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Examination of the magnitude and timing of hip flexion torque in high degree of difficulty forward somersault dives on the 3m springboard

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EXAMINATION OF THE MAGNITUDE AND TIMING OF HIP FLEXION TORQUE IN HIGH DEGREE OF DIFFICULTY FORWARD SOMERSAULT DIVES ON THE 3M SPRINGBOARD.

MASTERS THESIS

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ABSTRACT

While there has been much research published on the kinematics and kinetics of forward dives from a springboard, very little has been done on the effect the timing and magnitude of hip flexion torques has on forward dives. The purpose of this study was to investigate the relationship between the timing and magnitude of hip flexion torques prior to the take-off and the vertical velocity at take-off in high demand rotational forward dives. Twenty-six elite divers (14 males and 12 females) competing in the United Kingdom leg of the 2001 FINA Diving Grand Prix performed high demand rotational dives. The males performed a forward three and one-half somersault dive in the pike position (107B), whilst the females performed a forward two and one-half somersault dive in the pike position (105B) off the 3m springboard. A video camera operating at 60Hz recorded all dives in the preliminaries and finals. Video footage was digitised from the 10 frames preceding touchdown from the hurdle to 10 frames following take-off to yield vertical and horizontal velocity and angular displacement data. Furthermore, the hip joint torque was calculated via a six segment 'top-down' model. An independent sample t-test was used to determine whether there were any significant differences between the two gender groups for selected variables whilst a Pearson's Product Moment Correlation Coefficient (r) was calculated for both the male and female divers to establish whether the timing and magnitude of the peak hip flexion torque had an influence on vertical velocity at last contact and dive score. Results showed that the male divers produced significantly ($p<0.05$) greater normalised peak hip flexion torque ($p=0.000$) later in the take-off sequence ($p=0.000$) than the female divers. The male and female divers both exhibited significant relationships between the normalised peak hip flexion torque and the timing of normalised peak hip flexion torque in relation to last contact (r = -0.461 and 0.543 respectively). The male divers showed a significant relationship between the normalised time of peak hip flexion torque and dive score (r = -0.542). The male and female divers also exhibited significant relationships between the dive score awarded and vertical velocity at last contact (r = 0.476 and 0.748 respectively). From the findings of this study it can be seen that the timing and magnitude of peak hip flexion torque did not have a direct influence on vertical velocity. There were however, other statistically significant results obtained. The timing and magnitude of the normalised peak hip flexion torque were significantly related to each other.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

(iii) contain any defamatory material.

Signature: [redacted]

Date: 8. 12. 2003

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CHAPTER 1. INTRODUCTION

1.1 Background

In forward springboard dives, divers advance along a springboard using a step and 'hurdle' technique facing towards the end of the springboard. The 'hurdle' is a single legged jump performed as the diver nears the end of the springboard. This hurdle enables the diver to add energy to the springboard. As the diver descends from the hurdle the diver adopts a semi-crouched position to prepare for contact. After landing from the hurdle, the diver forcefully extends against the springboard to add energy to be used for achieving as much height as possible and to generate sufficient rotation to complete the required number of rotations in the designated position for the particular dive. Also, the diver seeks to avoid large horizontal velocity at last contact with the springboard because horizontal travel away from the springboard affects the overall score awarded by the judges (McCormick, Subbaiah & Arnold, 1982).

The diver's performance is scored by a set of judges sitting at the side of the pool, with the judge's scores being multiplied by a pre-determined degree of difficulty (DD) to calculate the final score. The divers then choose the dive that they can perform well, with a high DD, so that they can maximise their score. The number of rotations, the body configuration in which the rotations are performed and whether twists are performed in the dive, determine the DD of the dive. Dives performed in the pike position have a higher DD than those dives performed in the tuck position because the moment of inertia about the centre of mass is greater and, therefore, a greater quantity of rotation (angular momentum) must be generated to complete the dive. Prior to the performance of the dive, the diver considers the possible score of the dive given by the judges and the DD.

It is well known that the height achieved after final contact with the springboard and the successful completion of the designated number of rotations prior to entering the water are important to the dive score (McCormick, Subbaiah & Arnold, 1982). Creating height off the springboard is important for two reasons. Firstly, the judges award more points (McCormick et al., 1982) and secondly increased height provides more time for the diver to complete the dive (Miller & Munro, 1984). To achieve good height, the springboard diver must achieve a high vertical velocity at the initiation of flight (Miller & Munro, 1984; Sanders & Wilson, 1988). The diver achieves a high vertical velocity by utilising the energy stored in the springboard. To store the energy in the springboard so that it can be used to give the diver a high vertical velocity at last contact (the instant of last contact with the springboard) the diver maximises the downward velocity at the end of the hurdle by having as high a hurdle as possible. The diver then seeks to minimise the energy absorbed by the lower limb muscles after landing from the hurdle and to maximise the work done to store additional energy by extending the hips, knees and ankles during springboard depression. As the springboard recoils the diver seeks to use as much of the springboard energy to gain height and rotation as possible and to avoid absorbing energy in the muscles (Sanders & Wilson, 1988). Thus, three phases in the process of maximising storage and use of springboard energy may be identified. In the first phase the diver 'holds' a crouched position during the landing from the hurdle and in the second phase the diver extends forcefully against the springboard at full springboard depression to 'work the springboard' to put additional energy in it. The last phase requires the diver to 'hold' the extended position during the recoil phase of the springboard (Miller & Munro, 1984; Sanders & Wilson, 1988).

The rationale for the diver 'holding the crouched position', that is, minimising the amount of flexion of the hip, knee and ankle joints during the landing of the hurdle, is that it minimises the absorption of energy by muscles through eccentric action. Research by Sanders and Gibson (2000) indicated that males landed from the hurdle in a more flexed position than females without absorbing energy by flexing after landing. This was believed to be a major reason for the greater height gained by males when compared to females. It was suggested that this difference might have been related to males having greater hip and knee extension strength than females. To add further energy to the springboard, the diver 'works the springboard' by extending forcefully near the time when it is fully depressed (Golden, 1981; Miller & Munro, 1984; Sanders & Wilson, 1988). The greater the flexion at landing, the greater the range of extension available to 'work the board' to increase the stored springboard energy during it's depression.

Sanders and Allen (1993) found that the timing and sequencing of the lower limb joint torques was an important factor in achieving height whilst performing a drop jump from a compliant surface. The drop jump, in which a subject drops from a height onto a surface and jumps to maximise height, is similar to the method employed in the take-off of a running dive from a springboard. Many studies have been conducted on both, vertical and drop jumps and the significance of joint torques. The research found that the magnitude and the timing of peak joint torque was important in the production of height in a vertical and drop jump (Bobbert, Huijing, & Van Ingen Schenau, 1987a,b; Dowling & Vamos, 1993; Sanders & Allen, 1993; Sanders & Wilson, 1992; Van Soest, Roebroeck, Bobbert, Huijing, & Van Ingen Schenau, 1985).

To complete the necessary rotations, the springboard diver must leave the board with an adequate amount of angular momentum in the desired direction of rotation. High demand rotational springboard dives such as the forward three and one half-somersault dive in the pike position (107B) and forward two and one half-somersault dive in the pike position (105B) require the diver to generate a high rate of rotation with a relatively large moment of inertia.

To generate the amount of rotation required to perform the nominated dive, the diver must generate sufficient angular momentum in the small amount of time from the instant of initiation of board recoiling until last contact with the springboard. To generate sufficient angular momentum he/she must vigorously "throw down" the upper body at the last instant, utilising the hip flexors. This vigorous "throw down" would require the generation of a large magnitude of flexion torque about the hip joint. The hip torque generated would normally have the effect of rotating the legs in the opposite direction to the rotation of the trunk. However, the frictional forces acting at the feet whilst in contact with the springboard prevent this from happening. Therefore, the frictional force generated acts with a large moment arm about the diver's centre of mass, to generate the desired angular momentum required for the dive.

The final angular momentum of the diver is the sum of the initial angular momentum of the diver possessed at the time of landing from the hurdle, and the changes in the angular momentum that occur between the instants of landing from the hurdle and last contact with the springboard (Miller, 1981). The change in angular momentum occurs when the springboards reaction forces create a torque that acts upon the diver (Miller, 1981). Angular momentum is dependent upon the reaction force of the springboard, the length of the moment arm, and the length of time over which the force acts. At touchdown from the hurdle during a forward springboard dive, the diver rotates forward moving the centre of gravity in front of the line of action of the springboard reaction force. Initially, the horizontal component of the springboard reaction force is responsible for generating torque in the desired direction. As the centre of mass moves forward and the springboard reaction force increases as it is depressed, the vertical component of the springboard reaction force is then primarily responsible for the torques that develop angular momentum for rotation in forward springboard dives (Miller, 1981; Miller & Munro, 1985b; Sanders & Wilson, 1988).

Divers in forward rotational dives have also been found to flex at the hips during springboard recoil (Miller & Munro, 1985a; Sanders & Gibson, 2000; Sanders & Wilson, 1987). This movement creates additional angular momentum that is required for high demand rotational dives. The drawback with flexing at the hips is that the board is unweighted due to mass being accelerated towards the board. When considering hip flexion in terms of energy, it is apparent that hip flexion causes a loss of energy for the purpose of gaining height. Consequently, height may be lost due to this mechanism.

Golden (1981), Miller and Munro (1984, 1985a,b), Sanders and Gibson (2000) and Sanders and Wilson (1987, 1988), have found that divers produce rotation by flexing the hips and leaning the whole body prior to rotation. These researchers have investigated the required techniques for gaining both height and rotation in springboard dives. However, the timing of body movements, especially flexion of the hips, has not been adequately investigated. The timing of these movements is important so that the diver can maximise the height and rotation required for a high demand rotational dive. The effect of timing and the rationale underlying this study is made clear by consideration of the following two scenarios, which may represent extremes of what actually occurs in practice.

In the first scenario, which is typically evident among novice divers, the diver produces rotation by leaning the whole body forward during the recoil phase of the springboard. During take-off, the diver attempts to quickly generate sufficient rotation and consequently commences hip flexion early (Figure 1), that is, soon after the springboard starts to recoil whilst it is close to being maximally depressed and possesses a high magnitude of energy. Based on earlier knowledge gained from Miller and Munro, (1984, 1985a, b), Sanders and Gibson, (2000), and Sanders and Wilson, (1987, 1988) this early hip flexion would accelerate the diver's mass towards the springboard. This consequently reduces the reaction forces of the springboard and dissipates much of the energy that could have been used to generate height and rotation.

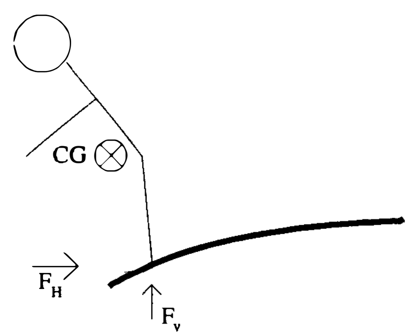

Figure 1. Production of rotation evident in novice divers from the horizontal (F_H) and vertical (F_V) forces. The centre of gravity (CG) is moved forward by flexing at the hips soon after springboard recoil begins.

In the second scenario, divers may be able to initiate rotation late in the dive by remaining extended until late in the period of contact. By maintaining an extended position until late in the period of springboard contact the diver gains a greater vertical velocity, which in turn, generates greater height than when the hips are flexed early. To generate sufficient rotation to perform the dive, angular momentum must be generated rapidly in the remaining time until last contact. The delayed flexion would require a vigorous 'throw-down' (throw-down implies flexion of the trunk at the hips) utilising the hip flexors and would necessitate large torques to be generated about the hip joint. This action generates large frictional forces acting from the diver's feet towards the fulcrum of the springboard (Figure 2). These forces would then assist in creating angular momentum as the diver leaves the springboard due to the large moment arm from their line of action to the diver's centre of mass.

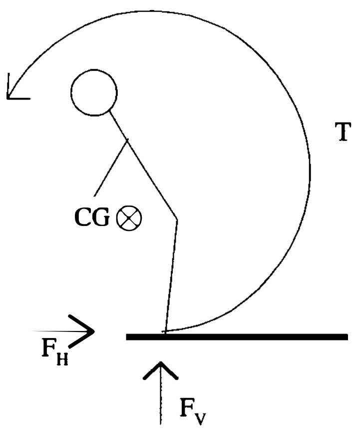

Figure 2. Production of rotation when remaining in an extended position until near the time of last contact. Hip flexion moves the centre of gravity (CG) forward. F_H and F_V depict horizontal and vertical forces respectively. Torque (T) can still be created whilst attempting to maximise vertical velocity.

