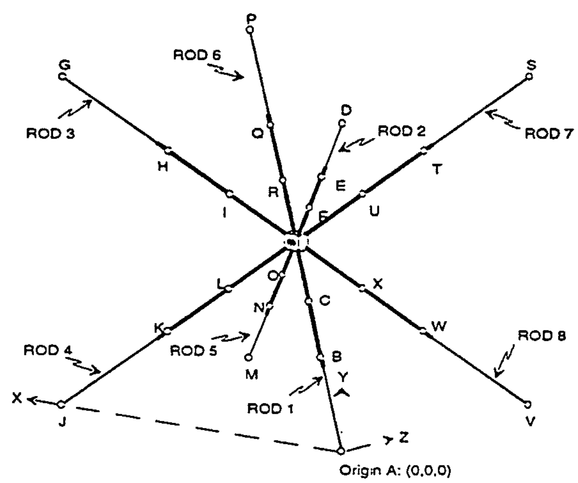


Figure 3-15. The calibration frame used for DLT calculations. (From Peak Performance Technologies, 1994, p. 5-37).

The plastic float jugs were attached to the lower four arms of the calibration tree and they allowed the tree to float so that half of the metal arms were below the water surface and half were above the water surface (see Figure 3-16). The floating calibration tree was pulled out into the space were the kayaker would be performing the Eskimo roll. The tree was positioned so that all the arms could be

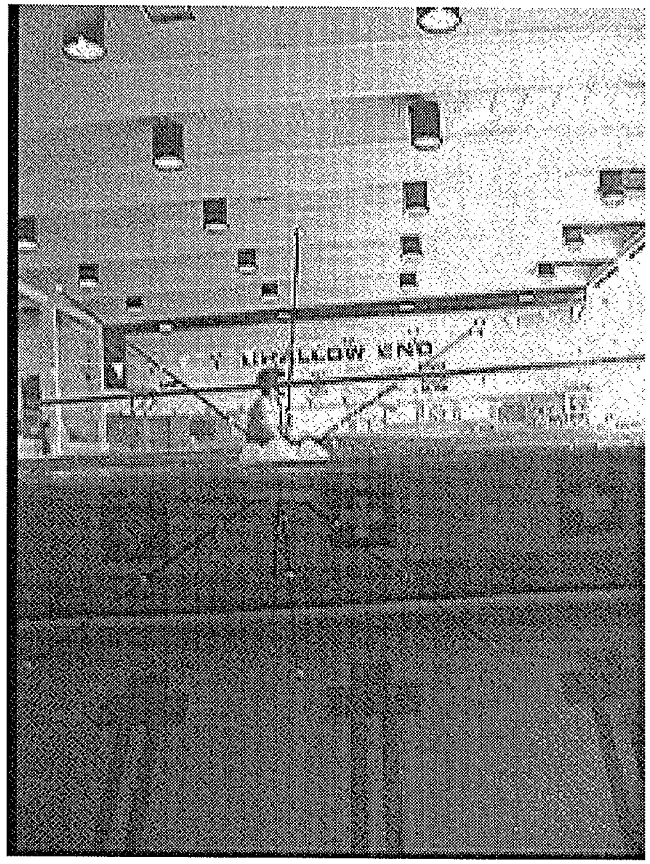


Figure 3-16. The calibration tree with attached floats to keep the tree floating at the water surface.

viewed and was filmed for four minutes before it was removed from the field of view. The cameras continued filming with no further adjustments for the remaining time in which the data was collected.

Test Protocol

White tape was used to approximate the joint positions of the wrist joints and elbow joints of the subjects. The tape was wrapped around the wrist and upper forearm to help identify the position of the joint. The white tape did not indicate the exact joint center but was used only as a guide to the joint position. White tape was used because this color best contrasted with the dark water and the pictures obtained by the video camera. The tape was wrapped loosely so as to not restrict normal function of the joint. A strip of white tape was also placed on the kayak to indicate the approximate position of the feet in the kayak since the true position of the lower body could not be seen.

The two subjects performed the Eskimo roll using the same kayak. The subjects were allowed to take some practice warm-up rolls. The subjects were then positioned in front of the cameras and requested to complete at least five Eskimo rolls. The subjects were told to pause in the inverted position before rolling up on the side facing the sagittal view camera. The subjects both performed the right handed Screw type, Eskimo roll. Subject 1 actually completed 7 Eskimo rolls and Subject 2 completed 9 trials for a total possible of 16 trials. It was necessary to complete more than one trial to help ensure that at least one trial would be recorded that was not obscured by waves.

Film Analysis

The film analysis was completed on a video analysis system supplied by Peak Performance Technologies (1994). This analysis system consisted of a Sanyo GVR-S955 video cassette recorder, a Sony Trinitron monitor, an ALR IBM compatible personal computer supplied by Peak Performance Technologies, a MultiSync 2A computer monitor, a Hewlett Packard LaserJet series II printer and a Hewlett Packard 7475A plotter. The hardware of the system was controlled by a Peak5 software package version 5.2.1 supplied by Peak Performance Technologies (1994).

The spatial model that was used for this study consisted of a total of twenty-seven digitized points. This spatial model was the same spatial model as used in a previous study (Alexander, et al., 1994). This was chosen to maintain the compatibility between data sets and would eliminate the need to make any changes to the torque calculation program. The points included seventeen body points, one reference point, three kayak points and six points for the paddle (see Figure 3-17). The spatial model was the computer representation of the subject performing the skill. Segmental weights and the position of the center of gravity for each body segment were entered into the computer. The Peak5 software was programmed to calculate the center of gravity of each subject during the skill. The segment values used were the average male values from Humanscale 1/2/3 (Diffrient, Tilley, & Bardagjy, 1978)

Spatial Model Points

1 Reference point
2 Right Finger Tip
3 Right Wrist
4 Right Elbow
5 Right Shoulder
6 Center of Chest
7 Top of Head
8 Left Shoulder
9 Left Elbow
10 Left Wrist
11 Left Finger Tip
12 Middle of Hip
13 Right Hip
14 Right Knee
15 Right Ankle
16 Left Hip
17 Left Knee
18 Left Ankle
19 Bow of Kayak
20 Stern of Kayak
21 Bottom of Kayak
22 Right Pole Tip
23 Left Pole Tip
24 Leading Edge Right Paddle Blade
25 Trailing Edge Right Paddle Blade
26 Leading Edge Left Paddle Blade
27 Trailing Edge Left Paddle Blade

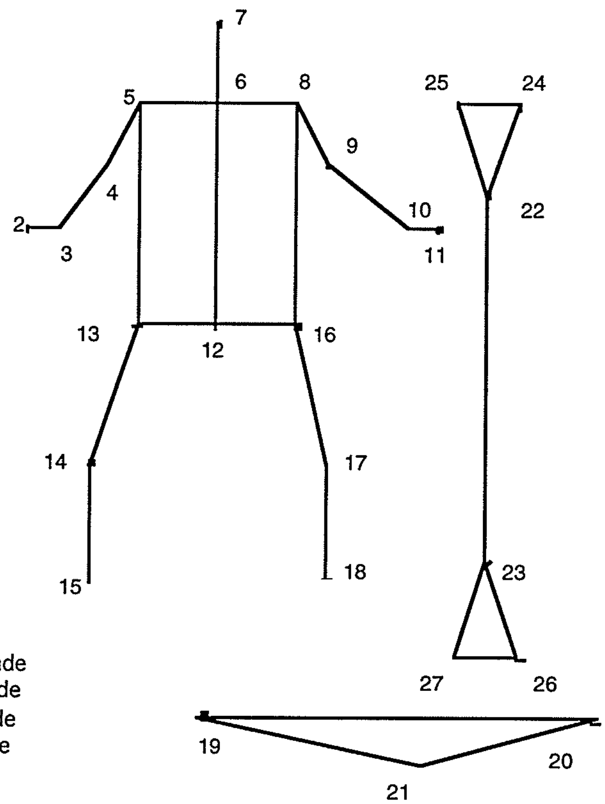


Figure 3-17. The spatial model that will be used in the proposed study. The points represent joint centers or ends of segments. The linking of the points is also shown.

The first step in digitizing was to digitize the calibration frame. This was accomplished by the computer first storing a picture of the calibration frame into memory and then displaying the picture on the monitor. A cursor, operated by movements of the mouse, was then used to mark the position of each of the balls on the calibration tree. The balls labeled E, F, I, P, R and U were omitted because of difficulty in determining their exact position on the videotape. This resulted in using a modified calibration tree consisting of a total of 18 control points. The position coordinates of each point were stored in the computer and used with the previously entered real-life distances between each ball to calibrate the space and create a conversion factor.

One trial was chosen from each subject for digitizing. The trial was chosen based on the following criteria: 1) a successful roll was completed, and 2) the trial could be viewed clearly from both cameras.

The trial chosen was digitized frame by frame for the entire skill. This digitizing involved manually selecting each point of the spatial model on each frame of the video using the cursor. This was accomplished by the computer first grabbing individual pictures from the video tape into memory. A cursor, operated by movements of the mouse, was then used to digitize the position of each of the twenty seven points of the spatial model. The position coordinates for each point were stored in the computer, to be used to calculate the real-life position coordinates, displacements, velocities and accelerations.

The skill started when the subject was in the inverted position and ended when the subject completed the roll and was sitting upright. The views from each camera were digitized separately and the exact corresponding frames from the two videotapes were easily determined by the time code which was recorded onto the audio track of each videotape.

Smoothing

The cut-off frequency for the Butterworth digital filter used in this study was chosen by visual inspection of the positional, velocity and acceleration graphs created at different settings. The smoothed data produced by the settings used in this study best represented the raw data by removing most of the noise. The smoothing frequency chosen for this study maintained the patterns of the raw data but did result in the underestimate of the peak magnitudes of values calculated from the raw data.

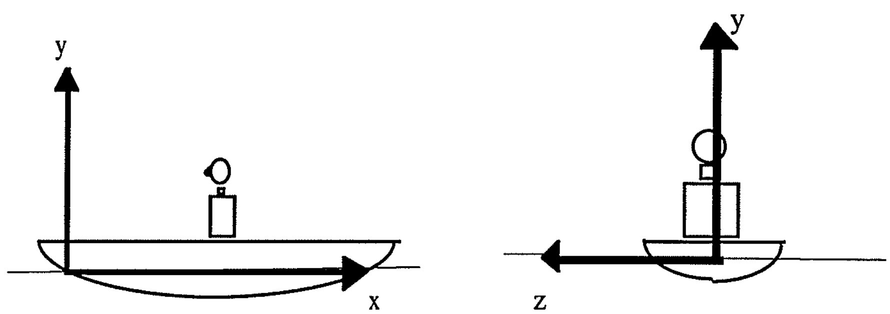
The raw data points were smoothed with a recursive Butterworth filter at a cut off frequency of 3 Hz before calculating the kinematic position variables and velocity variables. The Butterworth filter was chosen because it was described as a good general purpose filter to filter out the random noise that occurs with the constant 60 Hz sampling rate of the video cameras (Peak Performance Technologies, 1994). The raw data was filtered again at a cut off frequency of 2 Hz before calculating the acceleration variables. The additional smoothing was necessary to remove some of the noise in the data which was magnified by the acceleration calculations and resulted in the underestimation of the peak acceleration values.

Kinematic Calculations

The kinematic values calculated were determined by the values required for the torque calculation program. These kinematic values were first defined in the Peak5 Motion Analysis program and then could be calculated by the system for any number of trials.

The first calculation performed was to move the origin of the x, y, and z coordinate system to the kayak bow point (see Figure 3-18). This bow point was actually the point where the water level crossed the bow and thus varied in position during the execution of the roll.

The x axis was then rotated to pass through the point on the stern where the water level crossed the bow of the kayak. The y and z rotated automatically to remain perpendicular to the x axis. This created a reference axis with the x-axis that was always along the long axis of the kayak and was the axis about which the Eskimo roll would occur. Subsequent calculations were then completed with reference to this axis system on the kayak.



a b

Figure 3-18. The axes orientation for analysis purposes as seen from a) the sagittal plane view and b) the frontal plane view.

It was also necessary to calculate several angles for use in the torque calculation program including the paddle angle (see Figure 3-19). This was the angle between the segment, composed of the left trailing edge of the paddle (point 26) to the leading edge of the left paddle (point 25), and the horizontal (xz) plane. This angle was necessary to estimate the amount of lift created by the paddle.

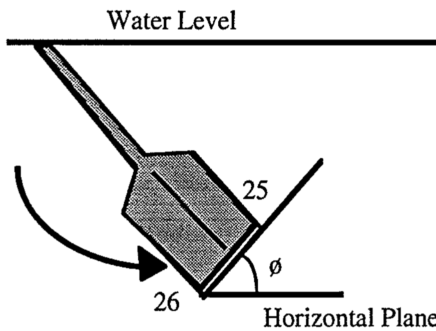


Figure 3-19. The paddle angle (ø) measured in this study with point 25 being the leading edge of the blade and point 26 being the trailing edge of the blade.

The second angle calculated was an angle measured in the frontal plane between the vertical (y) axis and the body segment (see Figure 3-20). The body segment was defined by point 5 (sternal notch) and point 11 (the midpoint of the hips). This angle would be used to describe the angular motion of the trunk about the longitudinal axis of the kayak. This axis was assumed to pass through the midpoint of the hips.

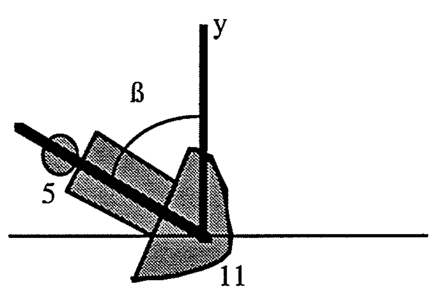


Figure 3-20. The body segment angle (ß) measured in the frontal plane with point 5 being the sternal notch and point 11 being the midpoint between the hip joints.

Position data of body landmarks were also calculated to be used for the torque calculations. The moment arm distances for each force were calculated for the torque program (see Figure 2-14). The horizontal distance in the frontal (z) plane from the midpoint of the hips to the end of the left paddle blade was calculated and represented the moment arm for the lift force created by the paddle. The horizontal distance in the frontal (z) plane from the midpoint of the hips to the center of gravity of the body was calculated and represented the moment arm for the weight of the body. The horizontal distance in the frontal (z) plane from the midpoint of the hip joints to the shoulder joint was calculated and used as the moment arm for the buoyant force. Half the horizontal distance in the frontal (z) plane between the midpoint of the hips and the top of the head was used as the estimate for the moment arm for the drag force.

The angular velocity of the trunk segment was calculated and used in the drag force calculation. The resultant linear velocity of the leading edge of the left paddle blade was calculated and used in the calculation of the lift force. The angular acceleration of the trunk segment about the x axis was also calculated. These velocity and accelerations were calculated by the Peak5 software programs, by differentiating the positional data, once for velocities and twice for accelerations.

Each Peak5 file had to be converted to ASCII format so that the values could be read into the torque calculation program which was written in the Pascal computer language. This conversion of files was accomplished with the use of a program supplied as part of the Peak5 software (Peak Performance Technologies, 1994).

Accuracy Measurements

The accuracy of the position data collected by the dome system was tested by calculating the length of a known object at different positions in the field of view of the cameras. The object measured was the length of a kayak paddle. Six different paddle positions were chosen, two with the paddle above the water, two with the paddle below the water, and two with the paddle half above and half below the water. The length of the paddle was calculated for three consecutive frames of film at each of the six positions. The length of the paddle over the three frame interval was averaged at each of the six positions to yield a total of six paddle length measurements for comparison.

Force Calculations

The four forces to be calculated to analyze the kayak roll were the 1) lift force, 2) weight of the body and kayak, 3) force of drag from the water on the body, and the 4) buoyant force of the water on the body (Alexander, et al., 1994).

The lift force created by the paddle blade was calculated by taking one half of the number obtained by multiplying the following values; a) area of the paddle (measured to be 0.08 m^2), b) coefficient of lift (0.1 if the paddle angle was greater than 10 degrees or else 0.6), c) density of water (estimated as 998 kg/m^3 (Hall, 1995)), and d) the square of the linear velocity of the leading tip of the paddle blade (Alexander, et al., 1994).

The force of gravity was calculated by multiplying the mass of the kayaker and kayak by the acceleration of gravity (-9.81 m/s^2) (Alexander, et al., 1994).

The buoyant force was estimated to be 785 N and acted at the center of buoyancy which was estimated as the midpoint between the hips and shoulder (Alexander, et al., 1994). This value represented only a portion of the weight of the volume of water displaced by the kayaker and kayak since the kayak floated above the water and was not completely submerged.

The drag force created by the water on the body was calculated by taking one half of the number obtained by multiplying the following values; a) area of the body facing the fluid flow (estimated to be 0.238 m^2), b) coefficient of drag (estimated to be 0.4), c) density of water (estimated as 998 kg/m^3 (Hall, 1995)), and d) the square of the linear velocity of the center of mass of the body only (calculated from the Peak5 software) (Alexander, et al., 1994).

Torque Calculations

The torques required to complete the Eskimo roll were calculated by the Pascal program (See Appendix B). The equation including all torques was as follows:

$$T_{unknown} = I\alpha - T_{lift} - T_{Buoyant} + T_{Drag} + T_{Weight}$$

The unknown torque to be determined was the combination of the known torques including: 1) angular acceleration of the rotating kayaker multiplied by the moment of inertia of the kayak and kayaker, 2) the calculated lift force multiplied by the moment arm for the lift force (d2), 3) the buoyant force multiplied by the moment arm for the buoyant force (d4), 4) the calculated drag force multiplied by the moment arm for the drag force (d1), and 5) the weight multiplied by the moment arm for the weight (d3) (Alexander, et al., 1994).

CHAPTER 4

RESULTS

Video Results of Method

The camera positioning behind the plastic domes resulted in the elimination of the refraction due to the water as shown in Figure 4-1. The lines on the refraction correction tool were aligned even when the tool was half submerged in the water. Note that the alignment was not perfect.

The cameras positioned at water level allowed for the videotaping of the movements of the subject both above and below the water (see Figure 4-2). The cameras then recorded the entire movements of the subjects as they performed the Eskimo roll (see Figure 4-3).