Obviously, the second scenario would be preferable as the diver can achieve good height as well as generating sufficient rotation to complete the dive successfully. However, to achieve this, the diver must have the ability to generate sufficient hip torque.

If the diver times the hip flexion close to last contact as described in the second scenario, the angle of hip flexion at last contact may be less than that for divers who use the first scenario to initiate rotation. Interestingly, Miller and Munro (1985a) and Sanders and Wilson (1988) found that better divers showed a more extended hip angle and a greater vertical velocity at last contact than worse divers, thereby allowing a greater vertical height to be obtained. The greater hip angle in the better divers would allow the diver to maximise the springboard's reaction forces and utilise more of the energy that could be used to generate height and rotation in keeping with the rationale described above.

1.2 Purpose of the Study

The purpose of this study was to investigate the relationship between the vertical velocity at take-off and the timing and magnitude of hip flexion torques prior to the take-off in forward dives with high rotational demand. This study may assist coaches and strength and conditioning professionals to design programs with sound rationale for divers.

1.3 Research Question

The research question for the study was:

i. Is there a relationship between high vertical velocity and the timing and magnitude of peak hip flexion torque in high demand forward rotating dives on the 3m springboard?

1.4 Hypothesis

The hypothesis for the study is:

i. In dives of high rotational demand (a forward three and one-half somersault dive (107B) by males and forward two and one-half somersault dive (105B) by females), the magnitude of vertical velocity at take-off will be positively related to the magnitude of normalised peak hip flexion torque and negatively related to the time of peak hip flexion torque with respect to last contact with the springboard.

1.5 Definition of Terms

Definitions of biomechanical and diving terms commonly used throughout this thesis are provided below.

1.5.1 Biomechanical Terms

i. Moment of Inertia: The resistance of a body to changing its angular motion.

ii. Angular Velocity: The rate of change of the orientation of a line segment in a plane.

iii. Angular Momentum: The product of a body's moment of inertia and angular velocity.

iv. Inverse Dynamic Analysis: The mathematical process of obtaining the kinetics (force, torque) of motion from the kinematics (acceleration, velocity). The formulae used in this process are:

$\Sigma F_x = ma_x$ (1)

where F_x = horizontal force; m = segment ι mass; a_x = horizontal acceleration.

$\Sigma F_y = ma_y$ (2)

where F_y = vertical force; m = segment ι mass; a_y = vertical acceleration.

$\Sigma T = I_i \alpha$ (3)

where T = torque; I_i = moment of inertia of segment $_i$; α = angular acceleration.

v. Kinematics: The area of biomechanical research that is concerned with the position, velocity and acceleration of a body.

vi. Kinetics: The area of biomechanical research that is concerned with the forces that act on a body.

vii. Linear Momentum: The product of a body's mass and velocity.

viii. Torque/Moment of Force: The turning effect of a force.

ix. Videography: The method of capturing images onto videotape.

1.5.2 Diving Terms

i. Degree of Difficulty: A value related to the difficulty of a performed dive by which the score given by the judges is multiplied. The degree of difficulty is given to each dive according to the height of the board on which the dive is performed, the orientation of the take-off, the position the dive is performed in, the number of rotations and the number of twists of the dive.

ii. 'Throw-Down': Vigorous flexion of the trunk seen when initiating rotation on the springboard.

iii. Touchdown from hurdle: The first video frame in which the foot was seen to be flat on the springboard when landing from the hurdle.

iv. Maximal Depression: The video frame in which the springboard was maximally depressed just prior to recoil.

v. Depression Phase: The time from when touchdown from the hurdle was observed to the time when maximum depression of the springboard is observed.

vi. Last Contact: The last contact of the diver on the springboard. However, if the gap between the toes and the board was very small and it was noticeable that the board was still weighted in the previous frame, then the frame in which the small gap was evident was selected

vii. Recoil Phase: The period of maximal depression to last contact of the springboard.

viii. Take-off Phase: The period between touchdown from hurdle to last contact.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Introduction

The following review of literature provides information significant to this investigation. The first section of this chapter refers to the kinematics and kinetics of the forward group of dives with relation to what has been studied in the past. The second section focuses on inverse dynamics and what has been achieved by using inverse dynamics to investigate joint torques. This section analyses the comparison between the 'top-down' approach of inverse dynamics, and the traditional 'bottom-up' process and compares the accuracy and relevance of both methods to calculating joint torque. The last section examines joint torques and specifically how hip joint torque plays a role in the achievement of height in vertical jumps and drop jumps.

2.2 Kinematics and Kinetics of Forward Dives in Springboard Diving

Researchers of springboard diving have focused mainly on two areas. The first area of research has been directed towards the kinematics and kinetics of the take-off of a springboard dive. This area of investigation has provided much information relevant to this study. The other area of research covers twisting and aerial manoeuvres. This area of research has not been reviewed as it has little relevance to the present study.

From earlier research cited on the take-off sequence in springboard diving, the kinematics prior to take-off have been found to be the major focus of many researchers. The majority of the research into the kinematics of a forward springboard dive was conducted throughout the 1980's by Golden (1981), Miller (1981, 1984), Miller and Munro (1984, 1985a,b), and Sanders and Wilson (1987, 1988). This research focused predominantly on the velocity of the diver and the angular displacement of the joints during the process of the take-off. Studies of the velocity of the diver have included the analysis of vertical and horizontal velocities and their relationship to height and rotation. Studies of joint displacement focused on the contributions to the height gained and the rotation of the individual segments as well as the body as a whole. These areas will now be discussed in turn.

2.2.1 Vertical Velocity of Springboard Dives

It is important to review the literature relating to factors that contribute to vertical velocity as vertical velocity of the centre of mass at last contact determines the height achieved in flight (Golden, 1981; Miller, 1981; Miller & Munro, 1984, 1985b; Sanders & Wilson, 1988). This is particularly important, as the timing of hip torque and its relationship to height achieved in flight, the focus of this study, had not been considered previously. The review of vertical velocity in springboard dives has provided important background information that contributed to the development of the rationale outlined in Chapter 1.

The vertical velocity of the diver at last contact in forward and reverse dives has been found to be highly dependent upon the vertical velocity of the diver at touch down from the hurdle, and the work done on the board prior to last contact (Miller, 1981; Miller & Munro, 1984; Sanders & Wilson, 1988).

Miller and Munro (1984) found that male divers tended to have a higher average negative (downward) vertical velocity than female divers when landing from the hurdle. The results of the study indicated that the male divers who performed a forward three and one-half somersault dive in the tuck position obtained an average vertical velocity at hurdle landing of $-4.32 m.s^{-1}$. Female divers who performed a forward two and one-half somersault dive in the pike position averaged a vertical velocity of $-3.55 m.s^{-1}$. The difference between the male and female divers was due to the higher hurdle of the male divers. This gave the males more time to drop to the board and consequently, the male divers achieved a greater downward velocity when they contacted the springboard (Miller, 1984; Miller & Munro, 1984). This higher downward velocity was found to be one of the contributing factors to male divers performing one full rotation more than female divers (Miller, 1984; Sanders & Gibson, 2000). Upon landing from the hurdle divers prepare to work the springboard to add further energy to it. The co-ordination and actions of the body parts will be discussed in a later section in this review.

To work the springboard, the diver co-ordinates several body parts to add further energy to the board to increase the springboard reaction force (Miller, 1981, 1984; Miller & Munro, 1984; Sanders & Wilson, 1988). The diver works the springboard by extending at the hip, knee and ankle joints adding kinetic energy to the springboard (Sanders & Wilson, 1988). The work done stores strain energy during the depression of the springboard, which is then used during the recoil of the springboard to increase the vertical velocity of the diver.

During the recoil phase the diver's vertical velocity, which is already positive (upward) prior to recoil, continues to increase with the maximum vertical velocity being reached shortly before last contact. The maximum vertical velocities found by Miller and Munro (1984) for males performing the forward three and one-half somersault dive in the tuck position and females performing the forward two and one-half somersault dive in the pike position were $5.17 m.s^{-1}$ and $3.92 m.s^{-1}$ respectively. It was found that the magnitude of vertical velocity prior to take-off decreased with increasing rotation in the dive (Miller, 1981, 1984; Miller & Munro, 1984).

Miller and Munro (1984) found that the difference in the magnitudes of the final vertical velocities of the divers was dependent on the number of rotations performed and the position in which the dive is performed. Dives performed in a tuck position required less rotation around the transverse axis (i.e. somersaulting axis), than those dives performed in both the pike position and layout position, in accordance with their relative moments of inertia (Miller, 1984).

2.2.2 Horizontal Velocity of Springboard Dives

The magnitude of the horizontal velocity generated by the diver has been found to be significant in the development of rotation of a diver in forward springboard dives (Sanders & Wilson, 1988). A high degree of horizontal velocity at last contact was associated with a reduced vertical component and height of the dive produced after last contact. Therefore, an optimal level of horizontal velocity needs to be produced for rotation without reducing the degree of vertical velocity produced required for height.

Horizontal velocity in the hurdle has been found to contribute to rotation, by generating a braking force. The braking force produces a moment to rotate the diver in the forward direction as the diver rotates so that the centre of mass is in front of the line of the vertical reaction force. The component then contributes to the development of angular momentum.

The horizontal component of velocity at last contact in a forward springboard dive allows a diver to move safely away from the board. The number of rotations performed in the dive influences the final horizontal velocity of a dive (Miller, 1981, 1984; Miller & Munro, 1985b; Sanders & Wilson, 1988). Dives that have a high horizontal velocity such as a forward two and one-half somersault dive, have been found to be associated with lower vertical velocities (Sanders & Wilson, 1988). The high horizontal velocities in high demand forward rotational springboard dives are due to the increase in forward lean required to complete these dives (Sanders & Wilson, 1988). Miller (1984) found that divers who could not generate a high final vertical velocity, from either a lack of skill and/or strength, compensated by generating a high degree of horizontal velocity to help generate rotation.

The movement of the diver's body partly determines the springboard's reaction forces transferred to the diver (Sanders & Wilson, 1988). To generate horizontal velocity, the diver can lean forward creating a high horizontal reaction force from the springboard (Miller, 1981, 1984; Miller & Munro, 1985b; Sanders & Wilson, 1988) as evident in Figure 1. If however, the diver leans too far forward, this lean will reduce the vertical reaction force of the springboard, resulting in a low vertical velocity, which in turn will diminish the diver's peak height after last contact (Sanders & Wilson, 1988).

As far as the researcher is aware, no other studies have examined the influence of horizontal velocity on the take-off of springboard dives. The importance of generating an appropriate horizontal velocity during the hurdle to generate the necessary rotation without detracting from the vertical component is of utmost importance in the success of a high rotational dive.

2.2.3 Lower Limb Joint Displacement in Springboard Dives

The contributions of the lower limb joints of the body have been found to be another major component to the success of a dive (Golden, 1981; Miller, 1981; Miller & Munro, 1984, 1985a; Sanders & Wilson, 1988). The reason for this is twofold. First, the lower limb joints involved in forward dives influence not only a diver's height gained after last contact, but also the development of angular momentum. Second, in the majority of studies cited (Golden, 1981; Miller, 1981; Miller & Munro, 1984; Sanders & Wilson, 1988) the influence of the segments in achieving height has been a major influence on the successful outcome of the springboard dive.

Given that the displacement of the lower limb joints has an influence on both the height achieved after take-off and rate of somersault rotation, it is important to review the literature relating to the lower limb joints and their movement throughout the take-off phase of the dive. The review of joint displacement, especially of the hips, has also provided important background information that has contributed to the development of the rationale discussed in Chapter 1.

To maximise height, a diver co-ordinates the acceleration of the body segments by extending the hip, knee and ankle joints. These joints contribute to the final vertical velocity at last contact of a forward dive (Miller & Munro, 1984, 1985a; Sanders & Wilson, 1988). The co-ordination of the body segments has been found to be most important during two distinct phases of the take-off in a springboard dive. These phases are the depression phase and the recoil phase of the take-off. The depression phase allows the diver to store energy in the springboard for later use during the recoil phase of the dive. During the recoil phase the diver utilises the stored energy to achieve a high vertical velocity and generates most of the angular momentum to perform the dive.

Miller and Munro (1985a) found that upon landing from the hurdle the diver minimally flexed the lower extremities for approximately the first 35% of springboard depression. The diver should aim to minimally flex the lower limbs during this time to avoid the absorption of energy through eccentric action of the lower limbs (Sanders & Allen, 1993). Sanders and Allen (1993) found that the minimal flexion of the lower extremities helped in minimising the eccentric action of the muscles following landing when jumping from a sprung surface. The study by Sanders and Allen (1993) was not aimed at diving research, but the findings of the study have implications for diving, as it looked at the kinetics and kinematics associated with jumping for maximal height from a compliant surface. The subjects in this study were found to adjust the timing and the sequencing of their lower limb joint torques over a period of time after practising first on a hard surface. The adjustment of the lower limb joint torques was found to help the subjects to achieve maximum height, through the minimisation of flexion upon landing from a drop jump. The most apparent change in the joint torque sequence found by Sanders and Allen (1993) was the increase in hip, knee and ankle extension torques early in the contact period of the drop jump. Though the findings were related to the extension phase of a drop jump, and were related to height, not rotation, the findings still illustrate the importance of lower limb joint torques in generating maximal height when jumping from compliant surfaces. These increases in extension torque were found to minimise joint flexion and the energy absorbed by the muscles of the joints following landing and help in the storage of energy in the spring. The decrease in joint flexion was found to coincide with the adjustment in the sequencing of the extensions of the lower limb joints from a hip-knee-ankle sequence to a knee-hip-ankle sequence.

This change in sequencing was found to be related to changes in the timing and sequencing of the net joint torques, with increased hip and knee torques early in the landing phase of the drop jump.

As Sanders and Allen's (1993) study closely resembled the take-off process of a springboard dive, by getting the subject to perform a drop jump from a compliant surface, the results found may be relevant to producing maximal height in springboard diving. Sanders and Allen (1993) performed the 'top-down' approach to inverse dynamics to calculate the joint torques required for the subjects to maximally jump from a drop jump onto a compliant surface. The information from the studies into drop and vertical jumping has provided important background information that contributed to the development of the rationale of the study outlined in Chapter 1.

When landing from the hurdle, the diver should extend against the springboard, depressing the springboard maximally before it's recoil, adding more energy to the springboard (Miller & Munro, 1984, 1985a; Sanders & Wilson, 1988). Miller and Munro (1985a) found that divers dedicated between 50% and 60% of the depression phase to actively pushing against the springboard. The extension phase in the depression of the springboard was found to be initiated from the extension of the hip, followed shortly thereafter by the knee and ankle joints (Miller & Munro, 1985a). This process is similar to the proximal to distal pattern found in vertical jumping (Umberger, 1998; Zajac, 1993). In comparison, the study by Sanders and Allen (1993) showed that when jumping from a compliant surface, the sequencing of the lower limbs in relation to the timing and sequencing of the lower limb torque changes. The change in the sequencing of the lower limb torque is indicated by the change in the timing of the peak torque produced by the hip, knee and ankle joints. This change in sequencing has yet to be seen in springboard diving research, as the majority of studies were conducted prior to this finding.

During the recoil of the springboard, divers should not unnecessarily flex the hip and knee joints, as this unwanted flexion absorbs energy from the springboard. The diver should try to stay as rigid as possible to gain the maximum amount of vertical velocity from the reaction force of the springboard following depression, though a degree of flexion at the hips occurs late in the take-off (Sanders & Gibson, 2000).

From the various studies described above as well as from a knowledge of joint kinetics it is established that for the energy absorption to be minimised the diver should generate hip and knee extension torque early and steadily increase the extension torque with peak extension torque occurring close to maximal depression of the springboard. This will enable the diver to hold the extended position during the recoil of the board and minimise the absorption of energy by the muscles. This is extremely important, as the end goal of the diver during take-off is to maximise height. For the diver to hold the extended position during recoil joint extension torques are required to overcome the reaction forces of the springboard. Prior to last contact, the diver should then rapidly generate peak flexion torque to flex at the hips for the generation of rotation as described in Chapter 1.

Golden (1981) found that as the rotational requirements for a dive increased the body position of the diver at last contact altered. In dives with little rotational demand the angle of the hip at last contact was greater in a high rotation dive. The forward dive and forward one and one-half somersault dive averaged hip angles of 168.6° and 147.6° respectively, whilst the forward two and one-half somersault dive and three and one half somersault dive averaged hip angles of 129° and 111.8° respectively. These findings suggest that the flexion of the hips may have helped in generating the rotation needed for the high rotation dives.

For the diver to generate angular momentum, contributions from the body segments are required. Miller (1981) found that during the generation of angular momentum the remote contributions of the limb segments (i.e. hand, forearm, upperarm, thigh, shank, and foot), accounted for approximately 80% of a diver's input to the total angular momentum prior to take-off. The trunk contributed the remaining 20% of angular momentum just prior to last contact. Therefore, it is hypothesised that when the diver vigorously 'throws down' the upper body and arms, the contribution to angular momentum of these segments will be large. This will be evident as the centre of mass of the arms and trunk move away from the line of the centre of gravity of the whole body, with the vigorous 'throw down' generating a high angular velocity due to the mass moment of inertia of these limbs. With the diver timing the 'throw down' to just before last contact great torques are required to be generated at the hips to cause the flexion at the hips due to the large moment of inertia of the trunk relative to the hip joint. This, as previously stated, will allow the diver to 'ride' the springboard longer to maximise height.

The contribution of the trunk to the generation of angular momentum is due to its large moment of inertia as outlined previously by Miller (1981). Divers flex late at the hips by utilising the trunk to initiate rotation, with the flexion occurring during the last 30% of the take-off phase (Sanders & Wilson, 1988). Late hip flexion was associated with height difference (r = 0.52), which was calculated between the divers centre of gravity at last contact and the maximum height during the flight. Therefore, it may be inferred, that if the diver initiates flexion late in the takeoff process, the difference between the height at last contact and the height gained at peak height may be greater than those divers that initiate flexion earlier. This finding is important to the development of the rationale outlined in Chapter 1.

Sanders and Wilson (1988) found that the variance in the peak height obtained after last contact between male and female divers (CG at peak height was 2.29m and 1.75m respectively for a 105B) could be explained by two uncorrelated variables, kinetic energy at touch down and the flexion of the hips at last contact. Sanders and Wilson (1988) suggested that further research was required to investigate the relationship between the segmental timing patterns and the storage and utilisation of strain energy to gain height and rotation. One suggestion for the difference in heights attained by male and female divers was that strength might be a limiting factor. This suggestion may carry over to the need for a vigorous flexion of the hips if a late 'throw-down' is required, as suggested in the rationale discussed in Chapter 1. It could be that strength may be a limiting factor in the generation of a large hip flexion torque required late in the period of take-off.

Divers use the whole body to help in generating angular momentum through leaning in the desired direction of rotation (Sanders & Wilson, 1988). However, if the diver leans excessively, a reduction in the springboard vertical reaction force will occur. This is brought about by a decrease in the acceleration of some of the body's mass with respect to the springboard. Golden (1981) found that the angle of lean at the instant of last contact increased with each additional somersault performed. Golden (1981) found that the forward dive and forward one and one-half somersault dive averaged lean angles of 6.6° and 11.1° respectively, while the forward two and one-half somersault dive and three and one-half somersault dive averaged lean angles of 12.6° and 16.2° respectively. These findings also hint that the lean of the body as a whole was employed to help in the rotational requirements of high rotational dives.

Miller and Munro (1984) suggested that a smaller hip angle and greater angle of lean of a diver during recoil reduced the vertical reaction force of the springboard. However, Sanders and Gibson (2000) found that male divers showed a smaller hip angle and greater angles of lean, when performing a 107B, than the female divers, who performed a 105B, while also achieving greater height than the females. This was primarily due to males imparting more energy to the springboard prior to recoil than the females.

With the diver flexing at the hips and leaning the whole body the timing of these factors may be important to attain maximal height. Several studies have indicated the influence these factors have on vertical height and rotation, by talking about the degree of flexion and the timing of when flexion occurs (Miller & Munro, 1985a; Sanders & Wilson, 1988; Sanders & Gibson, 2000). To date there has been no attempt to establish the effect the timing of flexion has on height, or whether it varies with ability.

2.3 Inverse Dynamics

Inverse dynamics analysis has been stated as "one of the most important techniques in biomechanics to determine the mechanical work produced by a subject during a certain movement" (Nagano, Gerritsen & Fukashiro, 2000, p 1313). Inverse dynamics helps to uncover parameters that are typically hidden, these parameters include internal force, torque and energy (Vieten, 1999). The data collected from inverse dynamics, can help in the development of simulations of higher complexity, than those obtained from direct measurements (Vieten, 1999).

To calculate joint torque it is necessary to calculate the kinetics of each body segment in a sequential manner. Kinetic calculations are based on the premise that the sum of the moments is equal to the product of the segment moment of inertia about the segment centre of gravity and the angular acceleration of the segment (Sanders & Allen, 1993). This can be seen in formulas one, two and three outlined in Section 1.6 (de Looze, Kingma, Bussmann & Toussaint, 1992; Enoka, 1994; Winter, 1990). These formulas are still the staple formulas used to this day, and have been found to be valid tools used in calculating joint torque and power.

Vieten (1999) utilised inverse dynamics through three distinct steps. Taking these three steps into consideration, and providing that gravity and, at the most, one additional external force is acting, the whole scenario is uniquely defined (Vieten, 1999). If additional external forces are acting on the model, these forces and the locations that they act upon must be included in the calculations.

Inverse dynamics can either be performed from the feet up ('bottom-up' approach), or from the hands down ('top-down' approach). When analysing data using the 'bottom-up' approach a force platform is used to calculate the ground reaction force vector, which acts at the centre of pressure (Barden & Robertson, 1994; de Looze et al., 1992). The line of action of the ground reaction force vector must be accurately known, as this greatly influences the calculation of the first net joint torque (Sanders & Allen, 1993). Therefore, in some circumstances where a force platform cannot be used, as in the case of a springboard dive where a subject is jumping from a moving surface, the line of action of the ground reaction force cannot be determined. In this instance, the 'top-down' approach has to be used to calculate joint kinetics.

The process of the 'bottom-up' approach as described by de Looze et al. (1992) shows that moments and forces at the ankle acting on the feet are first calculated, with knowledge of the ground reaction force. In accordance with Newton's third law, for every action there is an equal and opposite reaction, they next applied the same equations to the segments representing the shank, thigh and hips respectively. Ground reaction force data are required prior to the calculations for the feet.

The 'top-down' approach, which is used in this study, requires the same set of equations used for the 'bottom-up' approach. The 'top-down' approach however, starts at the hands, assuming that there are no external forces present other than gravity. From there, the equations are calculated through the forearms, upper arms, and trunk respectively, moving down the system. Ground reaction force data are not included in this method and a force platform is not required (de Looze et al., 1992).

Present thought about dynamic analysis is that the 'bottom-up' approach is the more accurate method for determining joint torques in the joints of the lower limbs than the 'top-down' approach. This is because errors in the first calculations effect subsequent calculations. Therefore, errors accumulate as the calculations progress along the chain of segments.

Calculating the net joint torques using the inverse dynamic approach has been found to be a highly dependable method (deLooze et al., 1992; Kadaba, Ramakrishnan, Wooten, Gainey, Gorton, & Cochran, 1989). One study conducted by de Looze and associates (1992) compared the 'top-down' and 'bottom-up' approaches. This study showed a high correlation between the two methods when calculating the moment present at the hip. The 'top-down' approach when modelled from the hands to the feet showed a high correlation (r = 0.88) when predicting ground reaction forces. When comparing results for the moments calculated at L_5-S_1 the 'top-down' and 'bottom-up' approach yielded a high correlation (r = 0.99). When testing either on the same day, or between days, the inverse dynamics approach proved to be highly reliable with same day correlations ranging between 0.856-0.992, and between day correlations ranging between 0.817-0.986 (Kadaba et al., 1989). From these findings, we can conclude that both the 'top-down' and 'bottom-up' methods are equally appropriate in assessing joint kinetics. With the production of reliable results that share a strong relationship to other variables, it may be expected that acceptably accurate and reliable results can be obtained with the 'top-down' approach.

Some experimental error related to inverse dynamics has been found to be almost impossible to eliminate (Nagano et al., 2000). From the literature cited, there are several sources of error that may affect the output of inverse dynamics calculations (de Looze et al., 1992; Nagano et al., 2000; Vieten, 1999; Wojcik, Thelen, Schultz, Ashton-Miller, & Alexander, 2001).

One source of error that has been found to affect the outcome is the error in kinematic data (Challis & Kerwin, 1996). Digitising errors and skin movement artefacts have been found to contribute to erroneous kinematic data (Nagano et al., 2000; Wojcik et al., 2001). With the movement of the body, skin movement is unavoidable. With this in mind, great care must be taken in digitising points in large movement such as those involved in springboard diving. The errors found in digitising can affect not only the point digitised, but the whole system, as inverse calculations require information from the previous point digitised. De Looze and associates (1992) found that errors made at one joint would appear in the next joint and all the subsequent joint locations. Therefore, great care and consistency must be taken when digitising data.