The motion of the waves in the pool resulted in many of the trials being partially or totally obscured when viewed through the cameras. These obscured views were similar to the views recorded in earlier studies (see Figure 3-1). The wave problem made it difficult to align the camera exactly at water level so that the waterline would appear as a thin line across the middle of the videotape.

Figure 4-1. The refraction correction tool used to find correct camera placement.

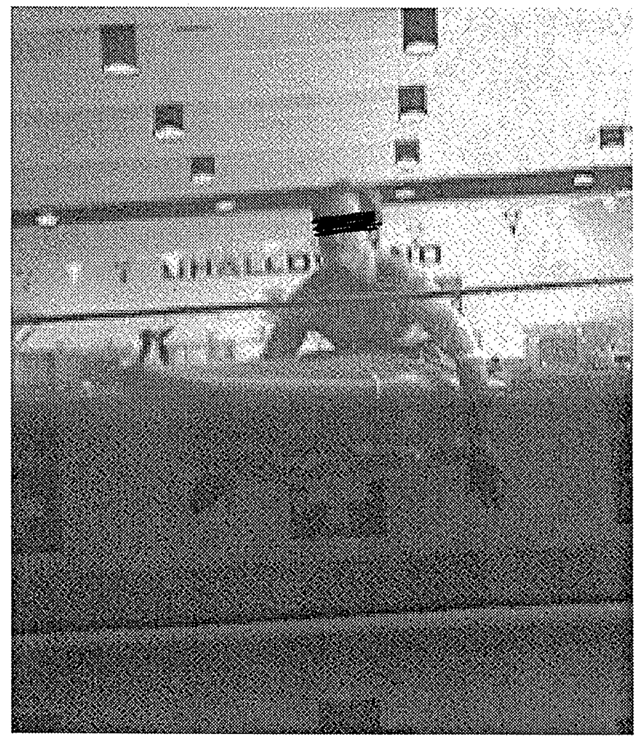


Figure 4-2. A simultaneous view of the above the water and below water fields of view as recorded by the videocamera.

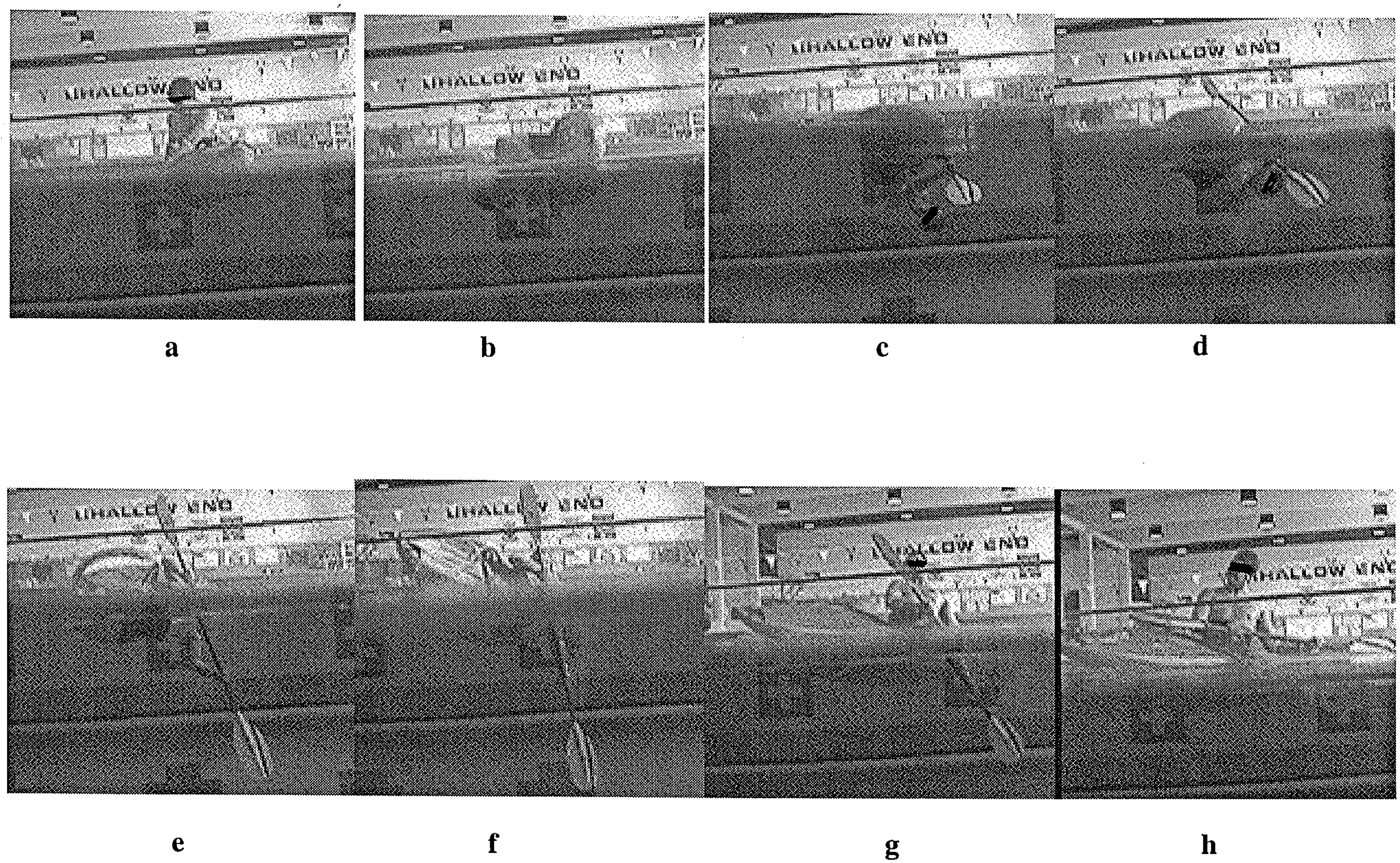


Figure 4-3. The entire Eskimo roll was captured by the video cameras as illustrated by the still photograph sequence taken from the videotape.

Accuracy of Method

The calculated length of the paddle of Subject 1 is shown in Figure 4-4 for the six different positions in the field of view. The two below water positions (2.09 m and 2.08 m) show a larger calculated length than the above water positions (2.01 m and 1.99 m) but show little variation within each group. The paddle position with half of the paddle submerged in the water shows greater variation and varied from 1.99 m to 2.10 m. The actual length of the paddle was 2.04 m.

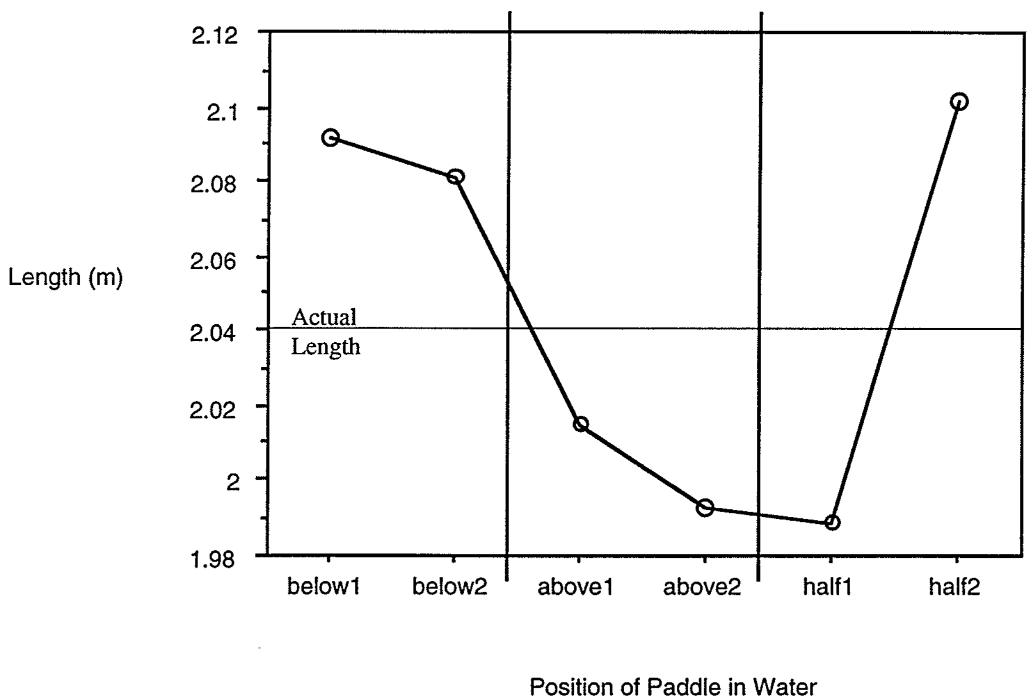


Figure 4-4. The calculated paddle length with the paddle held above the water, below the water, and in a half- submerged position at different places in the field of view of the cameras.

Subjects

The mass of the two subjects who participated in this study was recorded. The mass of Subject 1 was 83.5 kilograms and the mass of Subject 2 was 84.4 kilograms. These mass values were used in the torque calculation program to calculate the torque due to the weight of the body that was acting at some distance away from the axis of rotation and to calculate the magnitude of the buoyant force.

The mass of the kayak used in this study was 17.9 kilograms.

Kinematics of the Kayak System

The digitized trial for Subject 1 included 117 frames of tape for a total time of 1.95 seconds. The trial for Subject 2 included 144 frames of tape for a total time of 2.4 seconds. This total time includes a pause in preparation before executing the roll and a period of approximately 4 frames at the completion of the roll when the subjects were upright. The trunk segment for Subject 1 was observed to exit the water at approximately frame 69 and at frame 102 for Subject 2. The paddle movement into the sweep phase was first observed to start on frame 15 for Subject 1 and on frame 50 for Subject 2. The times from the start of the sweep phase to the completion of the roll (excluding the extra frames at the end of the skill) were 1.65 seconds for Subject 1 and 1.52 seconds for Subject 2.

It was noted that Subject 1 exited the water with a more fluid motion that resulted in less anterior and lateral translation of the kayak in the pool. The kayak showed more lateral and anterior movement when Subject 2 completed the roll. The left paddle blade of Subject 2 was swept deeper into the pool than Subject 1 but the paddle blade of both subjects swept downward in the pool at the end of the sweep phase.

Figure 4-5 illustrates the stick figure representation of the set up position for both subjects. Note that the left paddle position of Subject 2 started deep in the water. Figure 4-6 represents the trajectory of the paddle in the sweep phase. The paddles were swept from the bow of the kayak to the stern of the kayak. The trajectory is represented by the line following the path of the lower paddle blade in each picture. Figures 4-7 and Figure 4-8 represent the recovery position of each subject. Note that the trunk had extended backwards along the kayak's upper surface.

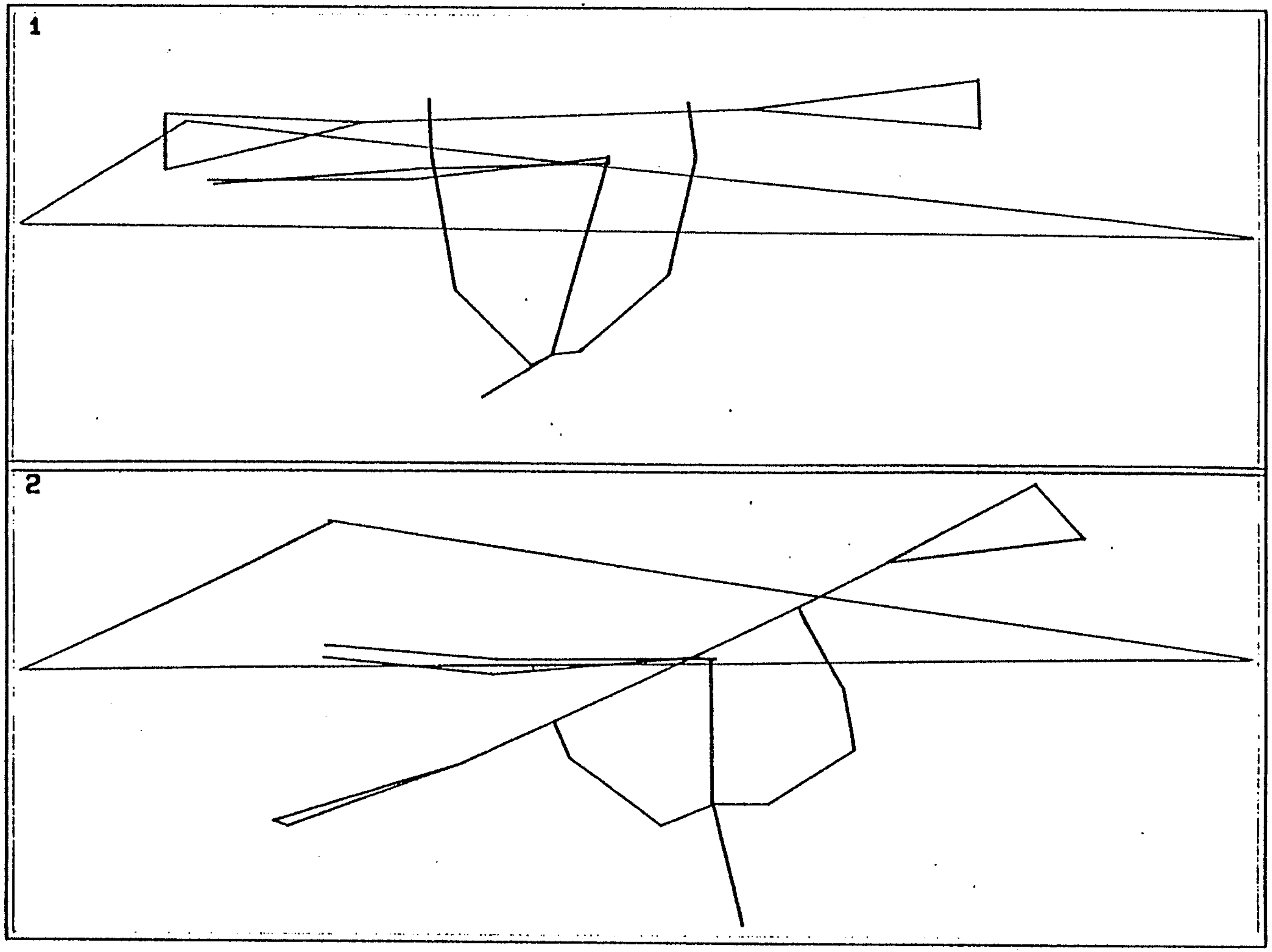
Calculated Angles

The two angles that were calculated by the Peak5 software to be used later in the torque calculation program were 1) the angle of the trunk segment in the frontal plane, and 2) the angle of the paddle blade with the horizontal.

Trunk Angle

The trunk angle (as defined in Figure 3-20) was equal to zero when the subject was sitting upright in the kayak and increased in magnitude as the subject rotated to their right about the x-axis. The angle of 180 degrees would correspond to the kayaker being in an inverted position. The magnitudes of this trunk angle are shown in Figure 4-9.

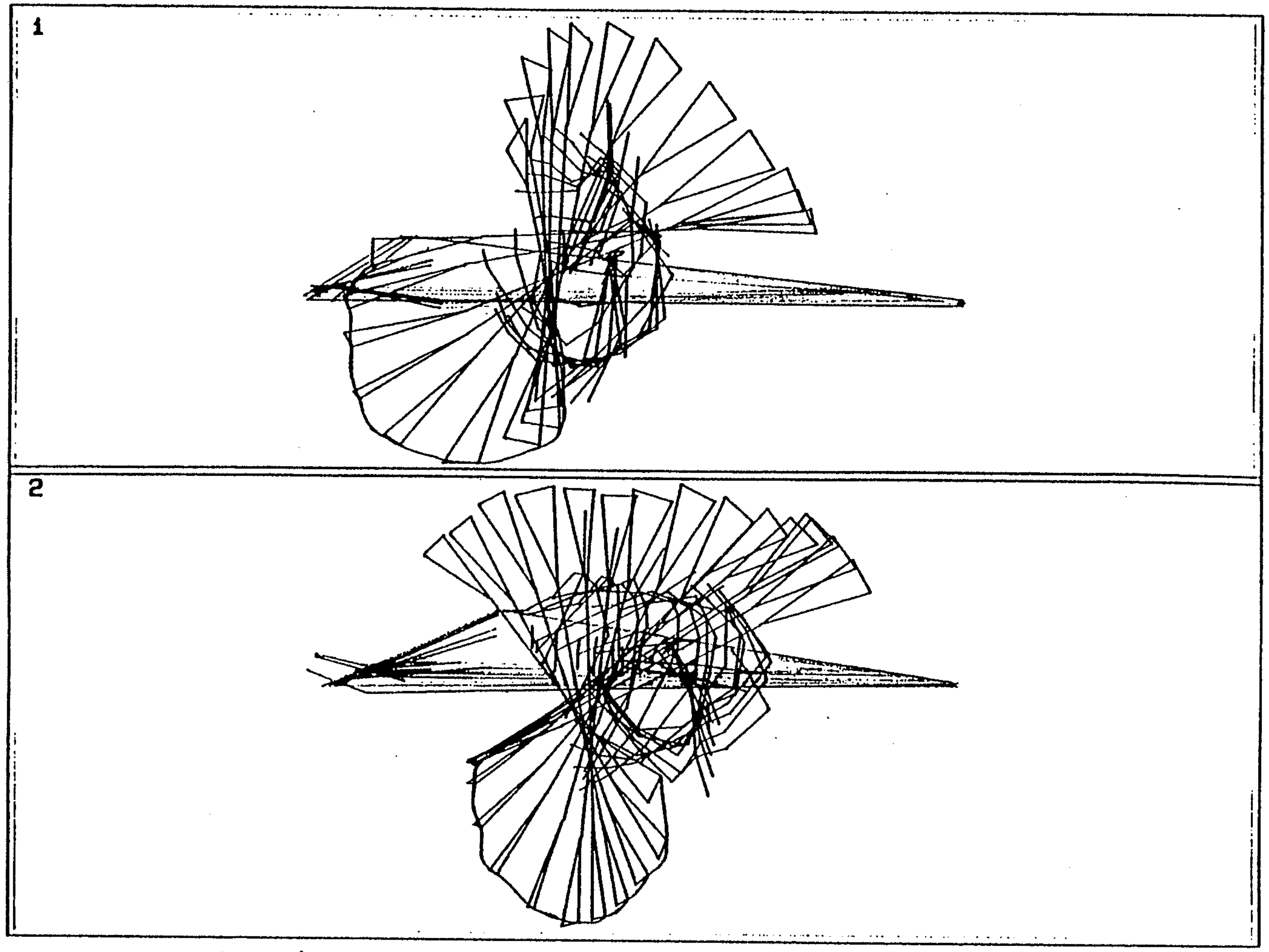
Subject 1 had a starting angle of magnitude 204 degrees and finished with the trunk angle of 368 degrees. This indicated that this subject started with his trunk 24 degrees past the vertically down



1 Subject 1
April96

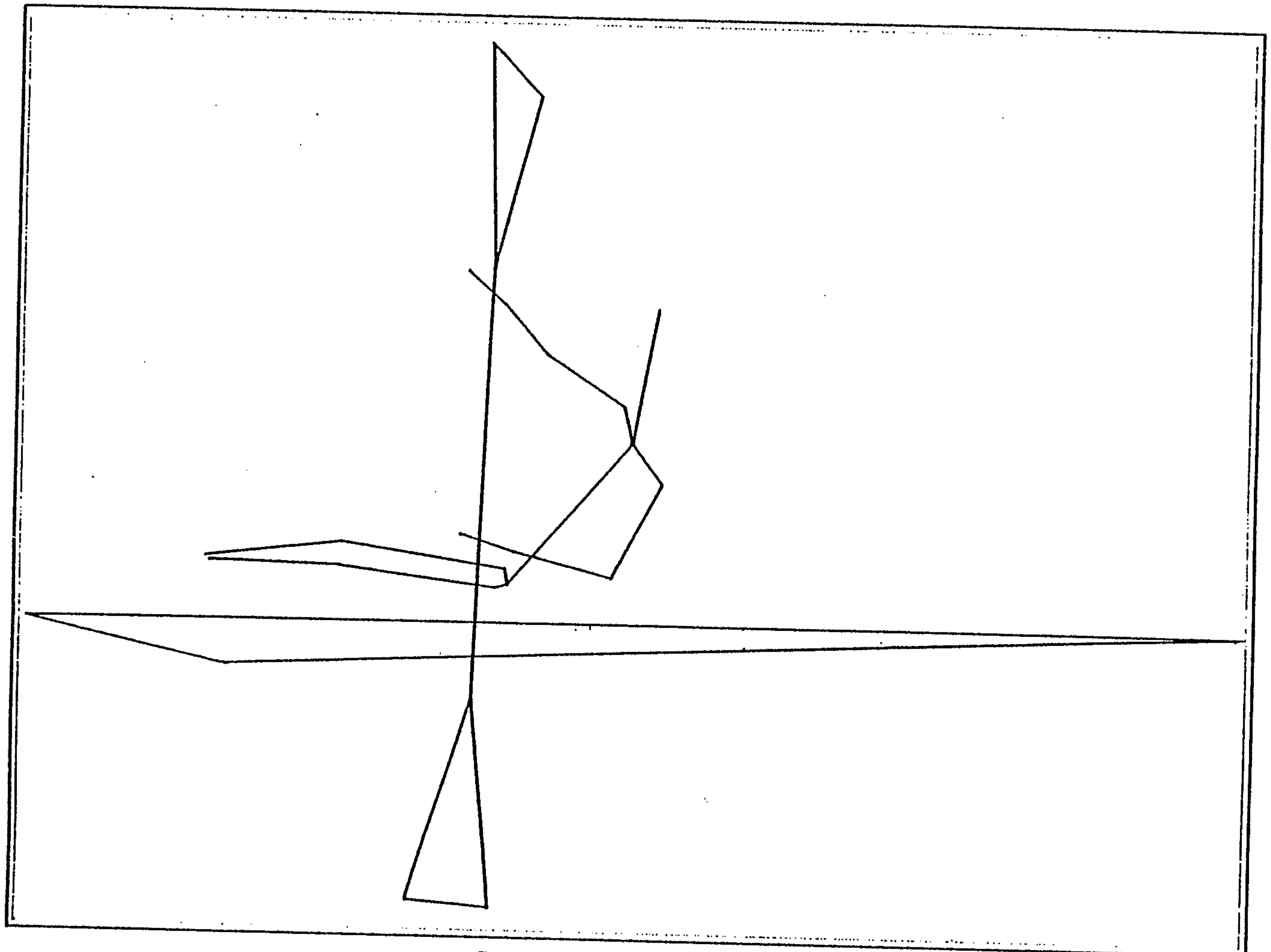
2 Subject 2
April96

Figure 4-5. The set up position for the Eskimo roll of both subjects. Note the low paddle position for Subject 2.



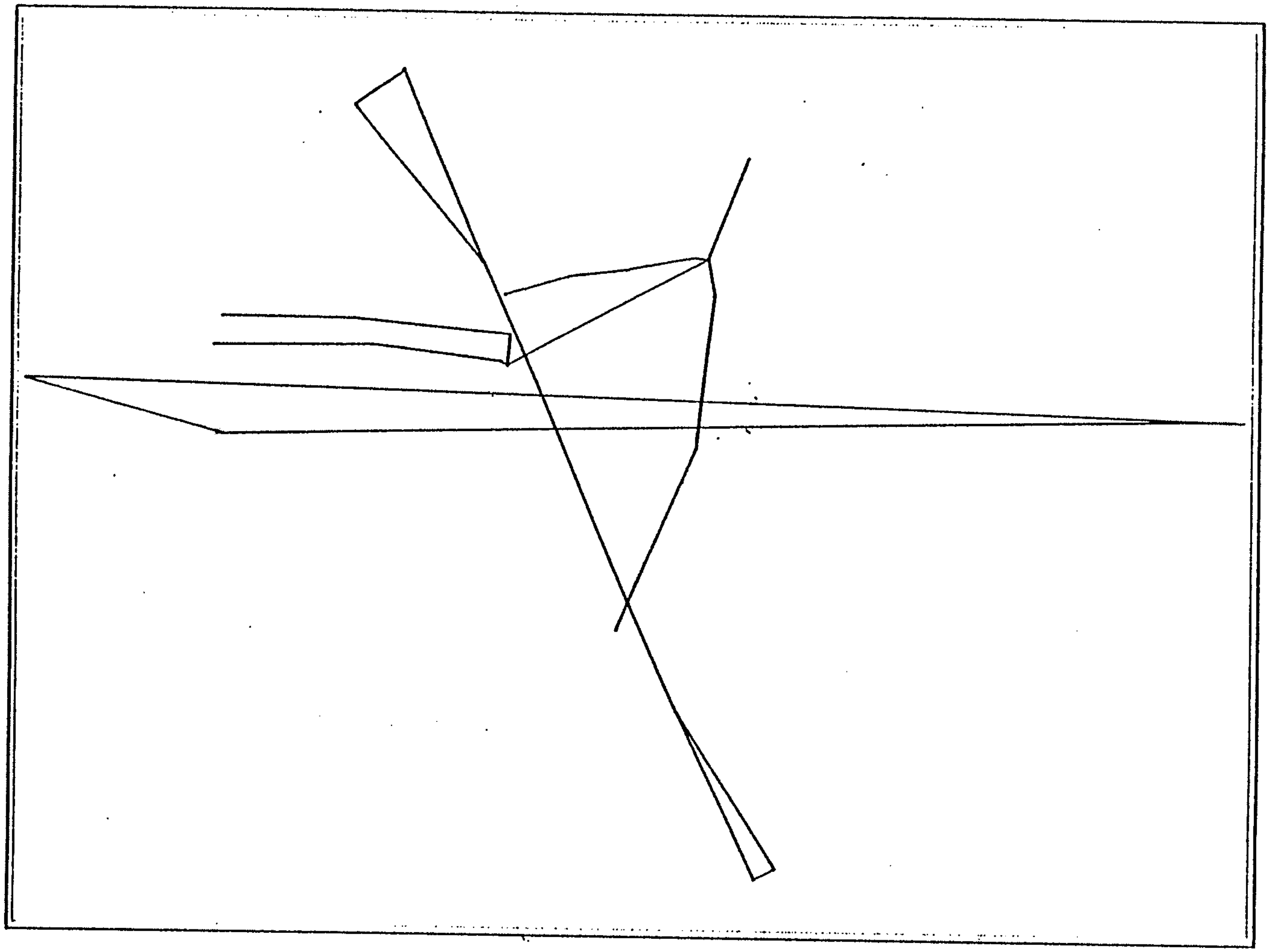
1 Subject 1   2 Subject 2

Figure 4-6. The trajectory of the left paddle blade for both subjects. The path of the blade is shown on each diagram.



Subject 1

Figure 4-7. The recovery position of Subject 1. Note the back extension.



Subject 2

Figure 4-8. The recovery position of Subject 2. Note the back extension.

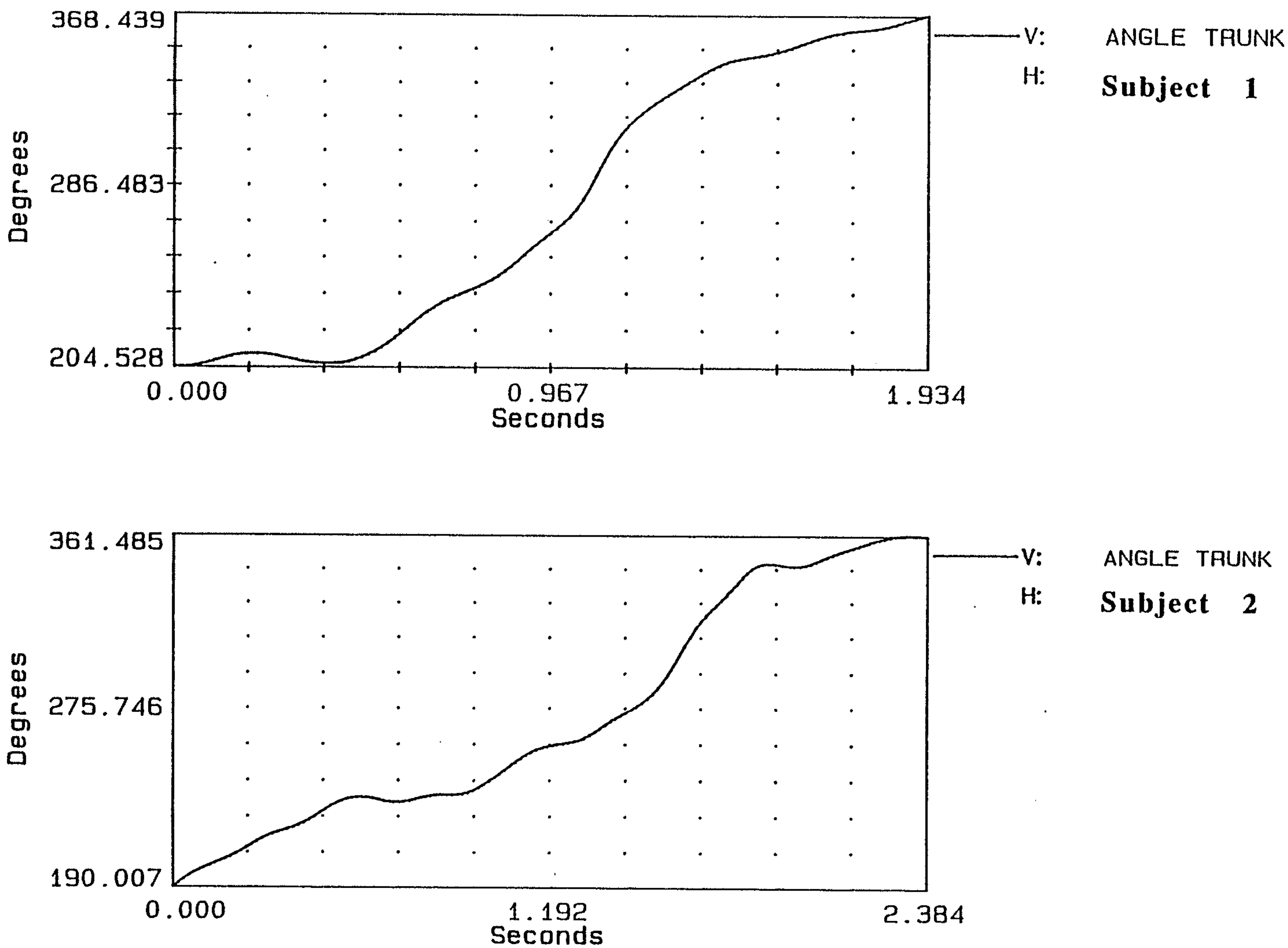


Figure 4-9. The angle between the vertical axis and the trunk segment as measured in the frontal plane.

position of 180 degrees and flexed in the direction of the roll. This angle increased as the subject rotated upright to the vertical position. The total displacement was 164 degrees to rotate the subject from the inverted position to the upright position.

Subject 2 had a starting angle of magnitude 190 degrees and finished with the trunk angle of 360 degrees. This indicated that this subject started with his trunk 10 degrees past the vertically down position and flexed in the direction of the roll. This angle also increased as the subject rotated upright to the vertical position. The total displacement was 170 degrees to rotate the subject from the inverted position to the upright position.

Paddle Angle

The paddle angle (as illustrated in Figure 3-19) was calculated to determine the angle of attack of the paddle blade. This would help determine the lift producing capability of the paddle (see Figure 4-10)..

The paddle blade started in the water for Subject 2 but out of the water for Subject 1. The angle of attack of the paddle blade remained small for most of the paddle movement but increased for each subject as the roll was nearing completion and the paddle was being removed from the water. Subject 1 maintained the paddle angle between 1 and 11 degrees for most of the paddle sweep while Subject 2 had a slightly higher paddle angle that ranged between 10 and 20 degrees for the sweep phase.

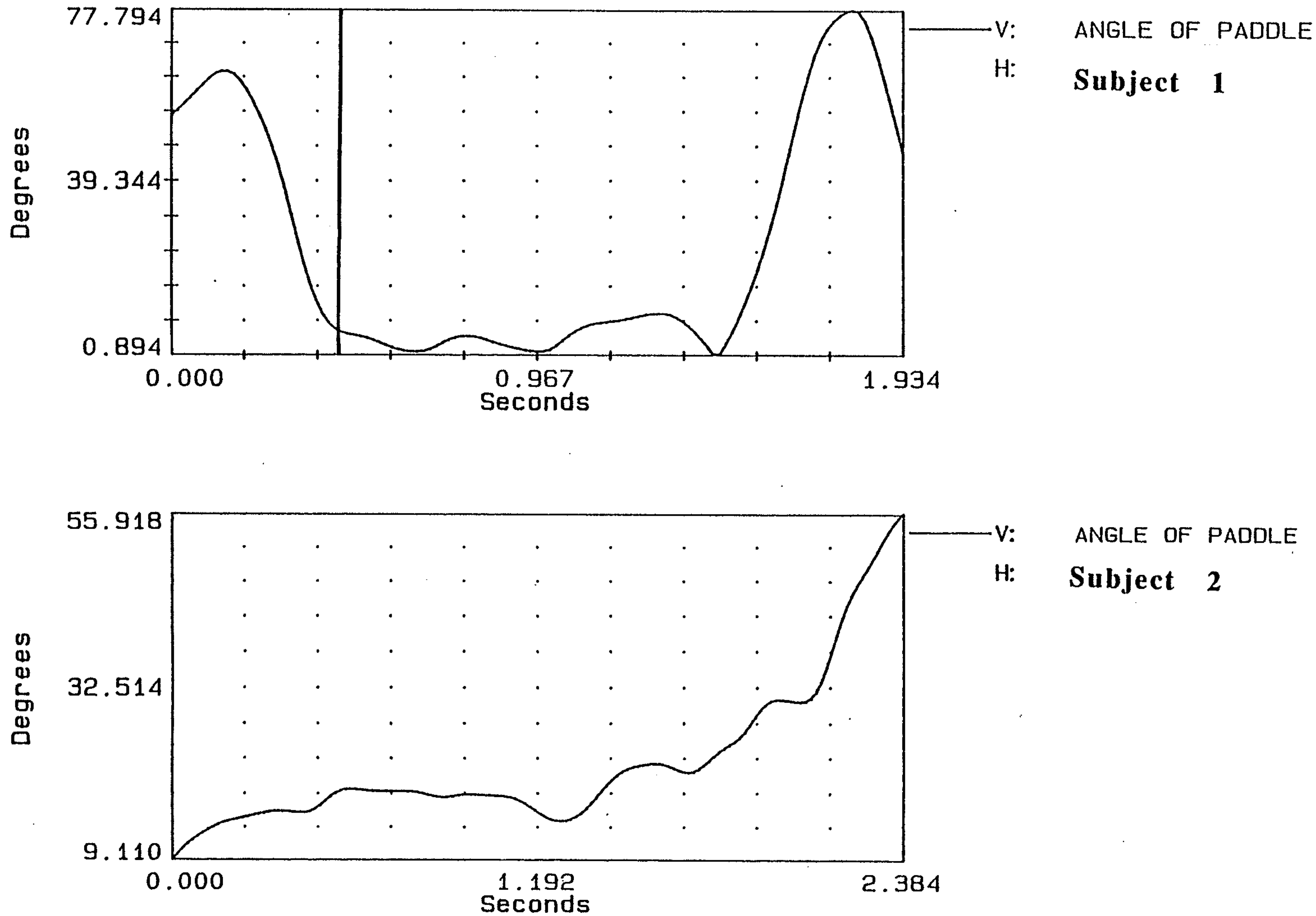


Figure 4-10. The attack angle of the left paddle blade. The solid vertical line on graph 1 represents when the blade first entered the water.

Other Angular Measurements

The previously defined trunk angle (see Figure 3-20) was used to calculate the angular velocity and angular acceleration of the trunk segment in the frontal plane. These values were required by the torque calculation program.

Trunk Angular Velocity

The trunk angular velocities are shown in Figure 4-11 and are measured in degrees per second. Angles increasing in the positive direction indicate that the angular velocities were in a direction to right the subject. The angular velocity for both subjects peaked as their trunk segments were exiting the water. Subject 1 showed one large peak angular velocity that occurred at frame 66 and was 345 degrees per second. Subject 2 had a lower peak angular velocity that only reached 268 degrees per second.