One other source of error found was the choice of the anthropometric data used (Nagano et al., 2000; Wojcik et al., 2001). To conduct kinematic and kinetic analysis, the body is modelled as a linked system of rigid segments (these segments include the hands, forearms, upper arms, head and neck, trunk, thigh, shank, and the feet). For reliable biomechanical analysis of total body motion, accurate estimates of the mass, centre of mass, centre of mass position and moments of inertia of all body segments is required (Plagenhoef, Evans & Abdelnour, 1983). Errors in these data have been found to be one of the major contributions to calculation errors in biomechanical analysis (Plagenhoef et al., 1983)

This error can occur as the location of the centre of mass for each segment is only an estimate for the true centre of mass. The above anthropometric error, and kinematic errors are related to each other due to the fact that the location of the segment centre of mass is calculated from the anthropometric data and the digitised points (Nagano et al., 2000). Therefore, great care must be used in choosing the anthropometric model to meet the requirements of the study. In the study conducted by deLooze and associates (1992), Winter's (1990) anthropometric data was used in their model to validate the 'top-down' approach with the 'bottom-up' approach.

2.4 Quantification of Net Joint Torque in Activities Related to the Diving Take-off

Sanders and Allen (1993) described drop jumping as a process in which a subject drops from a height onto a surface and jumps for maximal height. The process of a drop jump is therefore, similar to the method employed in the take-off of a forward somersault dive from a springboard. To quantify the timing and sequencing of the lower limb joint torques Sanders and Allen (1993) performed a 'top-down' approach to inverse dynamics. This approach allowed the researchers to calculate the lower limb joint torques of the subjects on a compliant surface similar to a springboard, without the use of a force platform.

Many other studies have applied an inverse dynamics approach to calculate joint torques in both drop jumps and vertical jumps (Bobbert, Huijing, & Van Ingen Schenau, 1987a,b; Dowling & Vamos, 1993; van Soest, Roebroeck, Bobbert, Huijing, & Van Ingen Schenau, 1985). A majority of these studies concluded that hip torque plays a major role in the achievement of height in a drop jump or vertical jump.

2.5 Summary

For the purpose of this study four main areas of research were reviewed. The first was the kinematics of springboard diving. The main focus of research into the kinetics and kinematics of springboard diving has been the analysis of the take-off (Golden, 1981; Miller, 1981; Miller & Munro, 1984, 1985b; Sanders & Wilson, 1988). The major areas focused upon in the literature were both vertical and horizontal velocity at take-off, and the lower limb joint displacement of the diver during the process of the take-off. The generation of angular momentum was also focused upon in these studies.

The second section focused upon inverse dynamics with Vieten (1999) describing inverse dynamics as a process that helps uncover parameters that are typically hidden in other forms of analysis. These parameters include internal force, torque and the energy produced. The data collected from inverse dynamics help in the development of simulations of higher complexity, than those that can be obtained from direct measurements (Vieten, 1999).

The process of inverse dynamics can be performed from both feet up ('bottom-up' approach) and hands down ('top-down' approach). When analysing data using the 'bottom-up' approach a force platform is used to calculate the ground reaction force vector (Barden & Robertson, 1994). When a subject is jumping from a moving surface, a force platform cannot be used, as in the case of a springboard dive, as the line of action of the ground reaction force is not possible to determine (de Looze et al., 1992).

The third section looked at the reliability of the 'top-down' approach when compared to the more traditional 'bottom-up' approach. One study conducted by de Looze et al., (1992) found a high correlation (r= 0.99) between the two methods when calculating the moment at the L_5-S_1 joint.

The last section reviewed studies related to analysis of kinetics in tasks similar to a springboard dive such as drop jumps for height. Many of these studies conducted on drop jumps concluded hip torque plays a major role in the achievement of height in a drop jump or vertical jump (Bobbert et al., 1987a,b; Dowling & Vamos, 1993; Van Soest et al., 1985).

CHAPTER 3. MATERIALS AND METHODS

3.1 Subjects and Experimental Protocol

Twenty-six divers competing in the United Kingdom leg of the FINA (La Federation Internationale de Natation) Diving Grand Prix held at the Manchester Aquatic Centre in Manchester City, England, during March 2001 volunteered to participate in the study. Height and mass for each of the divers were recorded (Table 1) using a Seca Stadiometer and Seca Beam Balance scale respectively. Informed consent was obtained from the divers prior to the competition, in accordance with the policy statement of the Edith Cowan University Ethics Committee.

A single JVC (JVC GR-DVL9800) digital video camera was used to record at 60 fields per second all males performing the forward three and one-half somersault dives in the pike position (107B) and all females performing the forward two and one-half somersault dives in the pike position (105B). All 107B and 105B dives recorded during the preliminaries and finals for their respective 3m-springboard event were analysed. Due to the competitive conditions under which the data were collected, the fulcrum position for the springboard adopted by each diver were not recorded. The specific dives for both the preliminaries and finals where recorded onto separate Panasonic mini digital videotapes (AY-DVM63EB) for ease of latter analysis. The divers were illuminated by a combination of both natural and artificial light at the aquatic centre, that is, the usual conditions for the diving competition. No additional lighting was provided for the research.

The video camera was positioned on a tripod (Manfrotto 116 Mk3) so that the lens was level with the end of the two 3m springboards used during the competition and perpendicular to the diver's plane of motion. The camera to subject distance was approximately 15m for one springboard and approximately 18m for the other. This ensured that the camera axis was perpendicular to the diver's plane of motion throughout the dive. The viewing frame was aligned with the vertical and horizontal axes of the earth reference system and was fixed at that orientation. The camera was manually focused and zoomed to ensure that the size of the diver, with the diver's height being approximately half the height of the viewing frame when outstretched, was sufficient to yield accurate measures of joint angles to be obtained during subsequent digitising. Before and after each diving round, a one-metre square calibration frame was placed in the field of view of the video camera and recorded.

In this study, the take-off phase was defined as the time from board contact, in which the foot was flat on the springboard following the hurdle, to the last frame when any contact was observed prior to flight. Digitising commenced 10 frames prior to the touchdown from the hurdle, and continued until 10 frames after the last contact of the dive.

Table 1
Diver Height and Mass.

		Height (cm)	Mass (kg)
Divers	*n*	*M* *(SD)*	*M* *(SD)*
Male	14	169.6	68.4
		(4.7)	(10.4)
Female	12	160.1	55.1
		(6.8)	(5.4)

3.2 Data Processing

Video footage was captured then stored in digital form using the 'Pinnacle Systems' (DV500) video capture software installed on a Dell Precision 220 mini tower. The resulting digital files were digitised using the Ariel Performance Analysis System (APAS), to create a two-dimensional model of the dive performed. The APAS converts digital video images into a computer 'pixel map', and the locations of each point selected are identified as an x-y co-ordinate location. To convert the image size to metric units the calibration object was digitised for each subject's dive. Data were smoothed using a fourth order dual pass Butterworth digital filter with a cut off frequency of 5Hz.

Subject's joint centres in this study could not be marked as the video footage of each dive was recorded during competition and minimal disruption to the diver's preparation was important. The landmarks that were identified in the study were the tip of the big toe, the ankle, knee, hip, shoulder, elbow, wrist joint, tip of finger and vertex. Only the left side of the diver was digitised throughout the period of interest.

As not all divers competed in the finals of the competition not all forward dives from the divers competing in both the preliminaries and finals were used in the analysis. The best dives of those divers who competed in both the preliminaries and the finals were used for subsequent analysis. This was done for both the male and female divers. Therefore, there were a total of twenty-six dives analysed (corresponding to the twenty-six divers that competed) instead of the forty-six dives that were digitised.

3.2.1 Repeatability of Acceleration Measurement

This study quantified hip flexion torque via a "top-down" inverse dynamics approach. As the process of deriving acceleration data from the digitised displacement data amplifies high frequency random errors, it was necessary to establish the reliability of the digitised data obtained after smoothing. Given the sensitivity of acceleration data to error, reliability of these data provided an indication of the reliability of the inverse dynamics calculations.

One trial was digitised five times to examine the repeatability of the x and y acceleration measurement for the centres of mass of selected body segments. The forearm and upper arm were examined, as they contained the highest accelerations and were therefore most likely to influence the magnitude of the hip torques. From these five trials, the mean and standard deviations were calculated for each point and compared to the five trials that were digitised. The mean and standard deviations for the acceleration data for the five trials are shown for the x-direction for the forearm (Figures 3a and 3b), forearm y-axis (Figures 4a and 4b), upper arm x-axis (Figures 5a and 5b) and the upper arm y-axis (Figures 6a and 6b) respectively. The mean percentage error was then calculated for each end point (Figures 3c, 4c, 5c and 6c), so that the effect of digitising error on the acceleration data could be calculated. The formula for the calculation of the mean percentage error is as follows:-

$$\text{Mean Percentage Error} = \frac{\text{Standard Deviation (error)}}{\text{Peak Acceleration}} \times 100$$

Due to the errors known to be associated with digital filtering, ten frames were digitised prior to and after the period of interest (Vaughan, 1982). From the figures depicting the standard deviations for acceleration measurement (Figures 3b, 4b, 5b and 6b) the areas' that showed the highest standard deviations were the areas outside the period of interest.

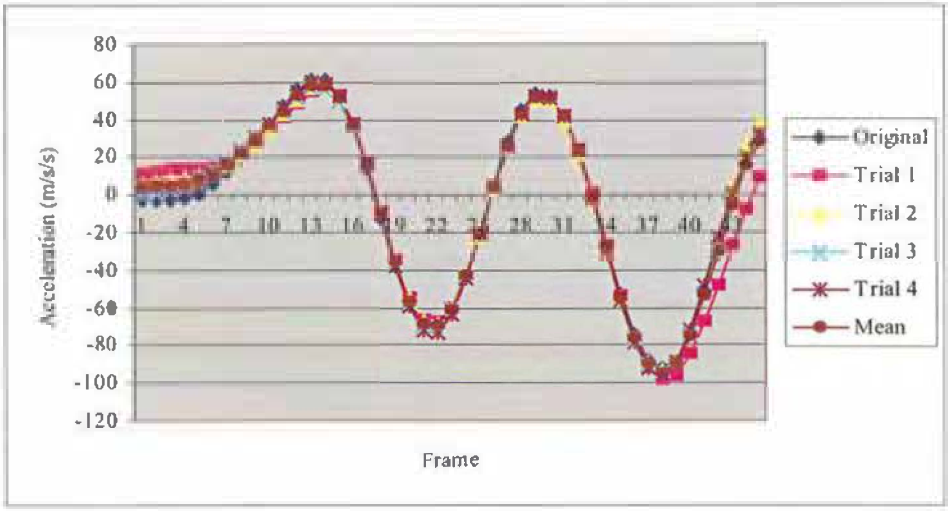

Figure 3a. Forearm X-axis acceleration data over five trials.

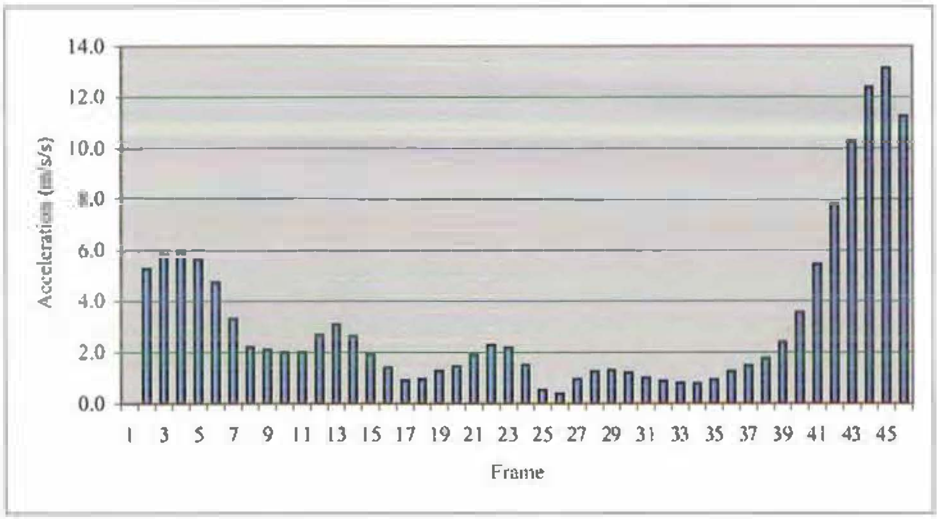

Figure 3b. Forearm X-axis standard deviations for five trials.