Trunk Angular Acceleration

The trunk segment angular accelerations are shown in Figure 4-12 and are measured in degrees per second squared. Angular accelerations becoming increasingly positive are in the direction to return the subject to the upright position. Subject 1 showed a greater positive acceleration (1455 degrees per second^2) than did Subject 2 (1370 degrees per second^2). These positive angular accelerations occurred just prior to the trunk exiting the water and were followed by a large negative acceleration. The large acceleration peaks near the end of each roll were omitted from the analysis since the roll had been completed by this time and the large

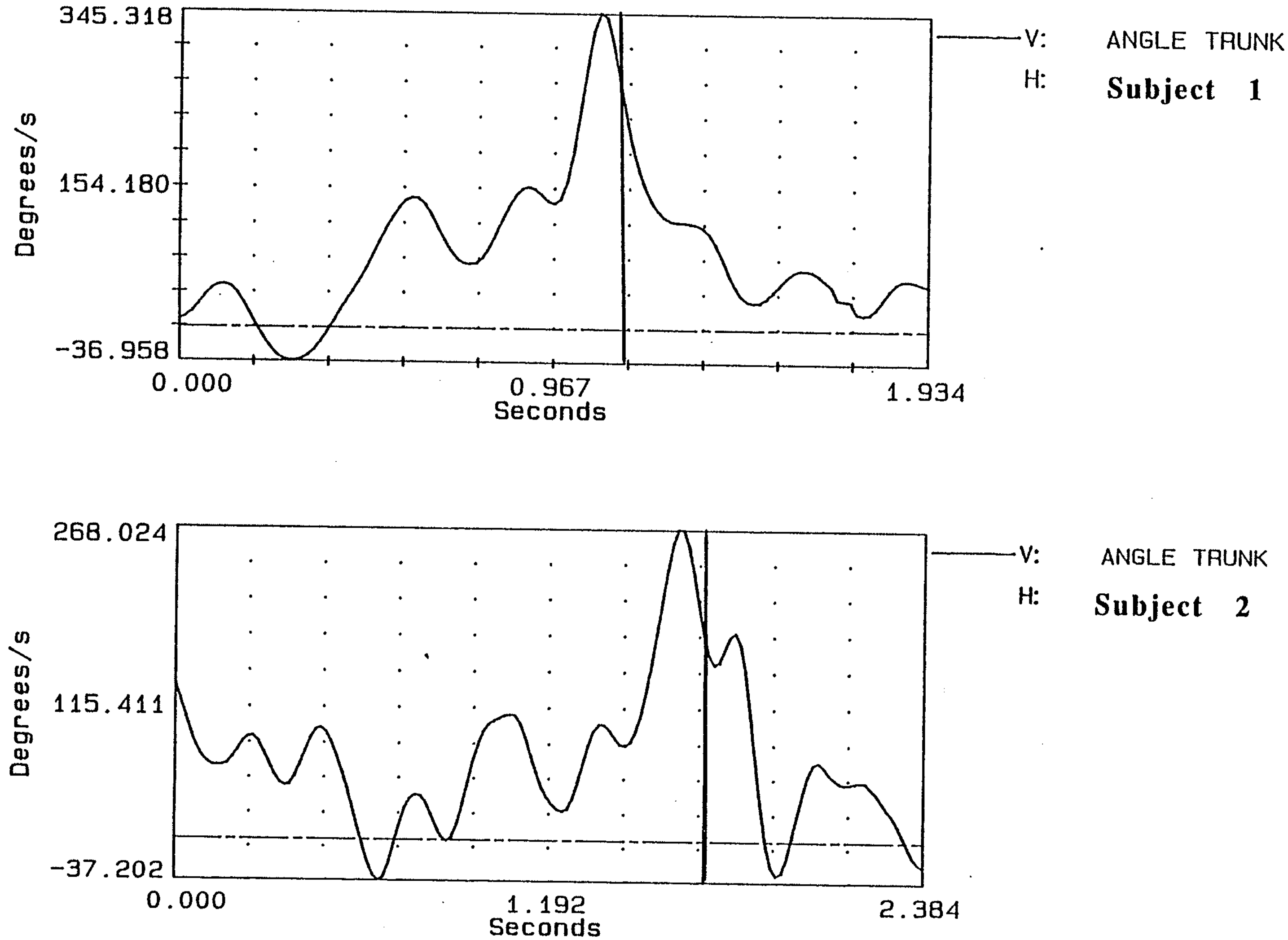
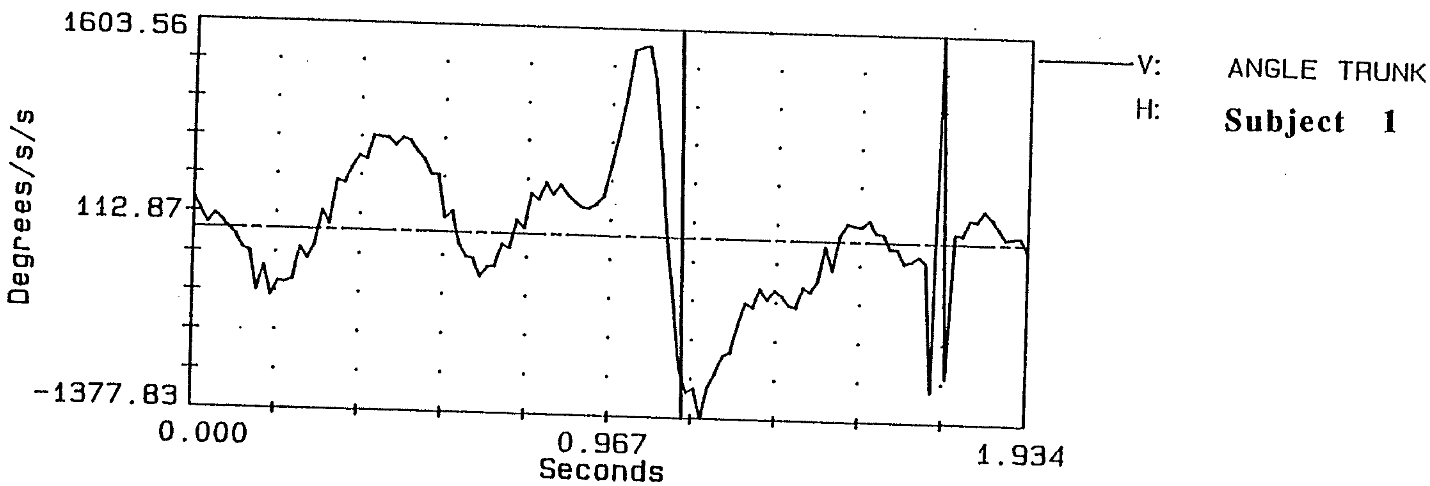


Figure 4-11. The angular velocity of the trunk in the frontal plane. The solid vertical line represents when the body segment exited the water.



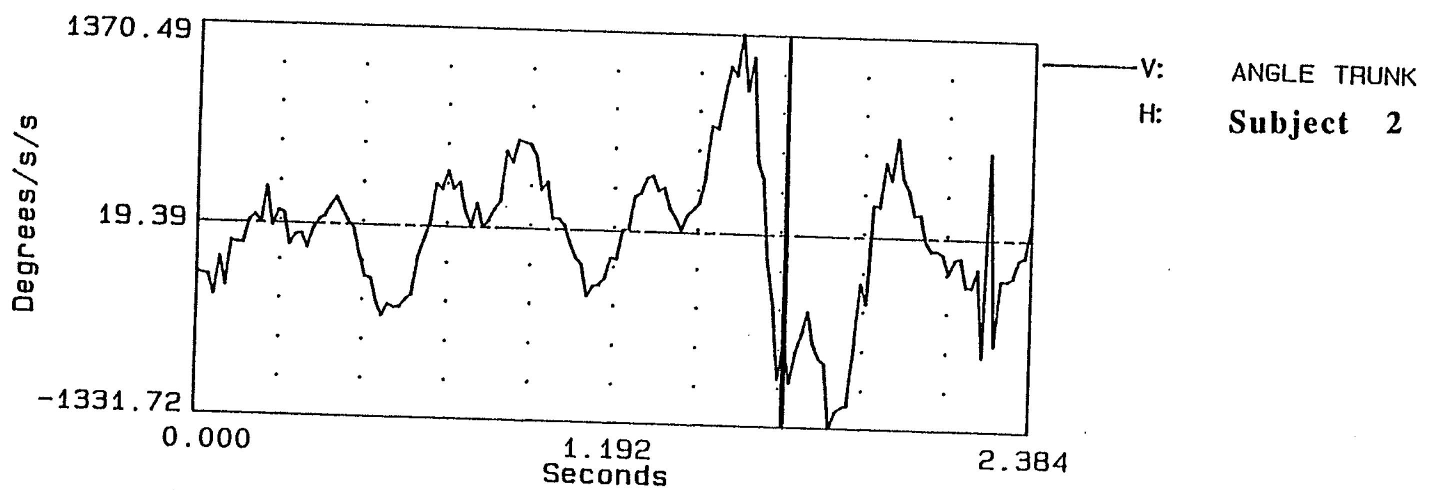


Figure 4-12. The angular acceleration of the trunk segment in the frontal plane. The solid vertical line represents when the body segments exited the water.

accelerations were due to the difficulty with tracking the slow moving trunk segment.

Paddle Linear Velocity

The magnitude of the linear velocity of the paddle blade relative to the kayak was calculated for the left paddle blade of both subjects (see Figure 4-13). The linear velocity measured was for the leading edge of the left paddle blade. Subject 1 and Subject 2 both had similar magnitudes of peak linear velocities of just over 3 m/s but the peak for Subject 1 occurred much earlier in the roll during the sweep phase.

Moment Arm Lengths

Moment arm lengths in the frontal plane were calculated for the different torque producing forces. The moment arms calculated for each subject included the moment arms for the lift, drag, buoyant and weight forces. These moment arm lengths were measured in meters and varied in length depending on the subject's body position.

The moment arm lengths are shown in Figure 4-14 for Subject 1 and in Figure 4-15 for Subject 2. The largest moment arm for both subjects was the paddle moment arm followed by the drag force moment arm, buoyant force moment arm, and the weight force moment arm. The paddle moment arm was at times more than 1 meter greater in length than the next largest moment arm.

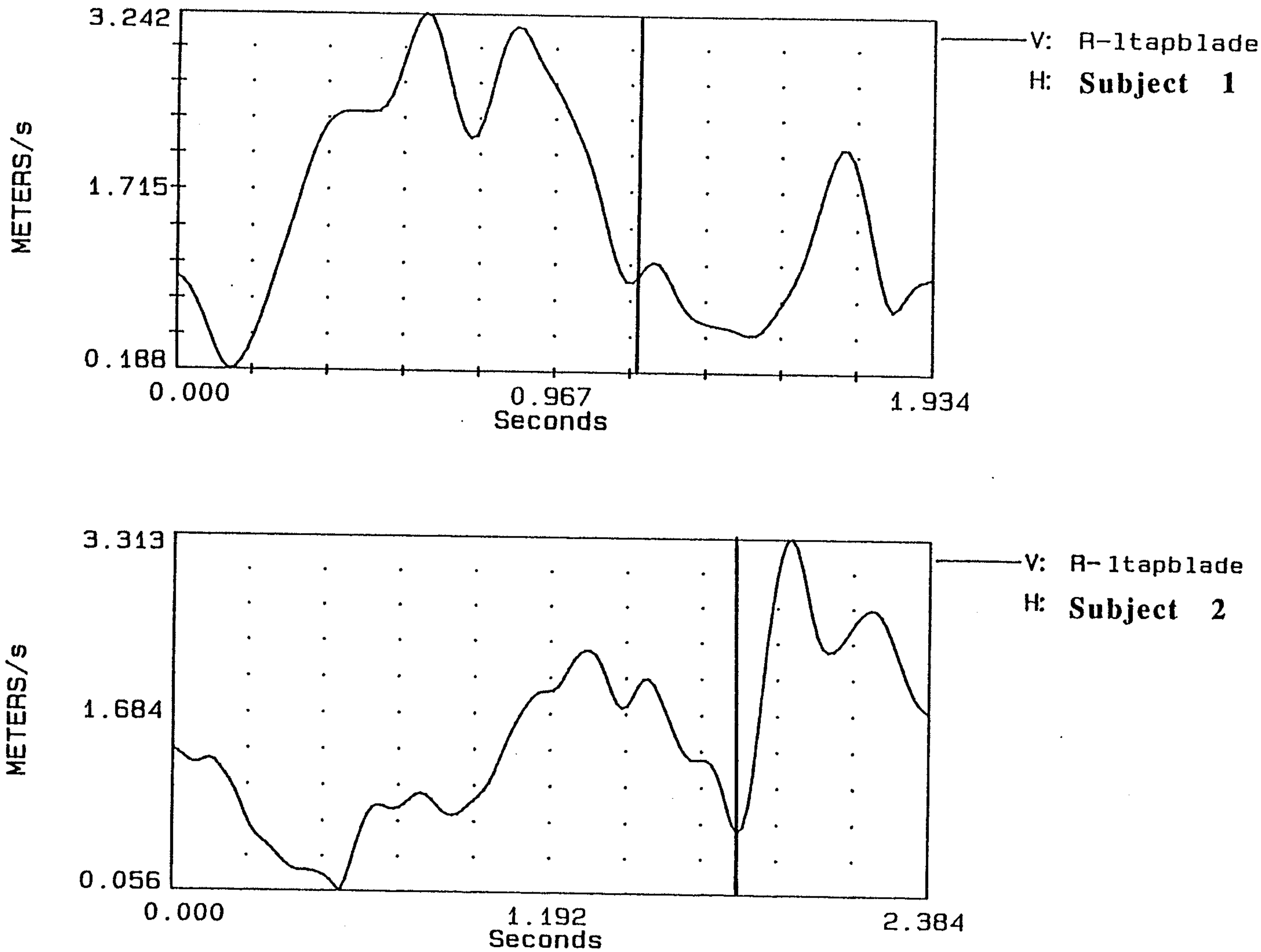


Figure 4-13. The resultant linear velocity of the lead edge of the left paddle blade. The solid vertical line represents when the sweep phase ended.

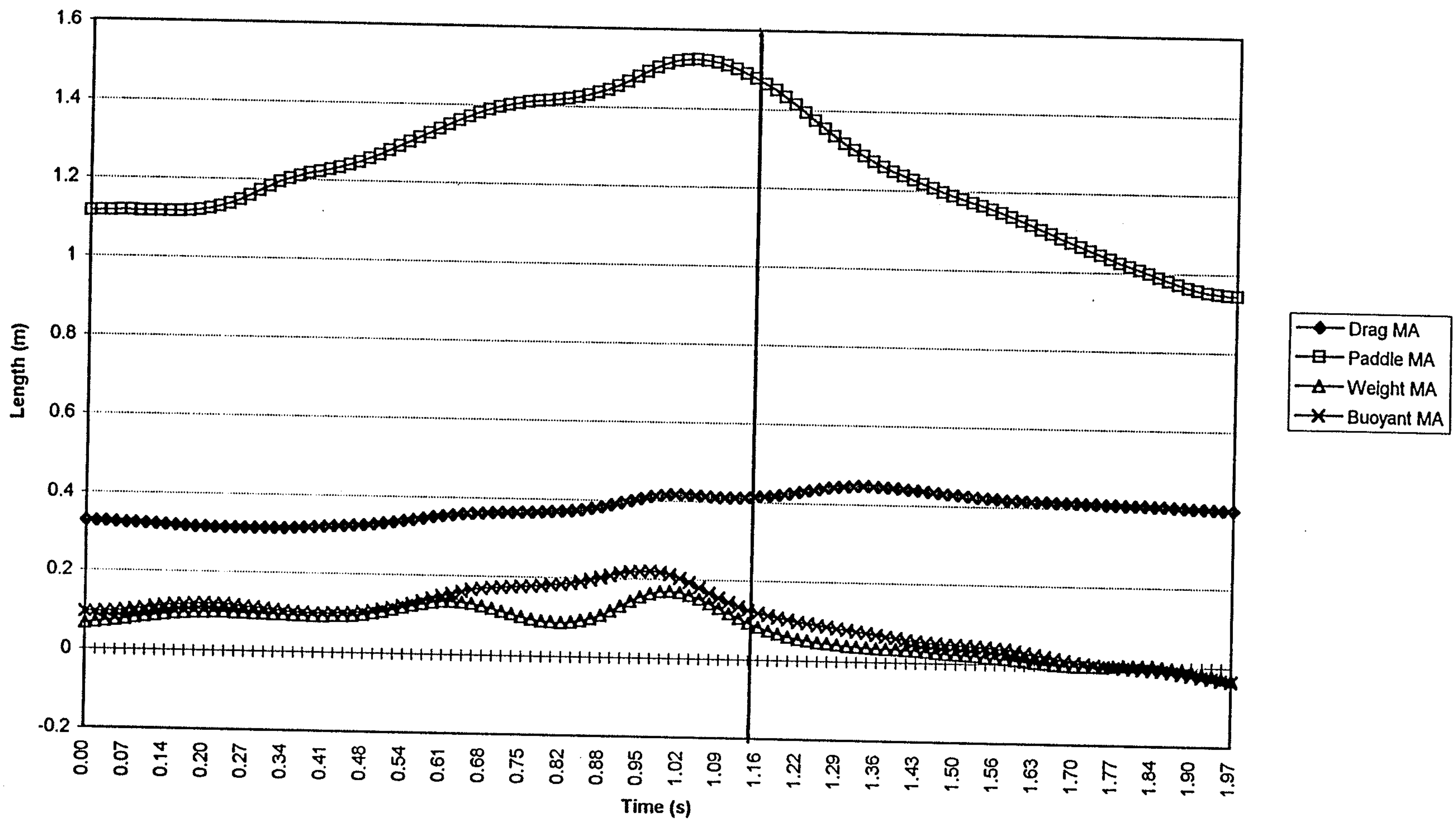


Figure 4-14. The individual moment arm lengths calculated for Subject 1. The vertical line represents when the body exited the water.

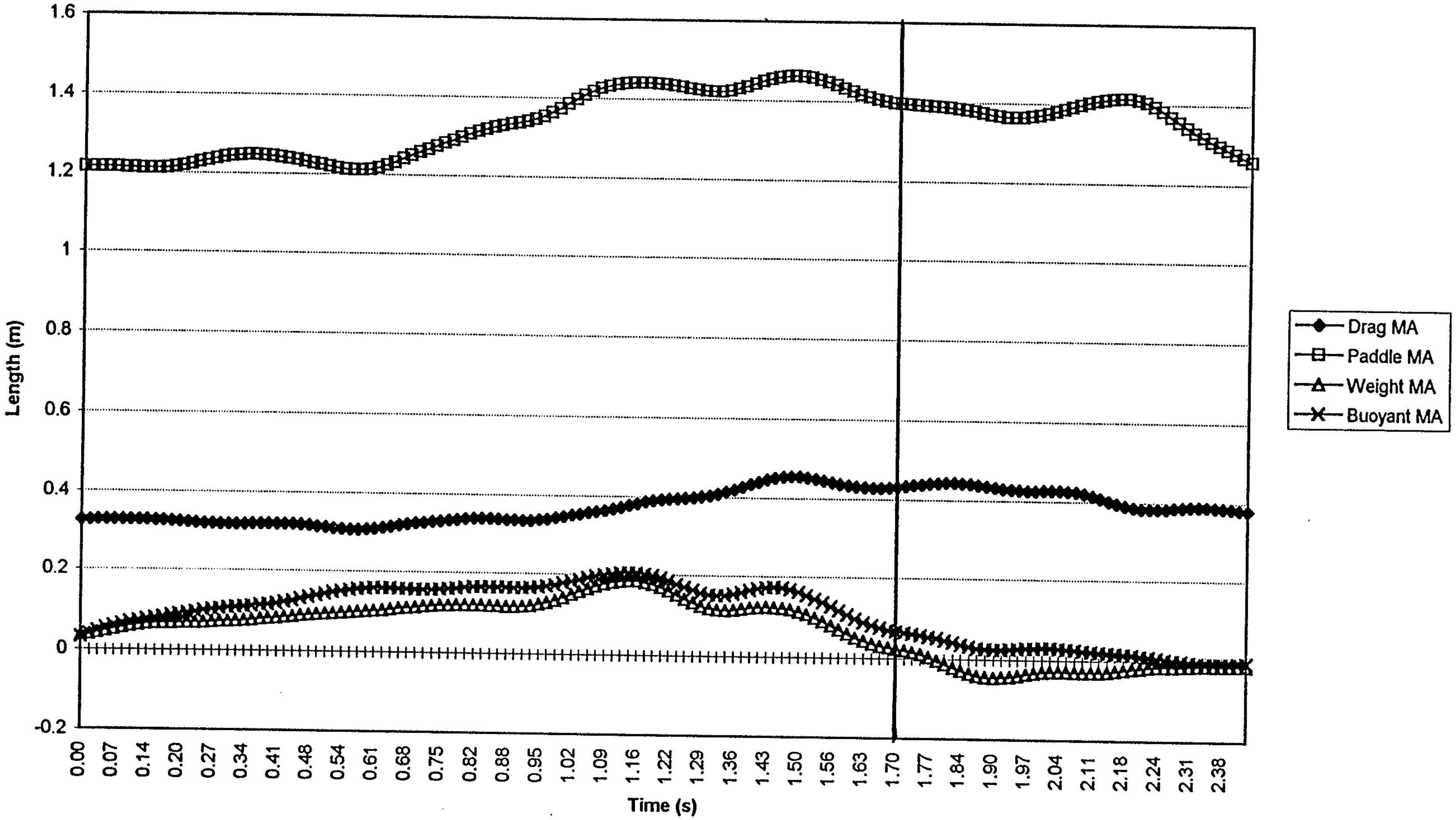


Figure 4-15. The individual moment arm lengths calculated for Subject 2. The vertical line represents when the body exited the water.

Individual Torques

The torques (measured in Nm) produced by each individual force component are shown in Figure 4-16 for Subject 1 and Figure 4-17 for Subject 2. The greatest variability can be seen in the torque due to the angular acceleration of the trunk segment (IAlpha) which reached peak magnitudes of -295 Nm for Subject 1 and -323 Nm for Subject 2. The remaining torques for the drag, lift, weight and buoyant forces remained at lower magnitudes and did not exceed a magnitude of 200 Nm for both subjects. The one exception was that the lift torques due to the paddle for Subject 1 were much larger than those for Subject 2. The peak lift torque for Subject 1 was -382 Nm and only -52 Nm for Subject 2.

Required Torque

The unknown additional torque that was required to right the kayak are shown in Figure 4-18 for Subject 1 and Figure 4-19 for Subject 2. These torque values, measured in Nm, represented the additional torque that must be applied about the long axis of the kayak to right the kayak. The magnitude of the peak torque for Subject 1 was -439 Nm and the peak torque for Subject 2 was -356 Nm. The torque values for both subjects changed from a negative torque to a positive torque just prior to the exit of the trunk from the water. The torques then returned to the negative values as the roll was completed.

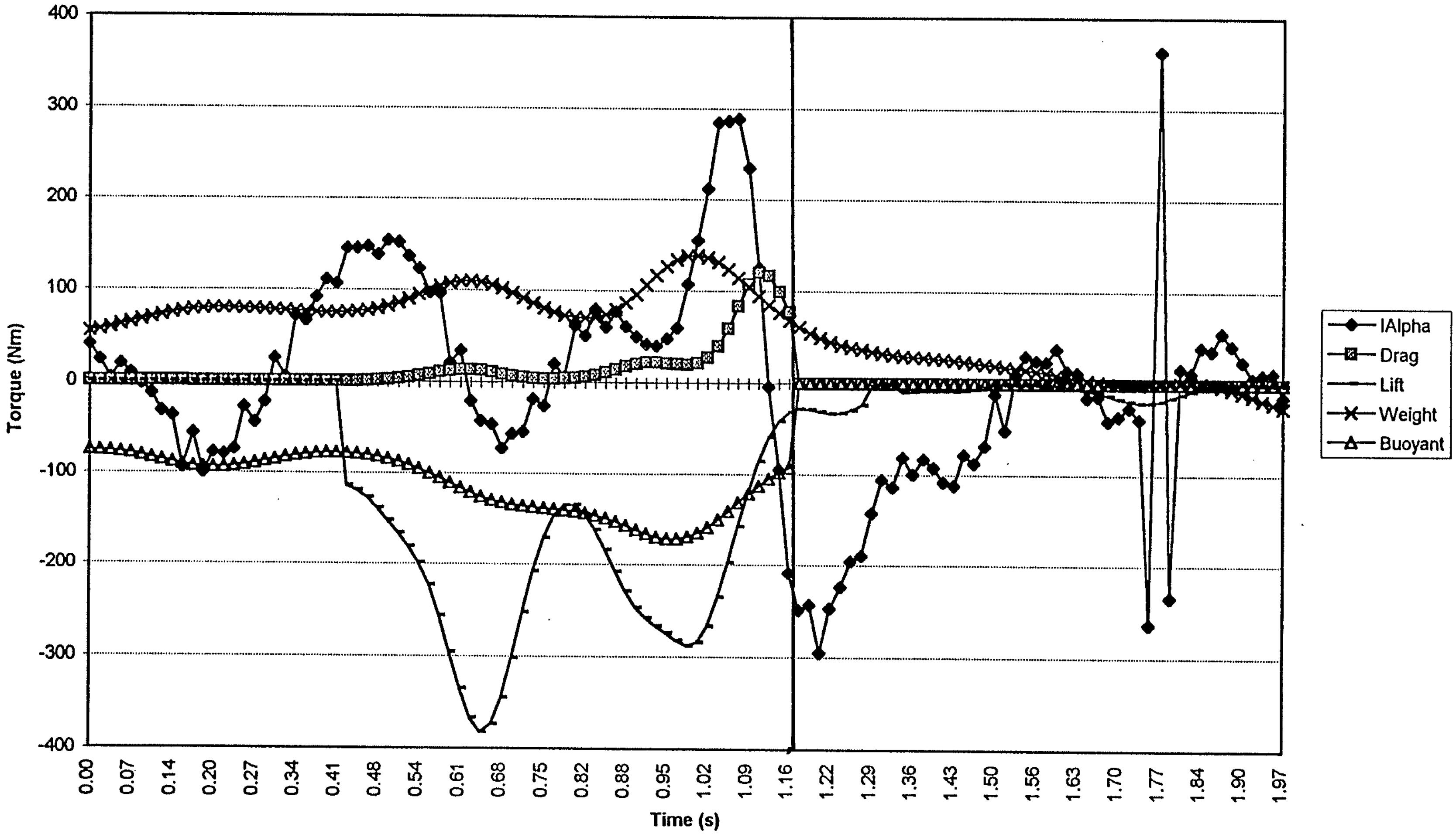


Figure 4-16. The known individual torques calculated for Subject 1 with the IAlpha torque representing the net torque about the long axis of the kayak. The negative torque values represent righting torques. The vertical line represents when the body exited the water.

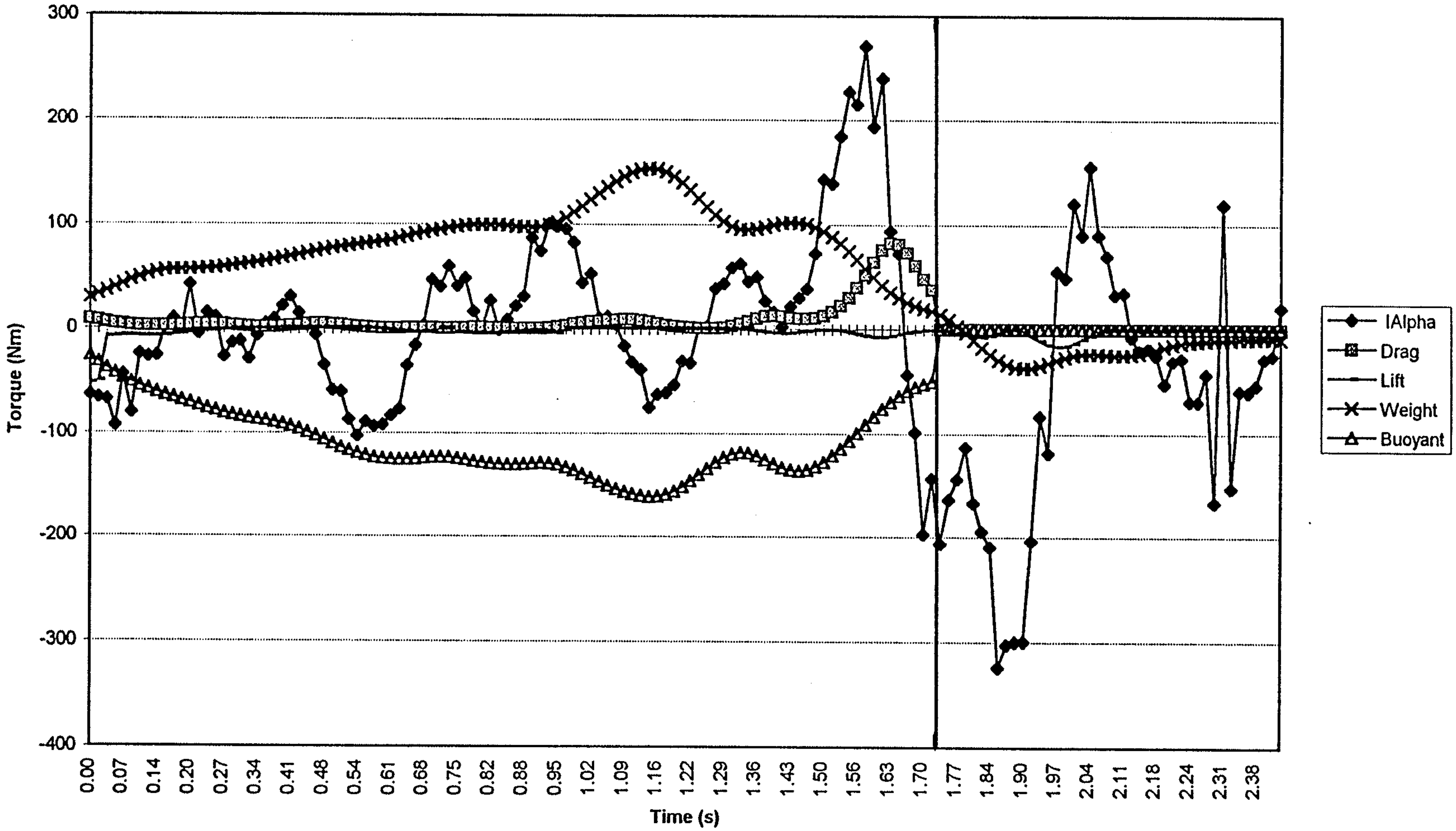


Figure 4-17. The known individual torques calculated for Subject 2 with the IAlpha torque representing the net torque about the long axis of the kayak. The negative torque values represent righting torques. The vertical line represents when the body exited the water.

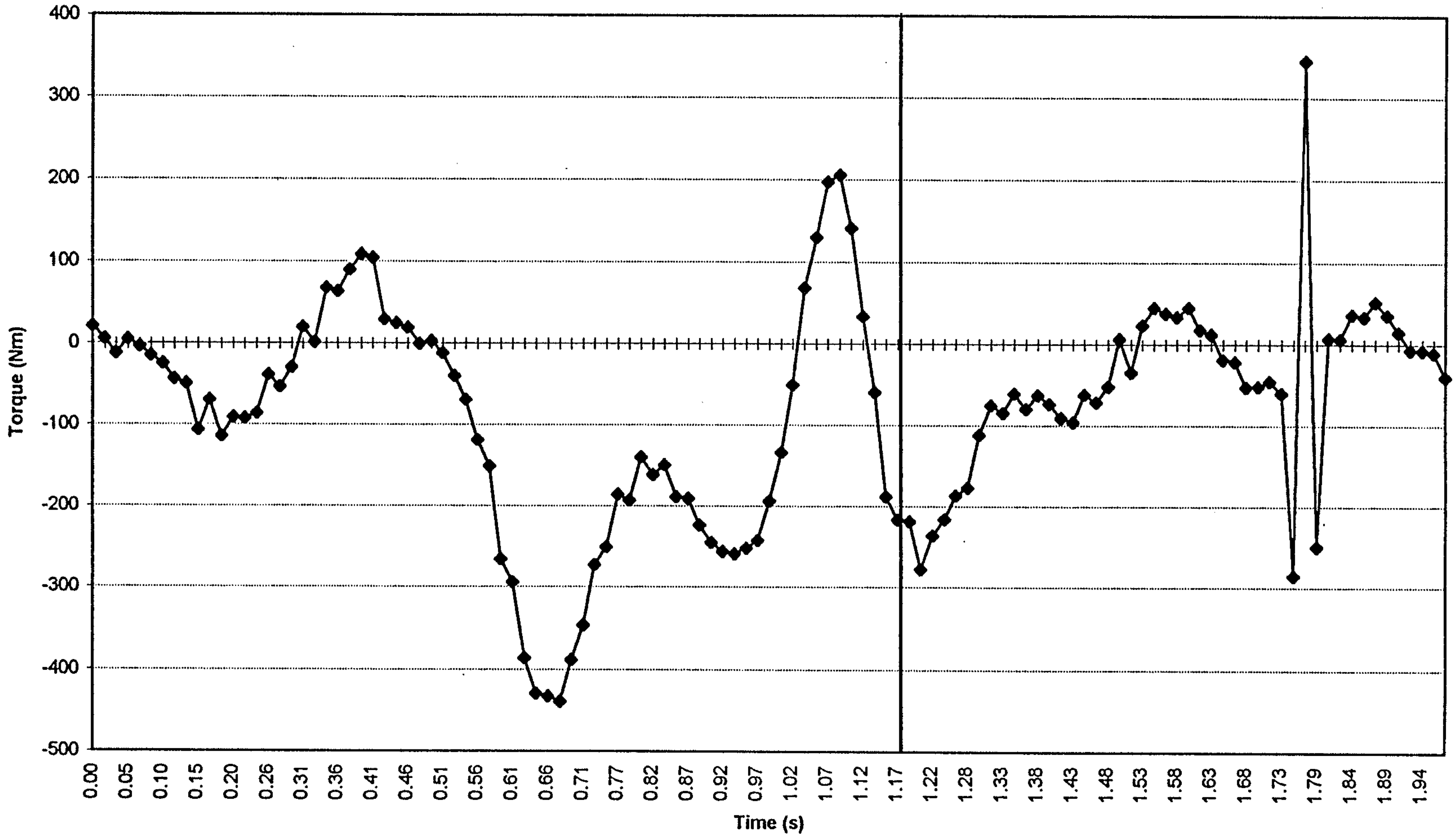


Figure 4-18. The unknown torque, calculated for Subject 1, that must be produced about the long axis of the kayak to right the kayak. The vertical line represents when the body exited the water.