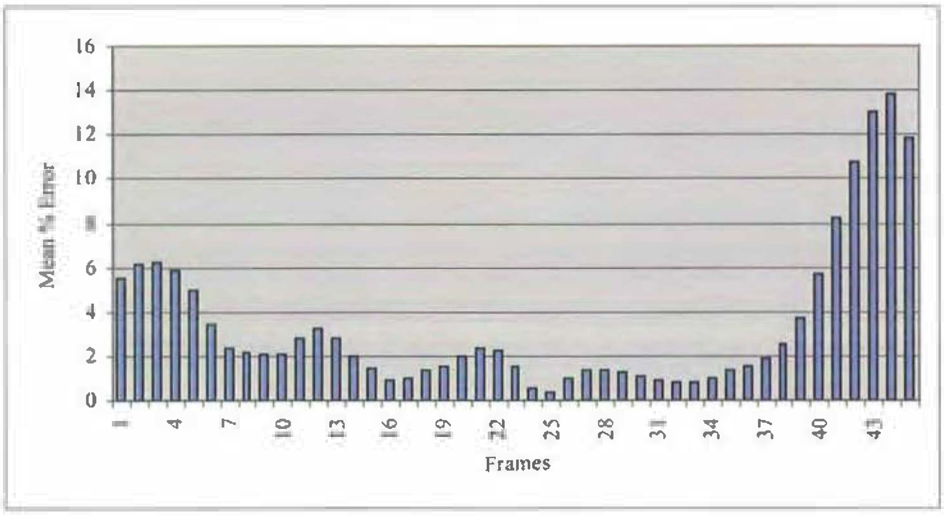

Figure 3c. Forearm X-axis mean percentage error for five trials.

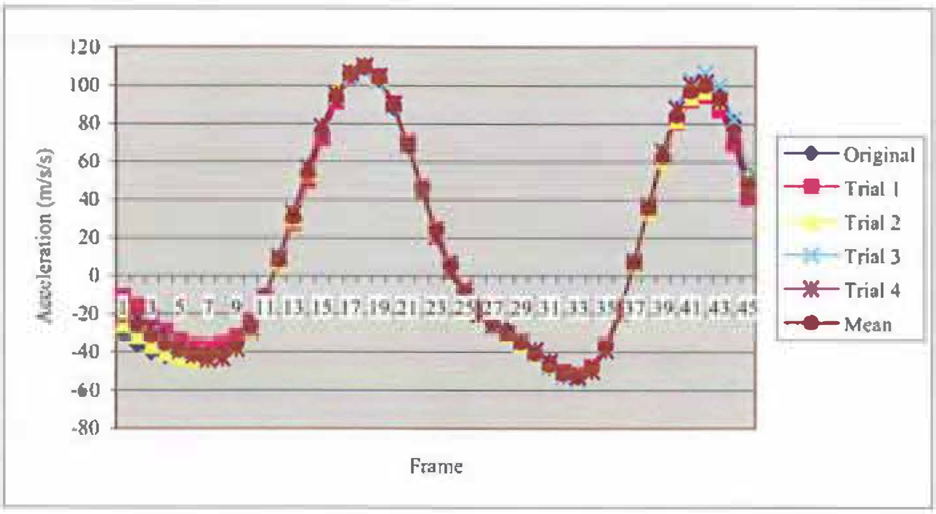

Figure 4a. Forearm Y-axis acceleration data over five trials.

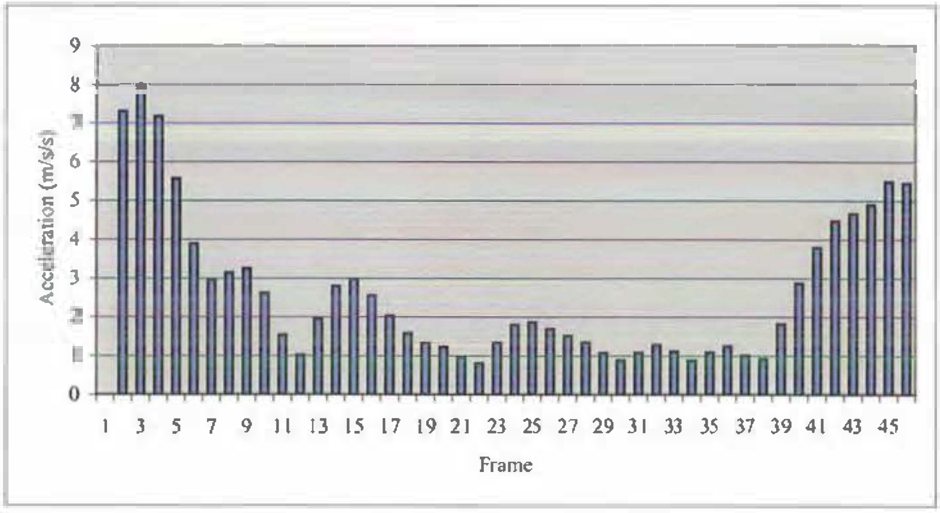

Figure 4b. Forearm Y-axis standard deviations for five trials.

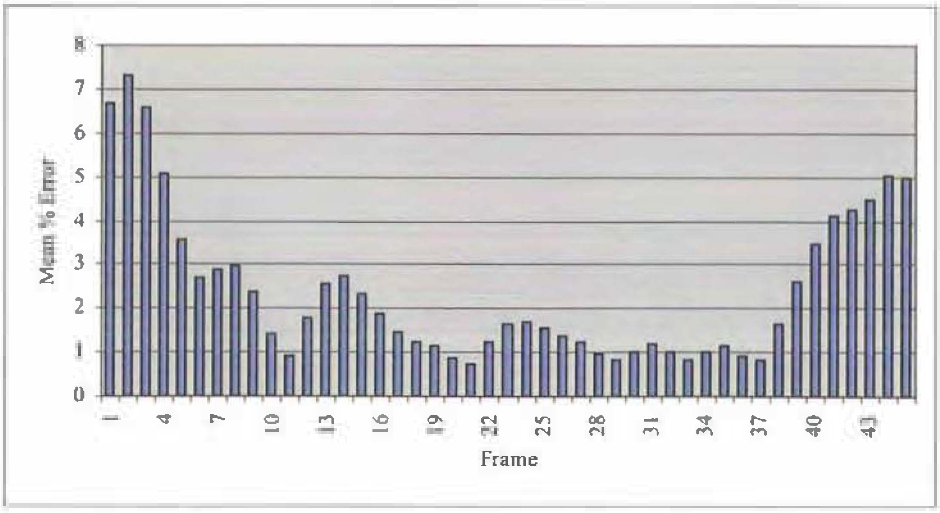

Figure 4c. Forearm Y-axis mean percentage error for five trials.

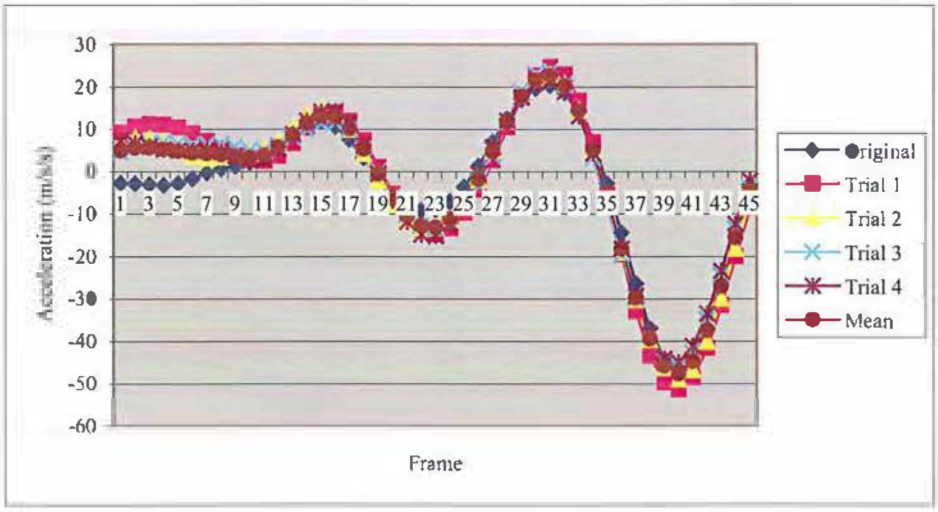

Figure 5a. Upper arm X-axis acceleration data over five trials.

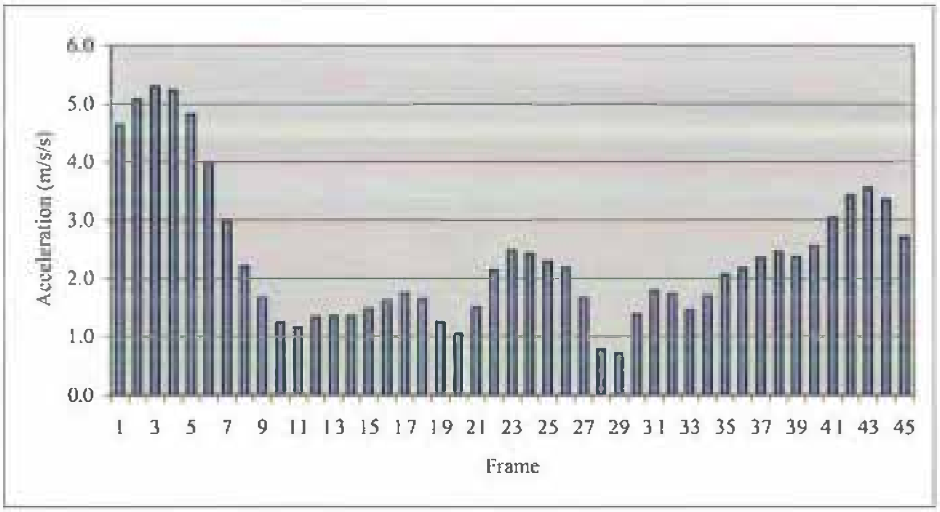

Figure 5b. Upper arm X-axis standard deviations for five trials.

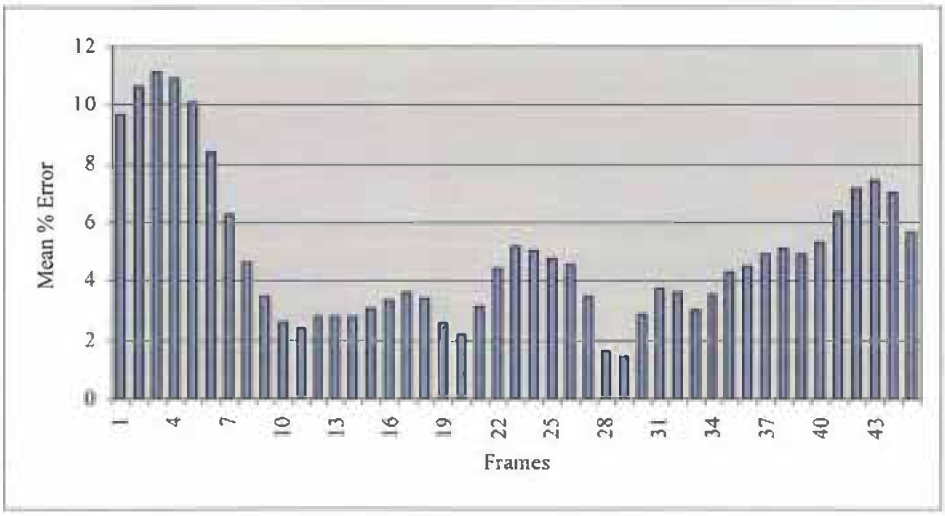

Figure 5c. Upper arm X-axis mean percentage error for five trials.

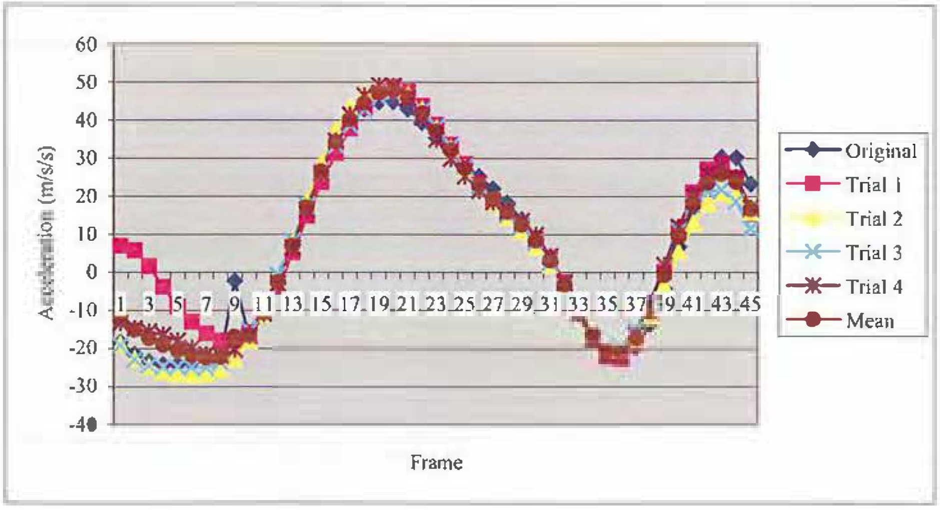

Figure 6a. Upper arm Y-axis acceleration data over five trials.