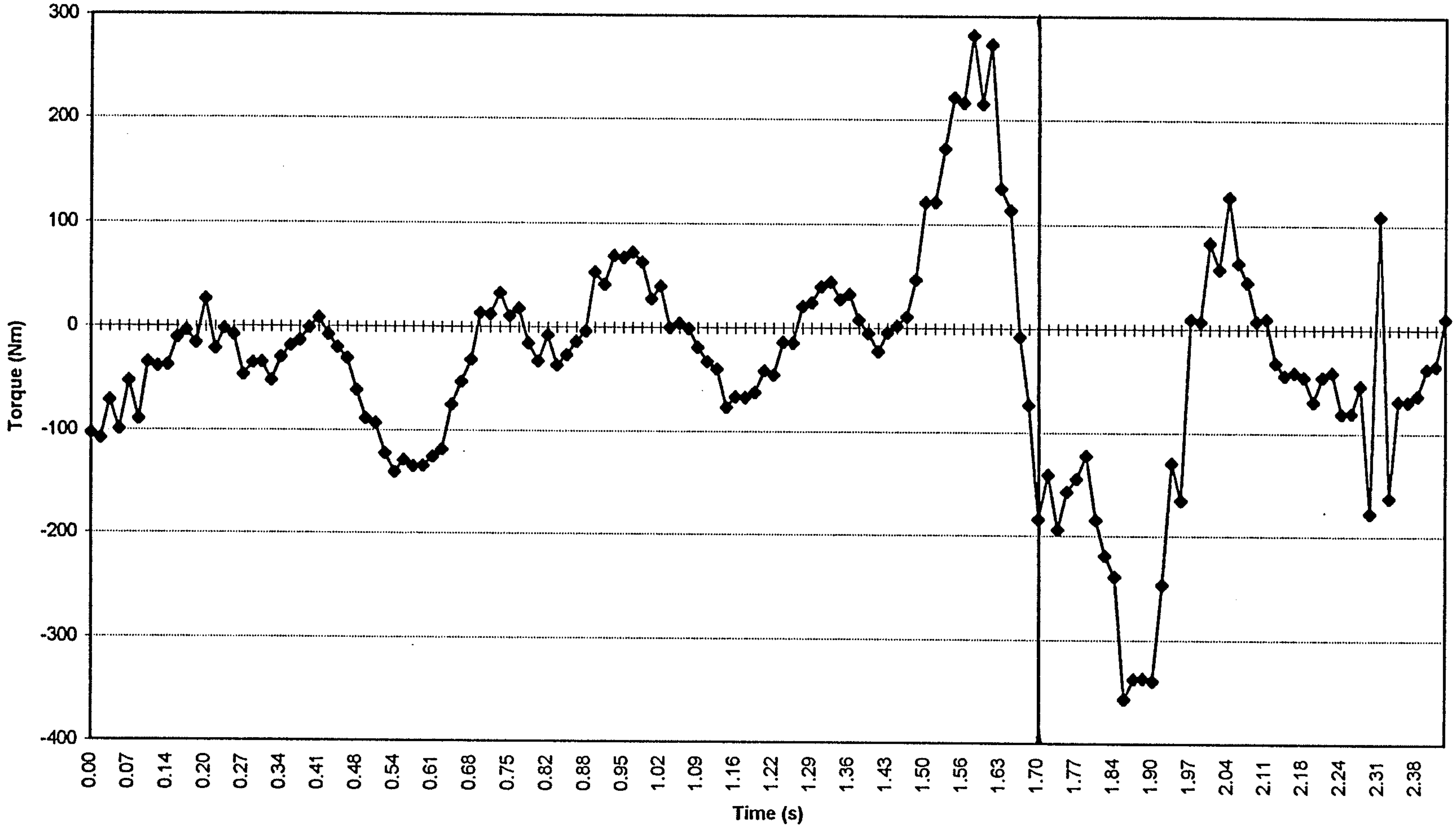


Figure 4-19. The unknown torque, calculated for Subject 2, that must be produced about the long axis of the kayak to right the kayak. The vertical line represents when the body exited the water.

Paddle Forces

The force that would be required on the paddle to create the additional required torque is shown in Figure 4-20 for Subject 1 and Figure 4-21 for Subject 2. These forces followed the same trends as was seen in the paddle torque graphs. The peak force for Subject 1 was larger than Subject 2 and was -316 N compared to Subject 2 whose peak forces reached -259 N. An increasingly positive peak force was observed for both subjects prior to their trunk exiting the water which was followed by a change to a negative force. The large peak forces at the end of each role was again omitted from the analysis since this was the artifact that resulted from the difficulty with digitizing the slow moving trunk segment.

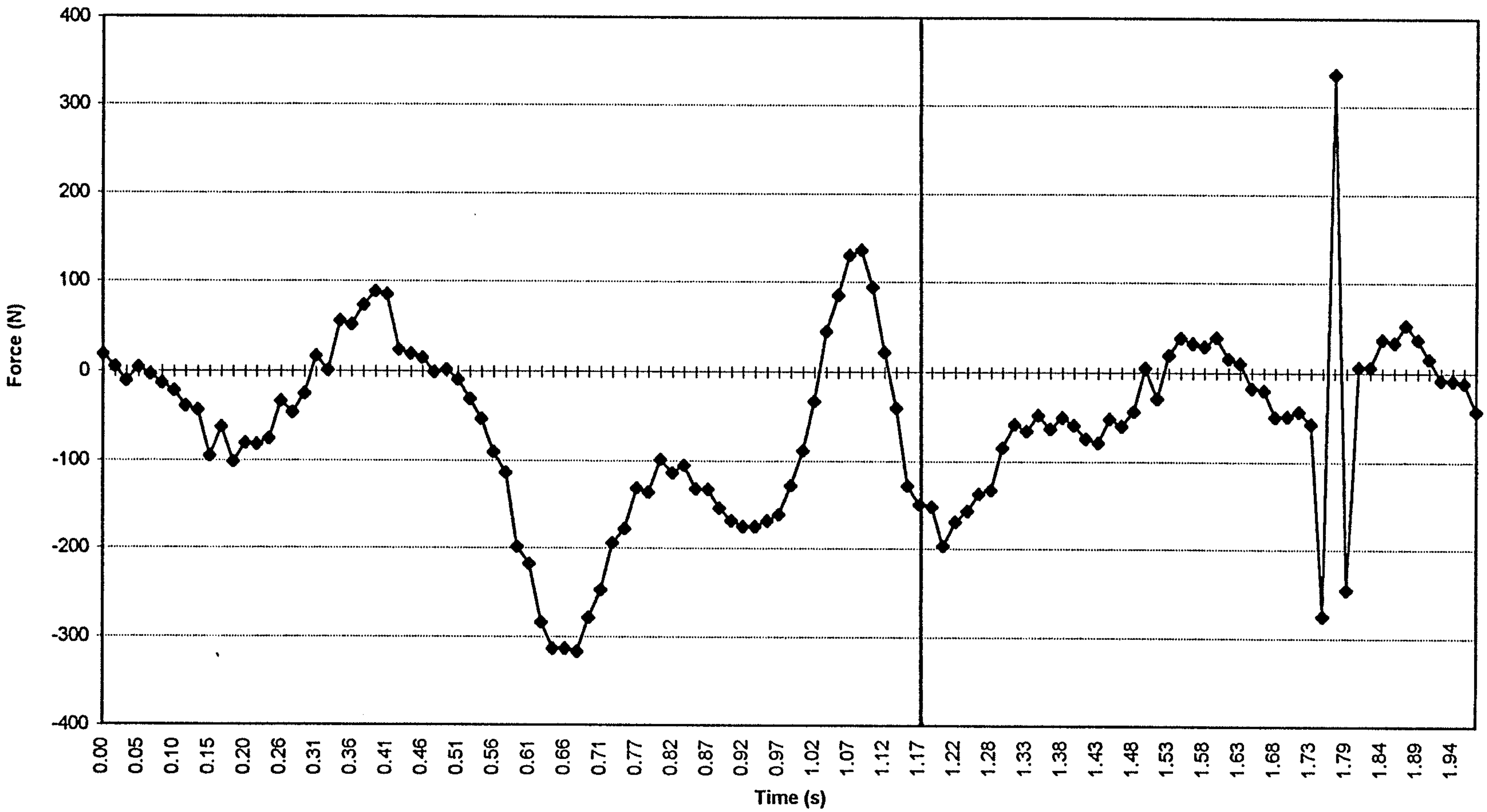


Figure 4-20. The force on the paddle calculated for Subject 1 if the required torque was produced by the paddle. The vertical line represents when the body exited the water.

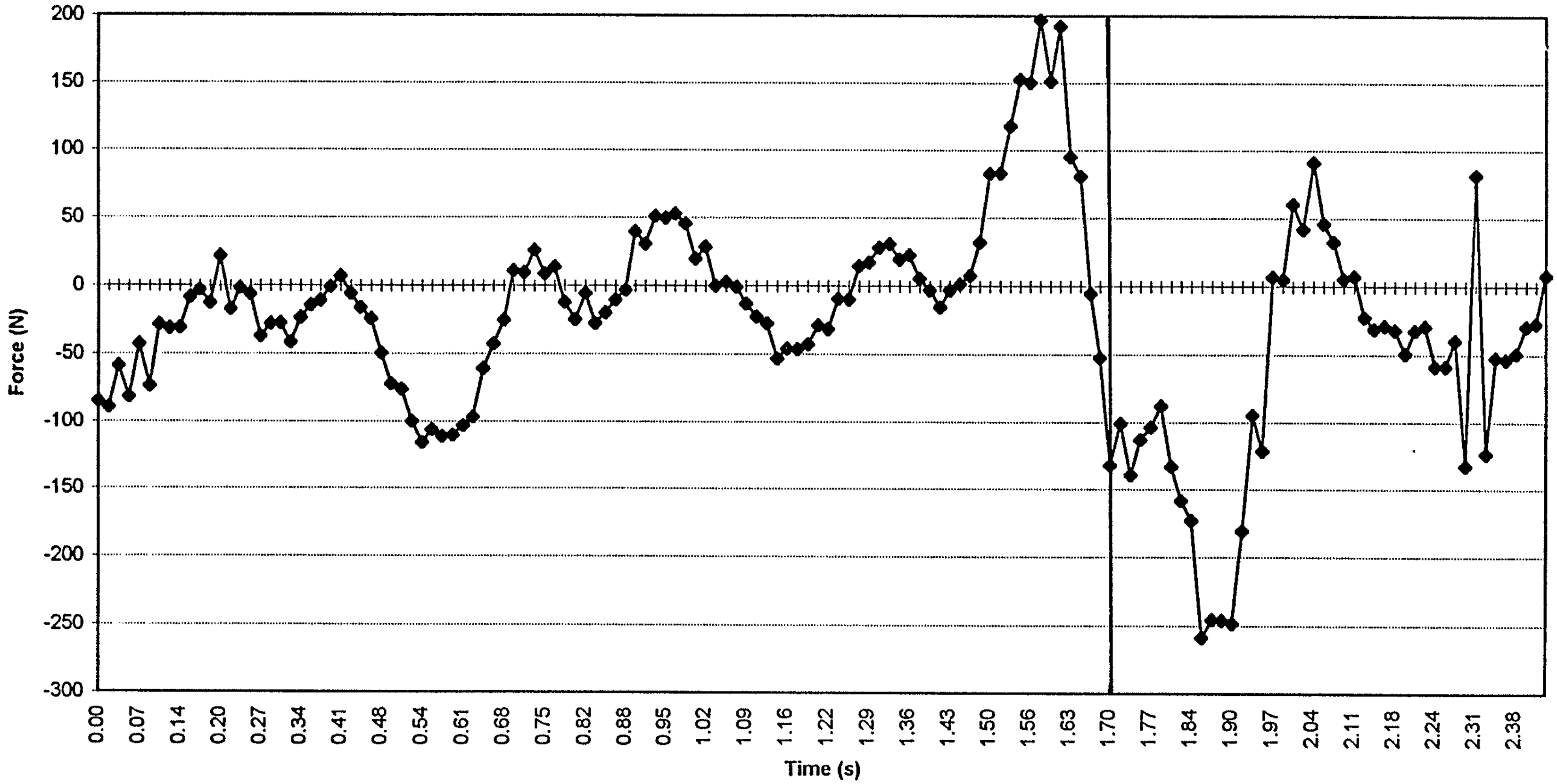


Figure 4-21. The force on the paddle calculated for Subject 2 if the required torque was produced by the paddle. The vertical line represents when the body exited the water.

CHAPTER 5

DISCUSSION

Video Results of Method

The method used in this experiment demonstrated that it was possible to videotape the entire Eskimo roll using two gen-locked video cameras set in plexiglass boxes (see Figure 4-2 and Figure 4-3). The cameras could be positioned at water level so that the field of view included both the above water movements and the below water movements.

The major problem encountered with this method was to secure the wave guards. The wave guards lessened the wave problems encountered in previous experiments (Hay & Gerot, 1991) but were not completely successful in stopping all the wave action in the pool from obscuring the camera view. These waves resulted in all of the trials being obscured to some extent and often not suitable for digitizing. The waves in the pool still caused the wave guards to move despite the addition of extra weights to the guards. The wave problem could best be solved by the installation of a permanent structure to act as the wave guard. A wave guard of this permanent nature would not be moved by the pool water and would ensure that the water in front of the camera lens remained motionless.

Accuracy of Method

The accuracy of this method depended on the camera positioning behind the clear domes placed in front of the camera lens. The use of these plastic domes worked well to eliminate most of the light refraction encountered when simultaneously videotaping the above water and below water views. The magnification and misalignment of segments was greatly reduced by positioning of the camera in the correct location behind the dome.

Visual inspection in the pool setting showed the camera view to be in correct proportions and alignment but the accuracy in calculating the length of the paddle indicated that there was a loss in accuracy (see Figure 4-4). The below water views measured the paddle to be slightly longer than it's actual length. The view with the paddle half submerged in the water showed some variability and loss of accuracy as the paddle was calculated to be longer and then shorter than the actual length. The views above the water calculated the length to be shorter than the actual length. The consistent underestimates of length above the water and overestimates below the water would indicate that some type of systematic error was occurring in all frames of film.

The maximum difference in measured length from the true length was 6 cm with a range of 11 cm. This amount of error represented only 2.9% error of the total length of the paddle but would represent a greater percent error for smaller segments. The 11 cm error was too large to be used to study small segments and movements. It is not possible to attribute this amount of error solely to the dome method as there were many other sources of error.

This loss of accuracy may have resulted from various sources. The plastic domes may not have been perfectly curved or the plastic used to construct the domes may not have been uniformly distributed over the entire dome surface. An imperfectly curved dome would not have a single, small center point and would make the alignment of the camera's optical axis and focal point difficult. The non-uniformly distributed plastic would cause some additional bending of the light rays in some areas and would actually distort the videotaped object. A high quality dome constructed specifically for optical use could have eliminated the dome distortion but would have created an additional expense.

The camera may not have been perfectly aligned behind the plastic dome and resulted in some additional error (see Figure 4-1). Previous experiments have used this same method of visual inspection to position the camera (Walton, 1988) and have obtained satisfactory results when studying the reaching abilities of subjects in spacesuits in an underwater test facility (Reinhardt & Walton, 1988). It was suggested that for experiments requiring further precision in the positioning of the camera, mathematical formulas to correct for optical and decentering distortion could be used to correct the camera images. The use of mathematical corrections would have helped to increase the accuracy in this study especially since the velocity and acceleration derivatives were studied. The mathematical corrections done before collecting the position data would have helped to smooth out the calculated velocity and acceleration graphs. The misalignment of the camera could account for the systematic error observed in calculating the length of the paddle. A misaligned camera would create the same error for the entire data collection period unless the camera were moved during the trial.

The camera positioning in this study was also made more difficult by the waves in the pool. The waves could not be completely eliminated so that when the camera was being aligned with the calibration tool, the tool was often obscured and difficult to view. Errors in the alignment of the calibration tool were observed when viewing the videotape using a frame by frame analysis in the lab but the wave action in the pool setting prevented these small misalignments from being easily observed.

The wave action also made it very difficult to align the camera exactly with the water level. The exact water level was difficult to determine when the waves caused the surface to move. Misalignment with the water surface would result in the water level not appearing as a thin line but would show some reflection from the topside or underside of the water surface. This would have the greatest effect on the accuracy of measurement of objects that cross the boundary between the air and water. The error would result in the object being measured as longer than it actually was.

The size of the field of view could also have resulted in the loss of some accuracy. The large field of view used (3 m) resulted in the digitizing cursor covering a larger percentage of the object or subject. The positioning of the cursor on the 1024 pixel diameter monitor resulted in a minimal 3 mm error each time the cursor was placed on the video screen. This type of error was common to other video studies (Angulo & Dapena, 1992) and the loss of accuracy was the result of the digitizing system and not the actual dome method. This type of error could be eliminated by zooming in more closely on the subjects, but this could not have be done without losing some of the kayak or body segments from the camera view.

The loss of accuracy due to the manual digitizing of the body markers was one of the largest sources of error. Markers were often hard to detect due to bad lighting, water bubbles and waves, and when other body parts blocked the view of the markers. The only way to reduce this type of error would be to use more cameras from many different angles which would ensure that a marker was visible from at least two camera views at all times.

Kinematics of the Kayak System

The videotaping method used in this study did permit a stick figure displacement description of the Eskimo roll to be created. The kayakers began the skill from the inverted position and started in the set up position (see Figure 4-5). It was noted that Subject 1 had a set up position like those described in other studies (Steidle, 1976) but Subject 2 started in a position with the left paddle blade lower in the water. This likely contributed to the fact that the paddle blade was swept deeper in the water by Subject 2 and resulted in the production of smaller lift torques (see Figure 4-17).

The path of the left paddle blade was from the bow to the stern of the kayak (see Figure 4-6). It was observed that the arc of Subject 1 was larger and did not go as deep into the water as Subject 2. The larger arc of Subject 1 allowed the moment arm for the lift force to be maximized (1.54 m) which in turn maximized the contribution of the lift torque to the righting of the kayak. The two subjects did not keep the blades at the surface of the water as had been described as the ideal motion (Williams, 1967) but Subject 1 was still able to produce substantial lift forces with the paddle (see Figure 4-16). The lift force direction and effectiveness was not optimal for these subjects, as indicated by the deep blade arc, and indicated a weak area in their technique.

The trunk was observed to rotate from facing the right side of the kayak to the forward facing position for both subjects. The recovery position showed that the trunk was now facing forward with the trunk extended along the rear deck of the kayak (see Figure 4-7 and Figure 4-8). This trunk extension was important for the kayaker to reduce the moment of inertia of the trunk segment and reduce the resistance to the rotation of the roll. The extension of the trunk over the rear deck of the kayak reduced the distance from the long axis of the kayak to the trunk segment. This had the effect of reducing the radius term (r) in the moment of inertia formula ($I=mr^2$) which greatly reduced the moment of inertia for the kayaker. The change in moment of inertia due to the extension of the trunk was calculated in the torque calculation program for each frame of film (see Appendix B). This movement was indicative of a skilled kayaker who desires to make the rotation of the kayak about the long axis as easy as possible to ensure a successful roll (Stuart, 1976; Trewiler & Smith, 1978).

Trunk Angle

Subject 1 showed a total range of motion of 164 degrees as the body rotated from the inverted position to the upright position (see

Figure 4-9). The movement occurred with the subject's right side leading the rotation. This range of motion was expected since 180 degrees of motion would be a complete half rotation. The starting position for Subject 1 was with the trunk rotated and flexed to the subject's right side which resulted in the total rotation being less than 180 degrees.

Subject 2 also showed a range of motion that was less that 180 degrees (see Figure 4-9). The total range of motion for this subject was 170 degrees. This subject also started the roll with his trunk rotated and flexed to the right side which resulted in a rotation of less than 180 degrees.

The slope of these angular displacement versus time curves represented the angular velocity of the movement. The curve of the graph (see Figure 4-9) was steepest when the movement was occurring with the greatest angular velocity. The steepest slope for Subject 1 occurred at nearly 1 second into the skill and 1.45 seconds for Subject 2. These steep slope corresponded correctly with the greatest angular velocities calculated in Figure 4-11.

Paddle Angle

The important aspect of the paddle blade angle was the angle of the blade when the blade was being moved through the water (see Figure 4-10). Subject 1 started with the blade out of the water in the set up position that was common to other studies (Steidle, 1976). The paddle blade was out of the water during the set up phase for Subject 1 and the angle started out being very large. The angle reached a value of 67 degrees but by the time the blade entered the water, the angle had been reduced to 3 degrees. The change in angle was accomplished by flexing the wrist to alter the orientation of the paddle blade as was observed in other Eskimo roll descriptions (Williams, 1967). The reduction of this angle as the blade entered the water had important influence on the ability of the kayaker to create lift with the paddle. The blade angle remained below 11 degrees for most of the sweep phase. The lift producing capability of the paddle was stated to be maximized at angles near 10 degrees (Alexander, et al., 1994) so this subject had kept the blade in an optimal position to produce lift during the lift phase. This helped to maximize the contribution of the paddle torque to the righting torque that must be produced to complete the rolling movement.

The angle increased rapidly once the kayaker was upright to an angle of 78 degrees. The large increase in angle started at frame 88 when the kayaker had completed the hip snap and the paddle was being lifted out of the water. The kayaker was nearly upright and no longer sweeping the paddle or pushing down on the water with the blade so the change in angle was done to aid in removing the paddle from the water. The increase in angle resulted in less resistance as the blade was lifted out of the water into a relaxed recovery position.

Subject 2 started the skill with the paddle in the water at a 9 degree angle. The fact that the kayaker started with the paddle in the water indicated that the kayaker had started with an incorrect set up position. The ideal set up position should be with the paddle blades held out of the water along the length of the kayak (Steidle, 1976). The blade angle ranged between 9 degrees and 20 degrees for the sweep phase and started to increase to 56 degrees when the kayaker's body had rotated out of the water. Subject 2 had a larger blade angle than Subject 1 which indicated that Subject 2 was not able to maximize the lift produced by the paddle as successfully as Subject 1 had done. The lift producing capabilities was stated to be decreased at these higher angles (Alexander, et al., 1994).

The paddle angle for Subject 2 also increased as the paddle was lifted out of the water at the end of the skill when the paddle was no longer being used to produce the righting torque.

Trunk Angular Velocity

The angular velocity of the trunk segment for Subject 1 peaked at 345 degrees per second on frame 66 of the skill (see Figure 4-11). This peak occurred as the body was being rotated out of the water and in close association with the timing of the hip snap. The trunk angular velocity remained below 154 degrees per second for the rest of the skill except for the one large peak. This showed when the body was rotating with the highest angular velocity and helped to identify the timing of the hip snap. The peak angular velocity occurred as the body was exiting the water and mid-way through the roll.

The angular velocity of the trunk was multiplied by the radius of rotation of the center of drag to calculate the linear velocity of the estimated center of drag. This was required by the torque calculation program to calculate the drag force on the body (see Appendix B). The large increase in angular velocity and a corresponding increase in the calculated linear velocity indicated that the drag forces were also increased at this time.

The angular velocity of the trunk segment for Subject 2 peaked at 268 degrees per second on frame 109 of the skill (see Figure 4-11). This peak also occurred in association with the timing of the hip snap. For the remainder of the roll, the angular velocity remained below 120 degrees per second. The peak angular velocity for Subject 2 was lower than Subject 1 and the 310 degrees per second found in previous studies (Alexander, et al., 1994). The increase in angular velocity would again suggest that the drag forces would be increased.

Trunk Angular Acceleration

The angular acceleration was used in the torque calculation program to calculate the net torque required to right the kayak. These angular acceleration curves were greatly affected by the amount of smoothing done on the raw data. The erratic graphs of the angular accelerations resulted from the double differentiation of the raw data which was not perfectly smooth or without noise. The angular acceleration was multiplied by the moment of inertia to calculate the net torque required to right the kayak.

The peak angular acceleration for Subject 1 (1455 degrees·sec^{-2}) was greater than that for Subject 2 (1370 degrees·sec^{-2}) but both were only slightly less than the accelerations reported in a previous study (2100 degrees·sec$^{-2)}$ (Alexander, et al., 1994). The difference in the findings between this study and the previous work may have been due to the differing amounts of smoothing performed on the two data sets and also due to the fact that the previous study did not use a method that captured the entire Eskimo roll on videotape. A large peak in angular acceleration occurred at the end of the skill but this was not included in the analysis since the roll had been completed by the time this peak occurred. Observation of the videotape did not depict any crucial movements at this point in time that would explain the observed peak. The peak was the result of digitizing error due to the difficulties with tracking the slow moving trunk segment. The small movements of the trunk were difficult to detect from frame to frame and often required several frames of film before the movement was observed. Digitizing these frames resulted in point coordinates that appeared almost stationary and then moved to a new location. The sudden movements of coordinate points to new locations resulted in the peaks observed in the acceleration graphs.

Subject 1 showed angular accelerations below 1000 degrees$\cdot$sec^{-2} for the entire skill except during the large peak period (see Figure 4-12). The large peak helps to indicate when the hip snap occurred as the body rotated quickly to the upright position. Subject 2 showed greater variation in angular accelerations and were below 700 degrees$\cdot$sec^{-2} except during the peak period. The large positive righting torque was always followed by a large negative torque to slow down the angular motion of the trunk. Truly variable angular acceleration would indicate a less fluid motion and would result in greater variances in produced torques. The torque variations due the trunk angular accelerations were kept minimal for Subject 1 for the majority of the motion except during the peak phase but Subject 2's greater change of acceleration throughout the skill would indicate that more variable torques were produced throughout the skill.

Paddle Linear Velocity

The linear velocity was required by the torque calculation program (see Appendix B) to calculate the lift force on the paddle blade. A greater linear velocity would help to create greater lift force and torque to help right the kayak.

The linear velocity of the left paddle blade for Subject 1 showed greater peak velocities earlier in the skill when the paddle was being swept from the front to the rear (see Figure 4-13). This velocity peaked 0.4 seconds after the start of the sweep phase at a value of 3 m/s. The linear velocity of the paddle blade for Subject 2 peaked much later in the skill at 1.1 seconds after the start of the sweep phase with a velocity of 3 m/s. These peak values were slightly lower than the 3.99 m/s value found in a previous work (Alexander, et al., 1994). The pattern exhibited by Subject 1 would be better to maximize the lift forces because the paddle was moving the fastest when the paddle blade was at the best angle to produce lift. The slower paddle blade sweep shown by Subject 2, combined with the less than optimal paddle blade angle, would indicate that the lift force and resulting torques were not used to their fullest advantage. The late peak shown by Subject 2 occurred as the paddle blade was being pulled in towards the kayak after reaching a position perpendicular to the long axis of the kayak. This high velocity movement of the paddle served the purpose to create drag against the water and not much lift since the paddle was no longer moving in the sweeping motion.

Moment Arm Lengths

The moment arm lengths in the frontal plane for the different forces were shown in Figure 4-14 and 4-15 for this study. The patterns for both subjects showed very similar values and trends. The moment arms for the weight force, drag force and buoyant force were all largely influenced by the position of the trunk segment. These moment arms were maximized midway through the skill when the trunk was extended perpendicular to the long axis of the kayak. In this position the moment arm length for the drag force and weight force would help to create larger torques to prevent the righting of the kayak while the buoyant moment arm would help to create larger torques to help right the kayak. The length of the moment arms were less at the beginning and end of the skill due to the fact that the trunk was aligned above or below the longitudinal axis of the kayak and not displaced horizontally from this axis.

The largest moment arm for both subjects was the moment arm for the paddle. This moment arm reached a peak value of over 1.4 m when the paddle had swept outwards and perpendicular to the longitudinal axis of the kayak. The long moment arm for the paddle would help to maximize the effect of the lift force produced by the paddle blade.

Individual Torques

The individual torque graphs (see Figure 4-16 and Figure 4-17) showed that the peaks in the inertial torques due to the motion of the system (IAlpha) were more variable than the peaks of the other torques. The inertial torque calculation utilized the angular acceleration of the trunk and since these values were very variable, it resulted in large, variable torque calculations.

The remaining individual torque calculations had similar values and patterns for both subjects except for the lift torque. The lift torque showed much greater values for Subject 1. This finding was not surprising since Subject 1 had held the paddle blade at a more optimal attack angle and moved the blade at a greater velocity during the sweep phase. The lift torque produced by Subject 2 remained small and did not offer much assistance to the righting of the kayak. This indicated a flaw in technique.

Required Torque

The unknown torque that must be produced to right the kayak are shown in Figure 4-18 for Subject 1 in Figure 4-19 for Subject 2. The peak torque for Subject 1 was -439 Nm and -356 Nm for Subject 2. These torque values were lower than the previously reported values of -700 Nm (Alexander, et al., 1994) which again may be the result of different frequencies of filtering. Negative torques were applied to the paddle during the sweep phase to create the righting motion.

The positive non-righting torque occurred for both subjects just prior to the trunk exiting the water. This would be the time at which the hip snap would have occurred. The non-righting torque required may be caused by the reaction to a strong hip snap. The paddle can be used as a brace at this time. The hip snap created a torque in the righting direction and the reaction to this hip snap movement was observed in the non-righting torque production by the paddle acting as a brace. The greater positive torque displayed by Subject 2 indicated that a more powerful hip snap movement was applied to the kayak and resulted in a greater reaction torque.

The initial negative torque was required to start the kayak rotation and the second negative torque was required to completely rotate the body out of the water once the kayak had finished rotating. The positive peaks observed in the paddle torques were not observed in previous work (Alexander, et al., 1994) but a change to less negative values was observed. A different smoothing frequency or the lack of reliable data on the movements above the water could be the cause of the differences.

Paddle Forces

If the unknown required torque were produced by the paddle during the hip snap, the resulting peak paddle force for Subject 1 was calculated to be -316 N and -259 N for Subject 2 (see Figure 4-20 and Figure 4-21). The negative value indicated that the force is acting downwards in a negative y-axis direction. These peak values were less than the -1100 N force found in other studies (Alexander, et al., 1994). These maximum force values were less than one body weight of force. If these low force values represent the forces that the muscles must produce, these findings would tend to support the concept that great physical strength was not required to complete the Eskimo roll (Bridge, 1978a; Diehl, 1982).

Sources of Error

The sources of error in this study resulted from the data obtained with the videotaping method, and with the values estimated in the torque calculation program.

The errors with the videotaping method were discussed previously and included 1) errors in camera positioning behind the dome, 2) the dome construction, 3) positioning of the camera box at water level, 4) wave action obscuring the subject or alignment tools, 5) digitization noise, and 6) the cursor size in relation to the size of the field of view.

Other sources of error encountered when calculating the torque values originated from the estimation of values in the torque formula. The coefficient of lift for the paddle and the coefficient of drag of the body were estimated based on similar shaped objects but may have not been exact for the kayaker. The coefficients would have also varied during the movements but they remained as constants in the torque calculation program. The buoyant force was estimated as a portion of the weight of the displaced water of the kayaker and kayak and assumed to remained constant. A more true buoyant force measurement would fluctuate based on the amount of the object that was submerged in the water at any given time.

In addition, the midpoint between the hip joints was used as an estimated position the long axis of the kayak as it passed through the body. This may have been a close approximation but resulted in some error in the length of the moment arms for each force.

The skill levels of the kayakers may also have caused some of the variation in results. The two subjects were both skilled kayakers but displayed slightly different variations of the screw roll. Subject 1 appeared more practiced at the sweeping type of screw roll studied here. The slightly different techniques would result in the different kinematic findings and make comparisons difficult. A more stringent selection of subjects with similar skill levels would result in more homogenous results. Variable results may continue to be found if it is true that each kayaker performs slightly different movements to produce the same amount of righting torque. The individual contributions from the individual torques to the net torque may remain varied for even highly skilled kayakers.

The use of a single segment model to describe a multi-segmental motion also caused some error. Motion between segments, such as the hip snap maneuver, could not be fully studied with this model. The influence of one segment movement on the attached segment was not studied.

The center of gravity of the kayak and the mass of the paddle were also omitted from this study. The kayak would have tended to lower the center of gravity of the entire system which may have changed some of the moment arm calculations. The mass of the paddle held at it's large moment arm distance away from the long axis of the kayak would have had a substantial influence on the moment of inertia for the entire system. The increased moment of inertia due to the paddle would have also changed the required and net torque values.

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The main purpose of this study was to develop a system to film all the movements performed by a kayaker to complete an Eskimo roll. It was shown that a video camera placed at water level would capture all the movements above and below the water in the Eskimo roll. The cameras were placed in plexiglass boxes to keep the cameras dry and to allow for the cameras to be gen-locked together. The gen-locked cameras were then used to complete a three dimensional video analysis of the Eskimo roll. One major problem encountered was eliminating the wave action in front of the camera lens. The portable wave guards used in this study lessened the wave problem but could not eliminate it completely.

The videotaping method made use of spherical domes, placed between the camera lens and the water, to eliminate the misalignment of the recorded images due to the refraction of the light. The camera was precisely positioned with the center of the dome aligned with the focal point of the lens. The correct camera position was determined by viewing a set of half immersed vertical lines placed in the field of view of the camera. The camera was correctly positioned when all the lines were aligned but this proved difficult to achieve due to the waves in the pool.

The accuracy of the data obtained with this method was shown to vary lack but the exact amount of accuracy that was lost due to

the dome method alone could not be determined. The accuracy was also affected by the use of a video system and the problem with the wave action in the pool. The wave action was the most critical source of error that had to be overcome to produce more successful videotaping sessions.

The kinematic findings indicated that these skilled kayakers executed most of the commonly accepted movements required to complete an Eskimo roll. Subject 2 had a slightly modified set up position and both subjects swept the paddle to a deeper level in the pool than was described by other authors (Stuart, 1976; Williams, 1967). Both subjects showed the recovery position with the trunk extended toward the rear of the kayak to make the rotation about the long axis of the kayak easier due to a decreased moment of inertia.

Subject 1 swept the paddle blade in an arc with the attack angle of the blade nearer to the optimal 10 degree position. Subject 1 also demonstrated a higher linear velocity of the paddle blade during this sweep phase. These two factors combined to create a larger lift torque for Subject 1 than was found with Subject 2.

The calculated torque on the paddle was influenced significantly by the torque due to the movement of the body. The large variation in calculated torques resulted from the variability in the smoothed acceleration data.

The forces on the paddle were calculated to be less than the subject's body weight. This supported the notion that the Eskimo roll does not require large amounts of absolute strength.

Conclusions

The following conclusions appear to be justified from the findings of the present study:

1. A single video camera can be used to simultaneously record the displacement movements of skills that occur across an air/water boundary.
2. Careful positioning of clear domes placed between the camera lens and the water environment can minimize the refraction of the light rays as they pass from the water to the air.
3. The wave action of the pool water created the greatest difficulty when setting up the apparatus and viewing the trials.
4. The use of wave guards eliminated some of the wave interference.
5. The movements of these skilled kayakers were similar to most of the previous descriptions of the Eskimo roll except that both kayakers swept the paddle deeper from the water surface.
6. The torque on the paddle blade showed large variations. These torque calculations were subject to errors from many sources, so will only serve as an estimate of the true values.
7. The forces generated on the paddle were less than one body weight of force.
8. The two subjects in this study did not show exactly the same movement and torque profiles. This may have been due to different skill levels or rolling techniques.

Recommendations

The following recommendations can be made for future studies on the Eskimo roll:

1. The wave motion must be eliminated by the use of a more permanent wave guard system. This would help to increase the reliability of the video analysis system and make the set up easier.
2. The estimation of variables in the torque model (see sources of error section) and equation should be investigated to produce more accurate values to be used in the calculations.
3. A model should be created that includes the hip snap since the hip snap appears to play a large role in the Eskimo roll. A three segment model could be developed to include the kayak, trunk, and arm and paddle segments.
4. A greater number of skilled kayakers should be studied to further support or disprove the findings of this study.
5. Subjects should be selected with the aid of a highly skilled kayaker to determined subjects with very similar Eskimo roll techniques.

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APPENDIX A

Personal Consent Form

INFORMED CONSENT FORM

You have been selected to participate in a study entitled "Filming Techniques for the Eskimo Roll in Kayaking".

The purpose of this study is to develop a method to accurately videotape the below water and above water movements required to perform the Eskimo roll. The videotaped data will then be used to produce three dimensional kinematic descriptions of the roll which can be used to calculate the torques required to complete the Eskimo roll.

In the following study, your weight and height will be measured and recorded. Tape markers will be attached to your shoulder joints, elbow joints and wrist joints. You will then be required to enter the pool with the kayak and perform five Eskimo rolls.

During the Eskimo rolls, two cameras will film your performance, and the video tapes will be used for the kinematic descriptions and the torque calculations. Your name will be recorded for identification by the investigator but your identity will remain confidential. The recorded films will not be redistributed or used for any purpose other than this research study.

Since you are an experienced kayaker it is assumed that you are capable of performing an Eskimo roll, and that the risk of injury is low.

I, ______________________________, have read the above information and understand the testing procedure, the risks involved, and I agree to participate at my own risk. I acknowledge that the Eskimo roll is within my capability and I can successfully perform this skill on a regular basis. I also understand that I have the right to withdraw from this study at any time I feel appropriate. In case of injury, I relieve the University of Manitoba and the Investigator of any liability that may result from my participation in this study.