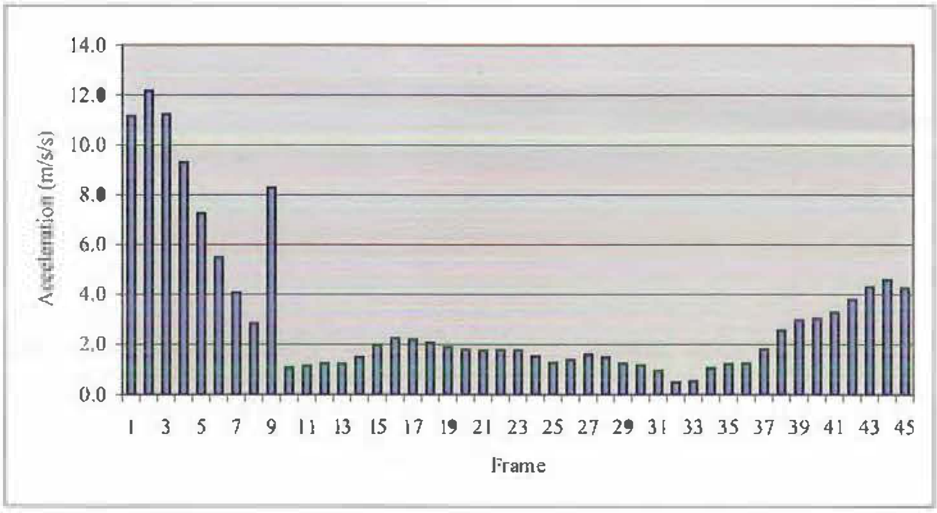

Figure 6b. Upper arm Y-axis standard deviations for five trials.

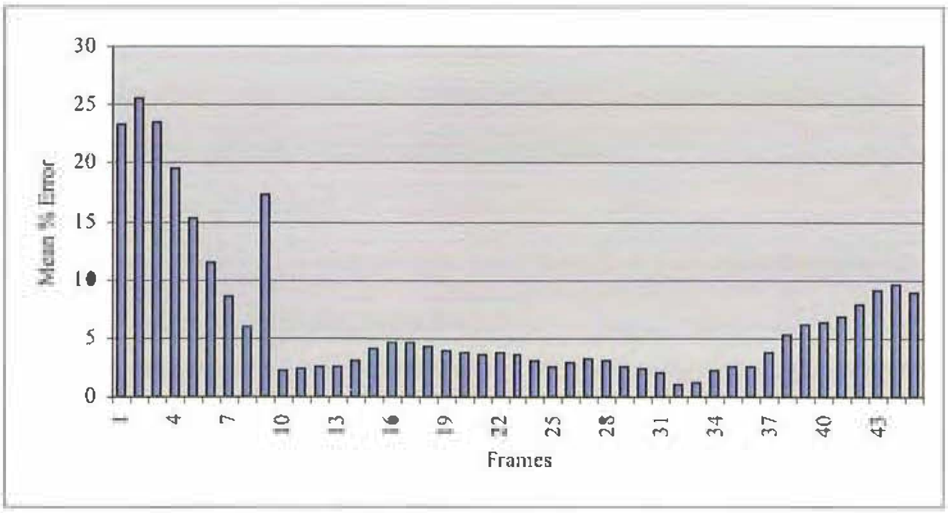

Figure 6c. Upper arm Y-axis mean percentage error for five trials.

Given that the standard deviations depicted (Figures 3b, 4b, 5b, and 6b) for each video frame were generally small relative to the magnitude of acceleration of the forearm and upperarm (Mean SD= 3.2, 3, 2.3, and 3 respectively) it may be concluded that the effect of digitising errors on reliability (Figures 3c, 4c, 5c, and 6c) of calculations were small (3%, 2%, 5%, and 7% respectively). Whilst at first glance there seems to be more variation in the data presented in Figures 5a and 6a when compared to Figures 3a and 4a, the scale of the y-axis has to be considered.

3.2.2 Model Description and Calculations

Kinetics about the hip joint were calculated via a "top-down" link segment model. The model used in this study, was a six-segment model similar to that described by Brown and Abani (1985). The segments contained in the model included the forearm and hand, the upper arm, the trunk (including the head and neck), the thigh, the shank and the foot. Having the forearm/hand and trunk/head/neck as single segments was deemed to be appropriate given that changes in joint angles between the component segments were small during the period of interest. The origins and end points for each of these segments can be found in Table 2.

The "top-down" model was dynamic in nature and was based upon Newtonian equations of motion as follows:-

$$\Sigma F_x = ma_x$$
$$\Sigma F_y = ma_y$$
$$\Sigma T = I\alpha$$

The assumptions made in the model were as follows: -

i. The diver was bilaterally symmetrical throughout the analysis.
ii. Body segments were treated as rigid bars.
iii. Joints were treated as frictionless and pinned.
iv. The shoulder/C7 connection was treated as a massless segment, which transferred force and torque.

Due to the dynamic nature of these calculations, segmental moment of inertia data had to be calculated. Segment anthropometric and moment of inertia data were taken from Dempster's data cited in Winter (1990). These data are shown in Table 2 below for each of the segments used for the model.

Table 2

Anthropometric Data Used in the 'Top-Down' Link Segment Model

Segment	Origin	Other	Norm Mass	2-D Mass	CM Norm	K Norm
Forearm/Hand	Elbow	Wrist	0.022	0.044	0.682	0.827
Upper Arm	Shoulder	Elbow	0.028	0.028	0.436	0.542
Trunk/Head/Neck	Shoulder	Hip	0.578	0.578	0.340	0.607
Thigh	Hip	Knee	0.100	0.200	0.433	0.540
Shank	Knee	Ankle	0.047	0.093	0.433	0.528
Foot	Ankle	Toe	0.015	0.029	0.500	0.690

Notes. Norm defines normalised mass in units of body weight and segment length. 2-D mass defines the combined mass of the left and right body segment. CM and K represent centre of mass with respect to the origin and radius of gyration respectively.

For each of the model's segments, the moment of inertia about the centre of mass was calculated via the following equation:-

$$I_o = m.(l * k)^2$$

where I_o – segmental moment of inertia (kg.m^2)
m – segment mass (kg)
l – segment length (m)
k – radius of gyration (% of length)

For each of the defined segments, F_X, F_Y and Torque were calculated. This was necessary, as calculations for the subsequent segment required these data. The equations were as follows:-

Calculations for Elbow Joint.

$$F_{ex} = -1*(m_f * a_{fx});$$
$$F_{ey} = -1*(m_f * (a_{fy} - g));$$
$$T_e = (I_f * \alpha_f) - (F_{ex} * L_f\rho_f \, Sin\theta) + (F_{ey} * L_f\rho_f \, Cos\theta)$$

Calculations for Shoulder Joint.

$$F_{sx} = F_{ex} - (m_u * a_{ux});$$
$$F_{sy} = F_{ey} - (m_u*(a_{uy} - g));$$
$$T_s = (I_u * \alpha_u) - (F_{ex} * L_u(1-\rho_u) \, Sin\theta) + (F_{ey} * L_u(1-\rho_u) \, Cos\theta) - (F_{sx} * L_u\rho_u \, Sin\theta) + (F_{sy} * L_u\rho_u \, Cos\theta) + T_e$$

Calculations for Hip Joint.

$$F_{hx} = F_{sx} - (m_{thn} * a_{thnx});$$
$$F_{hy} = F_{sy} - (m_{thn}*(a_{thny} - g));$$
$$T_h = (I_{thn} * \alpha_{thn}) - (F_{sx} * L_{thn}\rho_{thn} \, Sin\theta) + (F_{sy} * L_{thn}\rho_{thn} \, Cos\theta) - (F_{hx} * L_{thn}(1-\rho_{thn}) \, Sin\theta) + (F_{hy} * L_{thn}(1-\rho_{thn}) \, Cos\theta) + T_s$$

NOMENCLATURE

Segments.

f	forearm/hand;
u	upperarm;
thn	trunk/head/neck;

Joints.

e	elbow;
s	shoulder;
h	hip;

F_x	force in x-direction;
F_y	force in y-direction;
m	segment mass;
g	acceleration due to gravity (-9.8005 $m.s^{-1}$)
a_x	segmental centre of mass acceleration in x-direction;
a_y	segmental centre of mass acceleration in y-direction;
T	moment acting about a joint;
I	moment of inertia about segmental centre of mass;
α	segmental angular acceleration;
L	length of segment;
ρ	relative position of segmental centre of mass;
θ	absolute segment angle with reference to right hand horizontal

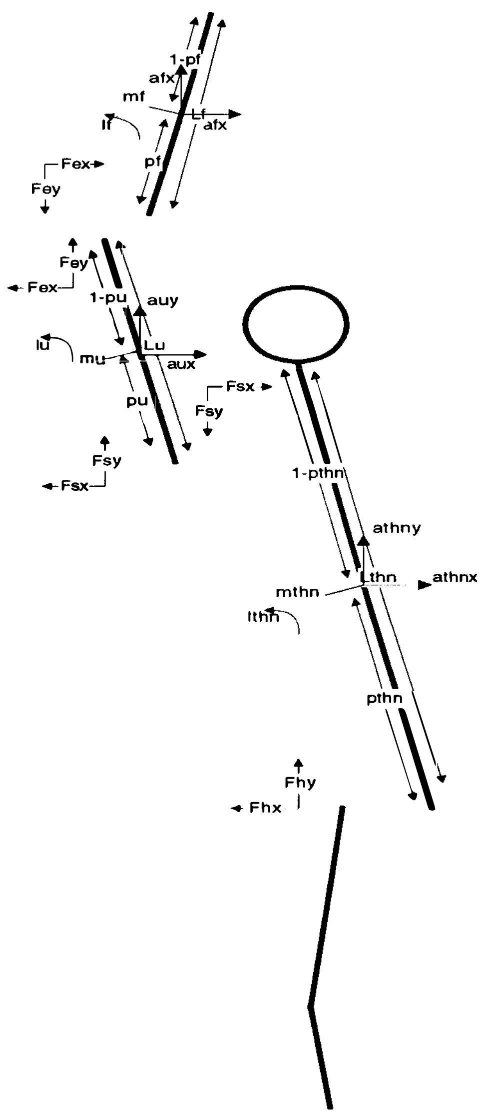

Figure 7. Free body diagram of ‘top-down’ link segment model.

3.3 Data Analysis

In accordance with the hypothesis of the study the following variables were investigated (or included in the analysis):

i. Vertical and horizontal velocities of the centre of mass.

ii. Lower limb joint and body lean angles.

iii. Dive score.

iv. Hip joint torque.

v. Temporal analysis of the take-off.

With the exception of the dive score, these variables were calculated for each dive during touchdown from hurdle, maximum depression and last contact. Dive score was included as a variable of interest after the initial analysis of the data and subsequent significant findings relating to the score awarded by the judges.

Board contact was defined as the frame in which the foot was flat on the springboard upon landing from the hurdle. Maximum depression was defined as the frame in which the springboard was maximally depressed just prior to recoil. Last contact was defined as the last contact of the diver on the springboard. However, if the gap between the toes and the board was very small and it was noticeable that the board was still weighted in the previous frame, then the frame where the small gap was evident was selected as outlined in Sanders and Gibson (2000).

The total take-off time for each dive was divided into two phases, these being springboard depression and springboard recoil. The springboard depression phase was defined as the period between the instant of touch down from the hurdle and the instant of maximum depression of the springboard. The recoil phase was defined as the instant of maximum depression to last contact.

3.3.1 Vertical and Horizontal Velocities During Take-Off

Raw displacement data from APAS were used to calculate the vertical and horizontal velocities of the centre of mass of the diver for each dive.

3.3.2 Lower Limb Joint and Body Lean Angles During Take-Off

Raw displacement data from APAS were used to calculate the lower limb joint angles and body lean angles for each dive. The lower limb joints were defined as the ankle, knee and hip joint respectively. The ankle joint was obtained by digitising the points corresponding to the knee, ankle and toe. The knee joint was obtained by digitising the points corresponding to the hip, knee and ankle. The hip joint was obtained by digitising the points corresponding to the shoulder, hip and knee.

The angle of lean was obtained by applying an arctangent function to the line connecting the digitised position of the toe to the calculated position of the centre of gravity of the diver, in each frame. If the diver was leaning in the direction of intended rotation (in this case towards the middle of the pool) then the angle was positive. Conversely, if the diver was leaning towards the fulcrum of the springboard the angle was negative.

3.3.3 Final Score Awarded

The final score was taken from the dive sheets collected after each round from the organisers of the competition. Seven judges judged the competition in accordance with FINA rules (FINA, 2002a). The traditional method for calculating the final scores, by multiplying the sum of the middle judges' scores by the degree of difficulty of the nominated dive was employed at this competition (FINA, 2002b). The degrees of difficulty of the nominated dives were 3.1 for the forward three and one-half somersault dive and 2.4 for the forward two and one-half somersault dive in the pike position (FINA, 2002b). The score was included to see whether the dives that obtained a higher score from the judges, were those dives that obtained a higher vertical velocity, or were influenced by the timing of peak hip flexion torque. The minimum and maximum scores were also given as an indicator of the range of scores within the two groups of divers.

3.3.4 Hip Joint Torque at Last Contact

The motion equations presented in 3.2.2 were coded in a customised software program (Burnett, 2002) written in LabVIEW Version 5.1 (National Instruments, USA). Raw displacement data from APAS were saved to file for input to the LabVIEW program. The above program calculated all segment angles, segment inertia data as well as acceleration data required for the inverse dynamic analysis. Segment CM acceleration data were calculated using the central difference formula with the digitised displacement acting as inputs (Winter, 1990). The standard central difference formula was used to calculate end point acceleration. Data were then imported into an Excel file and were time normalised to 101 equidistant values (0 to 100) from 10 frames prior to touchdown from hurdle to 10 frames after last contact. Therefore, particular values (e.g. time of max hip flexion torque) could be found and expressed as a percentage of the takeoff phase. The following formula was used to time normalise the data:-

$$\text{Normalised Time} = (fn-1)/(tf-1)*100$$

where fn – frame number of point of interest

tf – total number of frames analysed

Peak hip flexion torque was normalised by the following equation:-

$$\text{Normalised Hip Torque} \doteq \frac{T_h}{m*h^2}$$

where T_h – raw hip torque

m – body mass

h – height

The value of peak hip flexion torque and the time to peak hip flexion torque from last contact board contact were then determined.

3.3.5 Temporal Analysis of the Take-Off

The temporal data were calculated with the assistance of the 'display' option in the APAS software. The time differences between each distinct moment event of interest were then calculated to give the total dive times as well as the times for the depression and recoil phases of the dive.

3.4 Statistical Analysis

A two-tailed independent t-test was performed on the dive score, vertical velocity and the timing and magnitude of the raw and normalised peak hip flexion torques between the male and female divers. This was done to determine whether there were any significant differences between the two gender groups.

To establish whether the timing and magnitude of the peak hip flexion torque had an influence on vertical velocity at last contact and dive score a Pearson's Product Moment Correlation Coefficient (*r*) was calculated for both the male and female divers. The variables included in the correlation matrix were the dive score, vertical velocity, normalised hip joint peak torque, and normalised time of peak torque from last contact. The correlations for the raw magnitude and raw time of peak torque were not reported in the study, as upon investigation, the correlation between the raw and normalised magnitudes and timing of peak torque in relation to last contact were correlated strongly with their respective normalised variables. To determine whether the t-test and correlation coefficient values were significant, statistical tables were used to determine the value of the critical region (Thomas & Nelson, 2001).

CHAPTER 4 RESULTS

The first section of this chapter refers to the vertical and horizontal velocities of the centre of mass achieved by the divers during the take-off phase. The second section focuses on the lower limb joint and body lean angles during take-off. The third section refers to the dive score awarded by the judges. This is included as the dive score was found to be one variable showing a relationship to the timing of normalised peak hip flexion torque. The results referring to the analysis of the torque data is then reported, with the final section analysing the temporal data during the take-off.

4.1 Centre of Mass Vertical and Horizontal Velocities During Take-off

From Table 3 it can be seen that at the point of landing from the hurdle, the male divers achieved a significantly greater mean downward vertical velocity ($p<0.05$) of – 4.7 $m.s^{-1}$ than the female divers (- 4.1 $m.s^{-1}$). At last contact, the male divers also exhibited a significantly greater mean upward vertical velocity ($p<0.05$) of 4.7 $m.s^{-1}$ than the female divers (4.0 $m.s^{-1}$).

Table 3
Means and Standard Deviations of Velocity Data During Critical Points of the Take-Off for Male and Female Divers.

	Males (107B)	Females (105B)	p-value
Vertical velocity at board contact [$m.s^{-1}$]	-4.7 (0.2)	-4.1 (0.2)	0.000
Vertical velocity at maximal depression [$m.s^{-1}$]	1.2 (0.3)	1.1 (0.5)	0.267
Vertical velocity at last contact [$m.s^{-1}$]	4.7 (0.3)	4.0 (0.4)	0.000
Horizontal velocity at board contact [$m.s^{-1}$]	0.3 (0.1)	0.6 (0.1)	0.000
Horizontal velocity at maximal depression [$m.s^{-1}$]	0.9 (0.1)	0.9 (0.1)	0.425
Horizontal velocity at last contact [$m.s^{-1}$]	0.9 (0.2)	1.1 (0.2)	0.010

Notes: ( ) represents standard deviation.

The horizontal velocities at the point of landing from the hurdle (Table 3) were significantly higher ($p<0.05$) in the 105B dives performed by the females (0.6 $m.s^{-1}$)

than the 107B dives performed by the males (0.3 $m.s^{-1}$). At last contact, the male divers had the same horizontal velocity as shown at maximum springboard depression. In comparison, the female divers increased their horizontal velocity to 1.1 $m.s^{-1}$,a significantly greater ($p<0.05$) horizontal velocity than the respective horizontal velocity of the male divers.

4.2 Lower Limb Joint and Body Lean Angles During Take-off

Lower limb joint and body lean angle data for landing from the hurdle, maximum depression, and last contact are presented in Table 4. When landing from the hurdle, the female divers exhibited significantly ($p<0.05$) more extension at the hips (108.9°) and knees (116.3°) than the male divers (97.1° and 107.9° respectively). Further, the female divers showed significantly ($p<0.05$) greater extension at the ankle joint than the male subjects (98.9° and 102.8° respectively). The males displayed a greater backward lean (in the direction of the fulcrum of the springboard) (–10.0°) than the females (-8.9°).

At maximum springboard depression, the male divers were significantly ($p<0.05$) more flexed at the hips (144.2°) and knees (137.9°) than the female divers (153.7° and 144.0° respectively) and had greater plantarflexion at the ankles (109.8°) than the female divers (102.8°). Moreover, the male divers had a greater lean in the direction of rotation (5.0°) than the female divers (3.7°).

At last contact, the female divers were more extended at the hips (120.0°) than the male divers (105.4°). The male divers had a greater lean in the direction of rotation (15.6°) than the female divers (13.1°).

Table 4
Means and Standard Deviations of Lower Limb Joint Angles and Angle of Whole Body Lean During Critical Points of the Take-Off for Male and Female Divers.

	Males (107B)	Females (105B)	p-value
Ankle angle at board contact [°]	102.8 (4.3)	98.9 (4.2)	0.009
Knee angle at board contact [°]	107.9 (6.6)	116.3 (4.4)	0.001
Hip angle at board contact [°]	97.1 (7.7)	108.9 (9.5)	0.001
Lean angle at board contact [°]	-10.0 (1.7)	-8.9 (2.0)	0.046
Ankle angle at maximal depression [°]	109.8 (4.3)	102.8 (5.3)	0.000
Knee angle at maximal depression [°]	137.9 (5.4)	144.0 (8.1)	0.038
Hip angle at maximal depression [°]	144.2 (7.6)	153.7 (7.9)	0.003
Lean angle at maximal depression [°]	5.0 (1.5)	3.7 (1.5)	0.005
Ankle angle at last contact [°]	158.8 (4.8)	162.3 (4.1)	0.021
Knee angle at last contact [°]	175.2 (3.0)	173.0 (4.1)	0.068
Hip angle at last contact [°]	105.4 (10.3)	120.0 (8.5)	0.000
Lean angle at last contact [°]	15.6 (2.8)	13.1 (2.8)	0.005

Notes: ( ) represents standard deviation.

4.3 Final Score Awarded

The male divers in this study obtained a greater minimum and maximum overall score than the female divers (Table 5). Consequently, the results for the male divers exhibited a greater range of scores. Furthermore, the mean score obtained by the male divers was significantly greater than the mean score obtained by the female divers ($p = 0.003$).

Table 5

Comparison of Obtained Scores for Both the Male and Female Divers Including the Maximum, Minimum and Mean Score Awarded by the Judges.

	Males	Females	p-value
Min Score	39.06	36.72	
Max Score	73.01	54.72	
Mean Score	57.53	46.47	0.003
Standard Deviation	10.32	6.25	

4.4 Hip Joint Torque at Last Contact

From the means and standard deviations shown in Table 6 it can be seen that the difference between male divers (275 Nm) and female divers (74 Nm) was large and statistically different. When hip torque was normalised, the male divers still generated significantly ($p<0.05$) higher peak hip flexion torques than the female divers (1.39 $kg.m^2 \times 10^{-3}$ and 0.53 $kg.m^2 \times 10^{-3}$ respectively).

Table 6

Means and Standard Deviations for Raw and Normalised Peak Hip Flexion Torque and its Occurrence in Relation to Last Contact With the Springboard.

	Males (107B)	Females (105B)	p-value
Peak Hip Flexion Torque [Nm]	275 (87)	74 (40)	0.000
Norm Peak Torque [$kg.m^2 \times 10^{-3}$]	1.39 (0.33)	0.53 (0.32)	0.000
Time of PT from LC [secs]	0.018 (0.011)	0.164 (0.037)	0.000
Norm Time of PT from LC [%]	3.0 (1.9)	29.0 (5.6)	0.000

Notes: Norm torque defines normalised peak hip flexion torque. Time to LC defines the time from peak hip flexion torque to last contact of the springboard. ( ) represents standard deviation.

From Figure 8, it can be seen that the male divers produced their normalised peak hip flexion torques closer to last contact, with all normalised peak hip flexion torques occurring within 6.0% of last contact. The majority of the female divers produced their normalised peak hip flexion torques between 29% and 35% from last contact with the exception of subjects 2 and 6, who timed their normalised peak hip flexion torques closer to the instant of last contact.

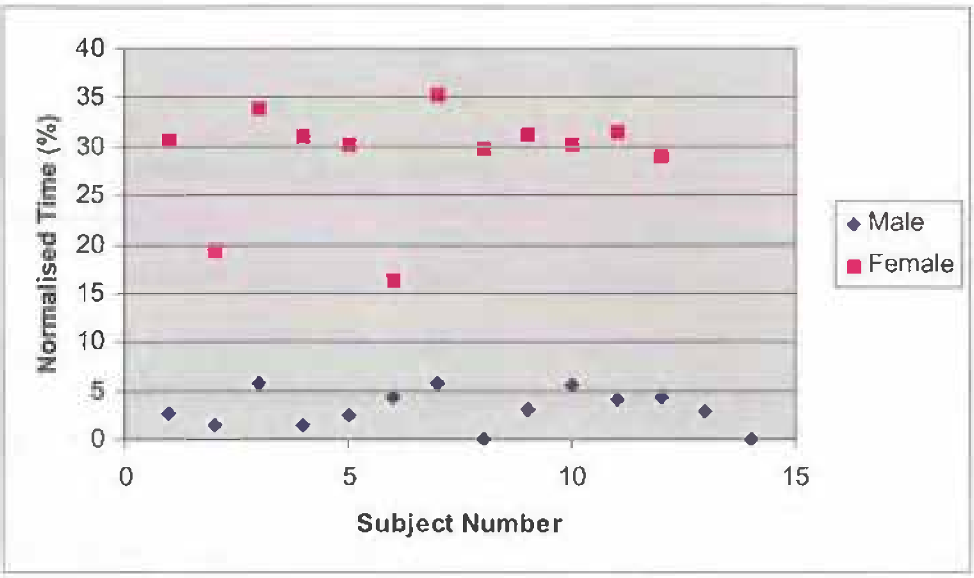

Figure 8. Individual male and female data for normalised time from peak hip flexion torque to last contact.

4.5 Correlation of Selected Temporal, Kinematic and Kinetic Variables During Take-off

The correlation matrices revealed that the raw values for the magnitude of peak hip flexion torque and the raw values for the timing of peak hip flexion torque in relation to last contact were not significantly correlated with the normalised values. Consequently, only the normalised values were included in the correlation matrices in Tables 6 and 7.