______________________________ ______________________
Signature of Investigator Date

______________________________ ______________________
Signature of Subject (Parent/Guardian) Date

______________________________ ______________________
Witness Date

APPENDIX B

Torque Calculation Program

```
Program kayak (input,output, file_name, outfile);

const
  rho = 998;                    {density of water kg/m3}
  gravity = 9.81;               {acceleration to earth center due to gravity
                                 m/s2}

  moment_of_inertia = 7.072;    { rotational inertia about the AP axis of an
                      athlete with their elbows extended.  Calculated by
                       converting lb-in-sec2 to lb-ft-sec2 then to Nm-sec2}

  A1 = 0.237946;                {Area of athlete using Humanscale m2}
  A2 = 0.08;                    {area of paddle m2}
  num_points = 27;              {number of points in the spatial model}
  drag= 0.4;                    {Coefficient of drag}
  buoyant_force = 785;        {Buoyant force acting on centre of buoyancy N}
  masskay=17.9;                 {mass of kayak in kg}
  kaydia=0.30;                {diameter of kayak m}

type
  { The original data that is read into the computer from the files that
  are stored by the Peak5 software program}

    info = record
      ang_accel: array [1..150] of real;   {ang accel of trunk segment}
      ang_velocity: array [1..150] of real;{ang vel of trunk segment}
      paddle_angle:array [1..150] of real; {angle of paddle}
      paddle_vel: array [1..150] of real;  {paddle resultant velocity}
      hip_position: array [1..150] of real;{hip position in z direction}
      paddle_position: array [1..150] of real; {Horiz. position of paddle}
      sternal_notch_position: array [1..150] of real;{sternal notch position
                                                      in z direction}
      CG_position: array [1..150] of real; {CG position in z direction}
      distance1: array [1..150] of real;   {half the distance from hip to
                                            top of the head}
      distance2: array [1..150] of real;   {distance from hip to l poletip}
      distance3: array [1..150] of real;   {horizontal distance from CG to
                                            middle of the hips}
      distance4: array [1..150] of real;   {horizontal distance from center
                                            of buoyancy to middle of the hips
                                            midpoint from hips to shoulder}
      torque: array [1..150] of real;       {Total torque produced at the
                                            paddle}
      Ycofg: array [1..150] of real         {y coordinate of c of g}
    end;


var
    data: info;                 {original data values from Peak5}
    name: string [8];           {file name that is to be used without the
                                 extension}
    file_name, outfile: text;   {Files used including the extension}
    temp_name: string [12];     {the file name plus the extension}
    num_frames, bodout, padin, x, y: integer; {x,y are counters
                                num_frames = number of frames digitized
                                bodout =frame number when body exits
                                       water and lift and drag are zero
                                padin= frame when paddle entered  water to
                                 create lift }
```

```
    mass, force, Fd, Fl, body_moment, buoyant_moment,
     velocity,Cl,distancetocofg: real;
            {mass= mass of kayaker
            Fd = force of drag
             Fl = lift force
             Cl = coefficient of paddle lift .6 if angle <=10
                                             .1 if angle >10
             body_moment = moment created on the body by gravity
             buoyant_moment = moment created on the body by force of buoyancy
             distancetocofg=distance from cof g to axis of rotation }
{---------------------------------------------------------------------------
 This procedure will take the files produced by the peak5 system and
  read them into a set of arrays. }

Procedure Init_linear (var file_name:text; var data:info; last, q:integer);

 {c - the first character read in by the computer, this will be converted
     from a ascii character into its numberic representation
  pos_exponent, neg_exponent, left_dec, right_dec, done, neg - these
        are all boolean expressions that have either the value of "true" or
        "false".  When certain conditions are met, the value will be changed
        from one value to the other.
  x, y, z, a, counter - are all counters used to run a series of lines
      over and over again until the required values have been met.
  fac - a value used to increase the number by ten, if and only if the
       decimal point has not been read in yet.
  exponent - the value that represents the exponent of the exponental notation
  number - the converted value of the character representing the exponent
  num - the converted value of the character representing the number
       being read into the array.
  decfac - a value that starts at 1/10 and is continually decreased by a
          factor of 1/10, until there are no numbers left to be read
           into the array
  totnum - the total value of the number being read into the array location}

var
    c: char;
    pos_exponent, neg_exponent, left_dec, right_dec, done, neg: boolean;
    x, y, z, a, fac, exponent, number: integer;
    num, decfac, totnum: real;

begin
  for x:= 1 to last do
    for y:= 1 to num_points do
      for a:= 1 to 4 do
        begin          {assignment of all the values to their initial value}
        done:= false;
        totnum:= 0;
        fac:= 1;
        decfac:= 10;
        neg:= false;
        left_dec:= true;
        right_dec:= false;
        z:=0;
        exponent:= 0;
        pos_exponent:= false;
        neg_exponent:= false;
        repeat         {compares the value read in to the values of
                      '-', '+', '.', 'E' and then changes the appropriate
                      boolean expression to the opposite value it had}
```

```
  read (file_name, c);
  if c='-' then
    neg:= true;
  if c='.' then
    begin
      right_dec:= true;
      left_dec:= false;
    end;
  if (c=' ') then
    done:= true;
  if (eoln(file_name)) then
    done:=true;
  if c='E' then
    begin
      fac:=0;
      read (file_name, c);
      if c='+' then
        pos_exponent:= true;
      if c='-' then
        neg_exponent:= true;
      read(file_name, c);
      read(file_name, c);
      exponent:=ord(c)-48;
    end;
  if (c in ['0'..'9']) then
    begin                         {calculataes the value of the number}
      num:= ord(c) - 48;
      if left_dec then   {if value is to the left of the decimal}
        begin            {multiply by ten, read next value, add}
          z:=z+1;        {the neww value to the existing value}
          if z=1 then
            fac:=1
          else
            fac:=10;
          totnum:= totnum * fac;
          totnum:= totnum + num;
        end;
      if right_dec then  {if value is to the right of the decimal}
        begin            {divide by ten, read next value, add}
          num:= num / decfac;{the new value to the existing value}
          totnum:= totnum + num;
          decfac:= decfac * 10;
        end;
    end;
until (done= true);

if neg then         {if value was negative multiply by (-1)}
  totnum:= totnum * (-1);

if pos_exponent then {if exponent was positive then multiply by
                      the value of the exponent}
  totnum:= totnum * exp(exponent * ln(10));

if neg_exponent then {if exponent was positive then multiply by
                        the value of the exponent}
  totnum:= totnum / exp(exponent * ln(10));


if q=1 then
  if (y=25) and (a=4) then
```

```
            data.paddle_vel [x]:= totnum;


         if q=2 then
           if (y=27) and (a=3) then
             data.CG_position [x] := totnum;

         if q=2 then
         if (y=27) and (a=2) then
            data.ycofg[x]:=totnum;

         if q=2 then
           if (y=11) and (a=3) then
             data.hip_position [x] := totnum;

         if q=2 then
           if (y=5) and (a=3) then
             data.sternal_notch_position [x] := totnum;

         if q=2 then
           if (y=25) and (a=3) then
             data.paddle_position[x] := totnum;


    end;
end;

{---------------------------------------------------------------------------
 This procedure will take the files produced by the peak5 distance
  program and read them into an array. }

Procedure Init_dist (var file_name:text; var data:info; last, q:integer);

var
    c: char;
    pos_exponent, neg_exponent, left_dec, right_dec, done, neg: boolean;
    x, z, fac, exponent, number: integer;
    num, decfac, totnum: real;

begin
  read (file_name, c);
  if (c=' ') then
    read(file_name, c);
  for x:= 1 to last do
      begin          {assignment of all the values to their initial value}
        done:= false;
        totnum:= 0;
        fac:= 1;
        decfac:= 10;
        neg:= false;
        left_dec:= true;
        right_dec:= false;
        z:=0;
        exponent:= 0;
        pos_exponent:= false;
        neg_exponent:= false;
        repeat          {compares the value read in to the values of
                       '-', '+', '.', 'E' and then changes the appropriate
                       boolean expression to the opposite value it had}
          if c='-' then
```

```
      neg:= true;
    if c='.' then
      begin
        right_dec:= true;
        left_dec:= false;
      end;
    if (c=' ') then
      done:= true;
    if (eof(file_name)) then
      done:=true;
    if c='E' then
      begin
        fac:=0;
        read (file_name, c);
        if c='+' then
          pos_exponent:= true;
        if c='-' then
          neg_exponent:= true;
        repeat                    {calculates the value of the exponent}
          z:= z+1;
          read (file_name, c);
          exponent:= exponent * fac;
          number:= ord(c) - 48;
          exponent:= exponent + number;
        until z=2;
      end;
    if (c in ['0'..'9']) then
      begin                       {calculataes the value of the number}
        num:= ord(c) - 48;
        if left_dec then   {if value is to the left of the decimal}
          begin            {multiply by ten, read next value, add}
            z:=z+1;        {the neww value to the existing value}
            if z=1 then
              fac:=1
            else
              fac:=10;
            totnum:= totnum * fac;
            totnum:= totnum + num;
          end;
        if right_dec then  {if value is to the right of the decimal}
          begin            {divide by ten, read next value, add}
            num:= num / decfac;{the neww value to the existing value}
            totnum:= totnum + num;
            decfac:= decfac * 10;
          end;
      end;
      read (file_name, c);
  until (done= true);
  if neg then          {if value was negative multiply by (-1)}
    totnum:= totnum * (-1);
  if pos_exponent then {if exponent was positive then multiply by
                        the value of the exponent}
    totnum:= totnum * exp(exponent * ln(10));

  if neg_exponent then {if exponent was positive then multiply by
                            the value of the exponent}
    totnum:= totnum / exp(exponent * ln(10));

  if q = 1 then
    data.distance2 [x]:= totnum;
```

```
        totnum:=totnum/2; {distance 1/2 the way from the axis
                           of the hips to the top of the head}
        if q = 2 then
         data.distance1 [x]:= totnum;

      end;
end;


{---------------------------------------------------------------------------}
{this procedure reads in angular acceleration and angular velocities}

procedure Init_angle (var file_name:text; var data:info; last, q:integer);

var
    c: char;
    pos_exponent, neg_exponent, left_dec, right_dec, done, neg: boolean;
    x, z, t, fac, exponent, number: integer;
    num, decfac, totnum: real;

begin
  read (file_name, c);
  for x:=1 to last do
    for y:=1 to 3 do
    begin
      done:= false;
      totnum:= 0;
      fac:= 1;
      decfac:= 10;
      neg:= false;
      left_dec:= true;
      right_dec:= false;
      z:=0;
      exponent:= 0;
      pos_exponent:= false;
      neg_exponent:= false;
      repeat
        if c='-' then
          neg:= true;
        if c='.' then
          begin
            right_dec:= true;
            left_dec:= false;
          end;
        if (c=' ') then
          done:= true;
        if (eoln(file_name)) then
          done:=true;
        if c='E' then
          begin
            fac:=0;
            read (file_name, c);
            if c='+' then
              pos_exponent:= true;
            if c='-' then
              neg_exponent:= true;
            read(file_name, c);
            read(file_name, c);
            exponent:=ord(c)-48;
```

```
          end;
        if (c in ['0'..'9']) then
          begin
            num:= ord(c) - 48;
            if left_dec then
              begin
                z:=z+1;
                if z=1 then
                  fac:=1
                else
                  fac:=10;
                totnum:= totnum * fac;
                totnum:= totnum + num;
              end;
            if right_dec then
              begin
                num:= num / decfac;
                totnum:= totnum + num;
                decfac:=decfac * 10;
              end;
          end;
        read (file_name, c);
      until (done= true);
      if neg then
        totnum:= totnum * (-1);
      if pos_exponent then
        totnum:= totnum * exp(exponent * ln(10));
      if neg_exponent then
        totnum:= totnum / exp(exponent * ln(10));

      if (q=1) and (y=1) then
       begin
          totnum:=totnum / 57.29578;   {converting from degrees to radians}
          data.ang_accel [x]:= totnum;

       end;

      if (q=2) and (y=1) then
       begin
        totnum:=totnum / 57.29578;  {converting from degrees to radians}
        data.ang_velocity [x]:= totnum;

       end;

      if (q=3) and (y=3) then
             data.paddle_angle [x]:= totnum;


    end;
end;

{------------------------------------------------------------------------}
{main program}
Begin
  temp_name:='';  {initialize the temporary sting to a null string}
  name:= '';

  write ('Please enter the file name to be used (maximum of 8 characters): ');
  readln (name);
```

```
 writeln;

 write ('Please enter the number of frames that were digitized: ');
 readln (num_frames);
 writeln;

  write ('Please enter the frame number when the paddle entered the water: ');
 readln (padin);
 writeln;

 write ('Please enter the frame number when the body exited the water: ');
 readln (bodout);
 writeln;

  write ('Please enter the mass of the kayaker: ');

 readln(mass);
 writeln;

{After assigning the input name to the temporary string with the appropriate
 extensions this opens the file chosen, and sends control to the procedure
 Init_linear to read in all values for the linear accelerations and
  positional data.}
 x:=1;
 temp_name:= name + '.alv';
 assign (file_name, temp_name);
 reset (file_name);
 Init_linear (file_name, data, num_frames, x);
 writeln ('linear velocity of paddle');
 close (file_name);

 x:=2;
 temp_name:= name + '.ald';
 assign (file_name, temp_name);
 reset (file_name);
 Init_linear (file_name, data, num_frames, x);
 writeln ('linear displacement of points 6 and 11');
 close (file_name);


{After assigning the input name to the temporary string with the appropriate
 extensions this opens the file chosen, and sends control to the procedure
 Init_linear to read in all values for the distance data.}
 x:=1;
 temp_name:= name + '.as1';
 assign (file_name, temp_name);
 reset (file_name);
 Init_dist (file_name, data, num_frames, x);
 writeln ('distance between CG and end of paddle');
 close (file_name);

 x:=2;
 temp_name:= name + '.as2';
 assign (file_name, temp_name);
 reset (file_name);
 Init_dist (file_name, data, num_frames, x);
 writeln ('distance between middle of hips and head');
 close (file_name);

{assigning the input name to the temporary string with the appropriate
```

```
extensions and then opens the file chosen and sends control to the procedure
Initialize_angle to read in all values for the angular accelerations and
angular velocities.}

 x:=1;
 temp_name:= name + '.aaa';
 assign (file_name, temp_name);
 reset (file_name);
 Init_angle (file_name, data, num_frames, x);
 writeln ('angular acceleration of segments');
 close (file_name);

 x:=2;
 temp_name:= name + '.aav';
 assign (file_name, temp_name);
 reset (file_name);
 Init_angle (file_name, data, num_frames, x);
 writeln ('angular velocity of segments');
 close (file_name);

 x:=3;
 temp_name:= name + '.aad';
 assign (file_name, temp_name);
 reset (file_name);
 Init_angle (file_name, data, num_frames, x);
 writeln ('angle of the paddle');
 close (file_name);

 temp_name:= name + '.da3';
 assign (outfile, temp_name);
 rewrite (outfile);
 write (outfile,'ang_accel  cg_pos. hip_pos s_notch');
 writeln (outfile,' ang_vel.  paddle_angle paddle_vel');
 for x:=1 to num_frames do
   with data do
       writeln (outfile,ang_accel[x]:9:3,cg_position[x]:8:3,
               hip_position[x]:8:3, sternal_notch_position[x]:8:3,
               ang_velocity[x]:10:3, paddle_angle[x]:11:3,
               paddle_vel[x]:12:3);
  close(outfile);

{the following few lines calculate the horizontal distance from the CG to the
axis of rotation, and the horizontal distance from the sternal notch to the
axis of of rotation}

 for x:= 1 to num_frames do
   with data do
     begin
       distance3[x]:= cg_position[x] - hip_position[x];
       distance4[x]:=(sternal_notch_position[x] - hip_position[x])/2;
     end;

 temp_name:=name + '.da1';
 assign(outfile,temp_name);
 rewrite(outfile);
 writeln(outfile,' D1        D2        D3        D4       paddle pos');
 for x:=1 to num_frames do
 with data do
       writeln(outfile, distance1[x]:8:6,
              distance2[x]:10:6,distance3[x]:10:6,distance4[x]:10:6,
```

```
              paddle_position[x]:10:5);
  close(outfile);
{The following section calculates the velocity, Fd, F1, body_moment, and
 buoyant_moment at each time interval and then places that value into the
 torque calculation equation, which stores the value in the right
  sequence of the array.}
  temp_name:=name + '.da2';
  assign(outfile,temp_name);
  rewrite(outfile);
  writeln(outfile,'Torque':10,'  =     IAlpha  +  FdD1    -     F1D2   +   mgD3
  writeln(outfile,' ');
    for x:= 1 to num_frames do
    with data do
      begin
        velocity:=ang_velocity[x]*distance1[x];{velocity=angular velocity
                               * Radius which in this case is half the length
                               of the hip to head segment}
        if(x>bodout) then Fd:=0   {drag force is assummed zero when body
                                   is not in the water}
         else
            Fd := (A1*drag*rho*velocity*velocity)/2;

        if paddle_angle[x]>10 then C1:=0.1
         else C1:=0.6;
        if (x<padin) then F1:= 0   {lift force zero when paddle is not in
                                    water}
            else
             F1 := (A2*C1*rho*paddle_vel[x]*paddle_vel[x])/2;

        body_moment:= mass*gravity*distance3[x];

       if (x>bodout) then buoyant_moment:=0 {buoyant force zero when body
                                               out of water}
        else
           buoyant_moment:= buoyant_force*distance4[x];

       distancetocofg:=sqrt(sqr(CG_position[x])+sqr(Ycofg[x]));
       torque[x]:=((moment_of_inertia+(mass*sqr(distancetocofg))
        +(masskay*sqr(kaydia)))*ang_accel[x]) + Fd*distance1[x]
         - F1*distance2[x] + body_moment - buoyant_moment;

     writeln (outfile,torque[x]:12:3,((moment_of_inertia
             +(mass*sqr(distancetocofg)) +(masskay*sqr(kaydia)))*
             ang_accel[x]):12:3, Fd*distance1[x]:12:3,
             F1*distance2[x]:12:3, body_moment:12:3,buoyant_moment:12:3);
      end;
   close(outfile);
{the following section outputs the torque values calculated and writes these
 values to a file with the same name as the original data files but has the
 extension of '.trq'.}

    temp_name:=name + '.trq';
    assign(outfile, temp_name);
    rewrite(outfile);
    writeln(outfile,'Torques');
    with data do
      for x:= 1 to num_frames do
          writeln (outfile, torque [x]:10:3);
       close (outfile);
```

```
temp_name:= name + '.frc';
assign (outfile, temp_name);
rewrite (outfile);
writeln(outfile,'Forces');
with data do
  for x:= 1 to num_frames do
    begin
      force:= torque[x]/distance2[x];
      writeln (outfile, force:10:3);
    end;
close (outfile);
end.
```