From Table 7 it can be seen that there was a significant ($p<0.05$) negative correlation for the male divers between the dive score and the normalised time of peak hip flexion torque in relation to last contact (r = -0.542). Vertical velocity was significantly correlated ($p<0.05$) with dive score (r = 0.476). Another significant ($p<0.05$) finding was between normalised time of peak hip flexion torque and the normalised magnitude of peak hip flexion torque (r = -0.461).

Table 7
<u>Correlation Matrix for Dive Score, Vertical Velocity and Normalised Peak Hip Flexion Torques and it's Occurrence Relative to Last Contact With Board for the Male Divers.</u> (n=14)

	Dive Score	Vertical Velocity	Norm Peak Torque	Norm Time of PT from LC
Dive Score	1			
Vertical Velocity	0.476*	1		
Norm Peak Torque	-0.330	0.170	1	
Norm Time of PT from LC	-0.542*	0.013	-0.461*	1

<u>Notes:</u> * denotes significant at $p<0.05$. Norm Peak Torque defines normalised peak hip flexion torque. Norm Time of PT from LC defines the normalised time of peak hip flexion torque from last contact.

From Table 8 it can be seen that there was a significant ($p<0.05$) correlation between the score achieved and the vertical velocity at last contact for the female divers (r = 0.748). The normalised time of peak torque in relation to last contact was the only other result found to have a significant ($p<0.05$) correlation with normalised torque with r = 0.543.

Table 8
<u>Correlation Matrix for Dive Score, Vertical Velocity and Normalised Peak Hip Flexion Torques and it's Occurrence Relative to Last Contact With Board for the Female Divers.</u> (n=12)

	Dive Score	Vertical Velocity	Norm Peak Torque	Norm Time of PT from LC
Dive Score	1			
Vertical Velocity	0.748*	1		
Norm Peak Torque	0.030	-0.120	1	
Norm Time of PT from LC	0.047	-0.168	0.543*	1

<u>Notes:</u> * denotes significant at $p<0.05$. Norm Peak Torque defines normalised peak hip flexion torque. Norm Time of PT from LC defines the normalised time of peak hip flexion torque from last contact.

4.6 Temporal Analysis of the Take-off

From the temporal data shown in Table 9, it can be seen that the male divers spent significantly ($p<0.05$) more time in the depression phase than the female divers. The male and female divers showed no significant difference in the time they spent performing the recoil phase. The total take-off times were significantly higher ($p<0.05$) in the 107B dives performed by the males (0.43 seconds) than the 105B dives performed by the female divers (0.40 seconds).

Table 9
Means and Standard Deviations of Temporal Data During Critical Points of the Take-Off for Male and Female Divers.

	Males (107B)	Females (105B)	p-value (p<0.05)
Depression phase [sec]	0.22 (0.01)	0.20 (0.02)	0.000
Recoil phase [sec]	0.21 (0.01)	0.20 (0.02)	0.072
Total time [sec]	0.43 (0.02)	0.40 (0.02)	0.000
Depression/recoil ratio [%]	52/48	51/49	

Notes: ( ) represents standard deviation.

CHAPTER 5 DISCUSSION

The purpose of this study was to investigate the relationship between the timing and magnitude of normalised peak hip flexion torques prior to last contact with the springboard and vertical velocity at last contact in high rotational demand forward springboard dives. The dives chosen for analysis in this study were the forward three and one-half somersault dive in the pike position (107B) and the forward two and one-half somersault dive in the pike position (105B). Studying these two separate dives was considered appropriate, as the 107B and 105B have been deemed to represent the current limits of competitive performance in springboard diving of male and female divers respectively (Sanders & Gibson, 2000).

The hypothesis developed for this study was that divers who generated greater peak hip flexion torque values closer to last contact with the springboard would produce a greater vertical velocity at take-off. The later flexion of the trunk at the hip joint would allow the diver to 'ride' the springboard vertically for a longer period of time without 'unweighting' it and absorbing springboard energy. As vertical velocity of the centre of mass at take-off is related to the height achieved in flight, this production of greater vertical velocity will enable the diver to produce greater height. The height generated by the diver in flight has been found to be an important variable cited by the judges when awarding a score for a springboard dive (McCormick et al., 1982).

There was no significant relationship between the timing and magnitude of normalised peak hip flexion torque and vertical velocity at last contact for either the male and female divers. Therefore, the hypothesis of the study was not supported. However, there were other significant findings that supported the underlying rationale of the study. One of these findings was the relationship between the timing of normalised peak hip flexion torque in relation to last contact and the magnitude of normalised peak hip flexion torque in both the male and female divers. Another significant finding was the relationship between the timing of normalised peak hip flexion torque and the score awarded by the judges. Lastly, a significant relationship was found between the dive score awarded by the judges and vertical velocity at take-off in both male and female divers. These findings will be discussed below in turn.

<u>5.1 The Relationship Between the Timing and Magnitude of Peak Hip Flexion Torque in Relation to Last Contact</u>

The results presented in Table 7 showed a significant ($p<0.05$) negative relationship between the normalised time and magnitude of peak hip flexion torque (r= -0.461) in males. Conversely, the results for female divers presented in Table 8, indicate a significant ($p<0.05$) positive relationship between the normalised time and magnitude of peak hip flexion torque (r= 0.543).

From these results it can be suggested that the male divers who generated peak hip flexion torque closer to last contact, produced a greater normalised peak hip flexion torque. In contrast the female divers showed the opposite relationship. That is, the female divers who timed peak hip flexion torque closer to last contact, produced a smaller normalised peak hip flexion torque, than those divers that produced their peak hip flexion torque earlier (as depicted in Figure 9). From this finding, it may be suggested that those divers who are able to produce greater normalised peak hip flexion torque should attempt to time their flexion later in the take-off period, so they can maximise their vertical velocity.

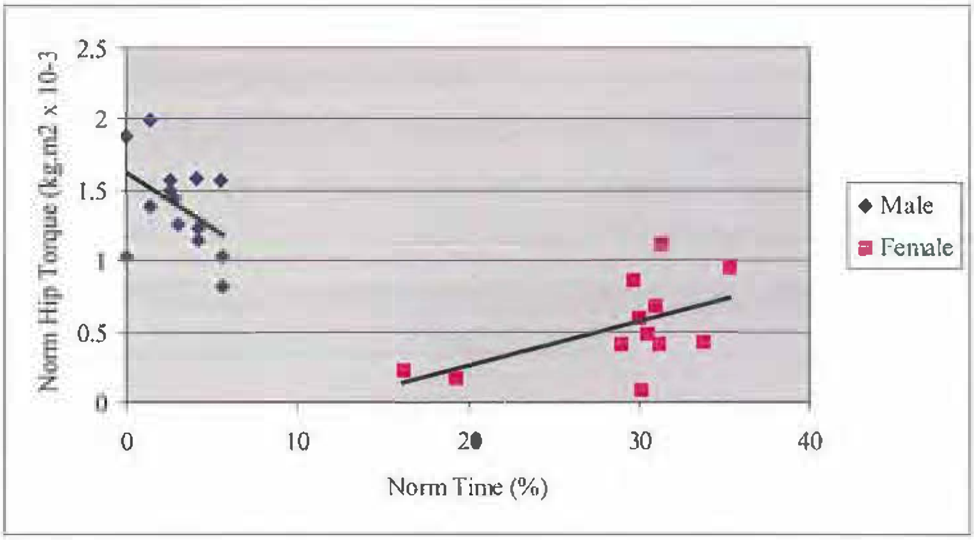

Figure 9. Scatterplot showing the relationship between the normalised times of peak hip flexion torque in relation to last contact and the magnitude of normalised peak hip flexion torque for the male and female divers.

When analysing the magnitudes of the normalised peak hip flexion torques between the two gender groups (Table 6), it is difficult to compare the results with previous research. Previous studies examining lower limb joint torques in jumping tasks have focused upon either the extension phase of take-off, or the magnitude of extension torque when landing from a drop from height and attempting to gain height without the necessity to complete rotation(s) afterward such as in diving. Thus, with no other known research, there are few data with which to compare hip joint torques when attempting to generate rotation in diving.

The significant ($p<0.05$) difference (Table 6) between the normalised magnitudes of the peak hip flexion torques generated by the male and female divers requires some discussion. Sanders and Gibson (2000) pointed out that as the 105B for females and 107B for males are the benchmarks in competitive diving for the respective genders, such a comparison is interesting and contributes to a deeper understanding of factors affecting the development of height and rotation. Other studies have also compared the results between male and female divers and reported the differences between the groups (Miller & Munro, 1985a; 1985b).

The question arises as to whether the normalised hip torques were greater in the males than females because the males were performing a dive with a greater number of somersault rotations. However, it would seem advantageous for females to generate greater angular momentum, so that they could complete their rotations quickly to maximise time to prepare for entry. Thus, it is logical to assume that females would generate greater hip flexion torque and thereby more angular momentum if they were able to do so. More research is required to determine what factors limit the ability of female divers to generate large hip torques. One possibility is because males have stronger hip flexion musculature due to a greater cross sectional area of the muscles crossing the hip joint (Sanders & Gibson, 2000).

Sanders and Wilson (1988) and Sanders and Gibson (2000) have commented on the possible influence of strength on success in springboard diving. Sanders and Wilson (1988) suggested that strength might be a limiting factor for many divers in the production of height required for springboard diving. As springboard diving and especially the take-off sequence are performed over a short period of time (between 0.40 and 0.43 seconds (Table 9)) the power produced by the diver about the hip joint would be a function of greater hip flexion torque. Sanders and Wilson (1988) found that male divers produced a higher hurdle, and obtained a deeper crouch at maximal depression than female divers. The authors found that the male divers, compared to the female divers, were able to 'hold' this deeper crouch. This would allow the male divers to better minimise the energy absorption, then near maximal depression perform a greater extension at the hips and knees to generate a greater amount of energy into the diver/springboard system. The results from Table 4 confirm the findings of Sanders and Wilson (1988) and Sanders and Gibson (2000) with the male divers showing a significantly deeper crouch at maximal depression than the female divers ($p<0.05$), with hip and knee angles of 144.2° and 137.9° compared to 153.7° and 144.0° respectively. Sanders and Gibson (2000) study suggested that the greater contribution to height during the final depression of the springboard may be due to greater strength of the male divers. This greater strength and power, as suggested earlier would enable the male diver's to perform more positive work on the springboard, which would help store more energy in the springboard.

The results of the present study suggest that in addition to gaining an advantage from an ability to apply large extension torques to transfer energy into the springboard, male divers also gain an advantage compared to female divers by being able to apply large hip flexion torques later in the period of contact thereby, maximising vertical velocity at last contact by not flexing at the trunk early. An interesting finding from this study was that those females that produced greater normalised peak hip flexion torque produced a similar torque magnitude (0.8622, 0.9475, and 1.1089 $kg.m^2 \times 10^{-3}$) to some of the male divers (0.8159, 1.0301, and 1.0242 $kg.m^2 \times 10^{-3}$) that managed to time their normalised peak hip flexion torque closer to last contact (Figure 9). This comparison may suggest that some of the female divers are capable of timing hip flexion torque closer to last contact.

While much more work needs to be conducted to gather evidence in support of the rationale outlined in the introduction, the results of this study indicate that if divers can generate large hip flexion torques, late in the period of contact, greater rotation may be achieved whilst minimising the loss of energy that reduces height.

5.2 The Relationship Between the Timing of Normalised Peak Hip Flexion Torque and Dive Score

The hypothesis for the study, as stated earlier, was that there would be a relationship between the timing and magnitude of normalised peak hip flexion torque and vertical velocity. However, this was not supported. One interesting finding however, was the relationship between the timing of normalised peak hip flexion torque and the dive score awarded to the male divers (r= -0.542). This negative correlation indicates that the closer the peak hip flexion torque was to last contact, the higher the score awarded by the judges (Figure 10). This finding was not demonstrated in the female divers examined in this study (r= 0.047) (Table 8).

One possible reason for the female divers not exhibiting a significant relationship between the timing of normalised peak hip flexion torque and dive score may be due to some female divers timing peak hip flexion torque much closer to last contact, but being awarded lower scores than those female divers who timed peak hip flexion torque earlier, as can be seen in Figure 10. The two female divers who timed their peak hip flexion torque closer to last contact produced normalised peak hip flexion torques well below the mean magnitude for the female divers (Table 6) with magnitudes of 0.17 and 0.23 kg.m^2 x 10^{-3} respectively. These two female divers were also awarded scores close to the average score (Table 5) exhibited by the female group with awarded scores of 39.96 and 47.16 respectively.

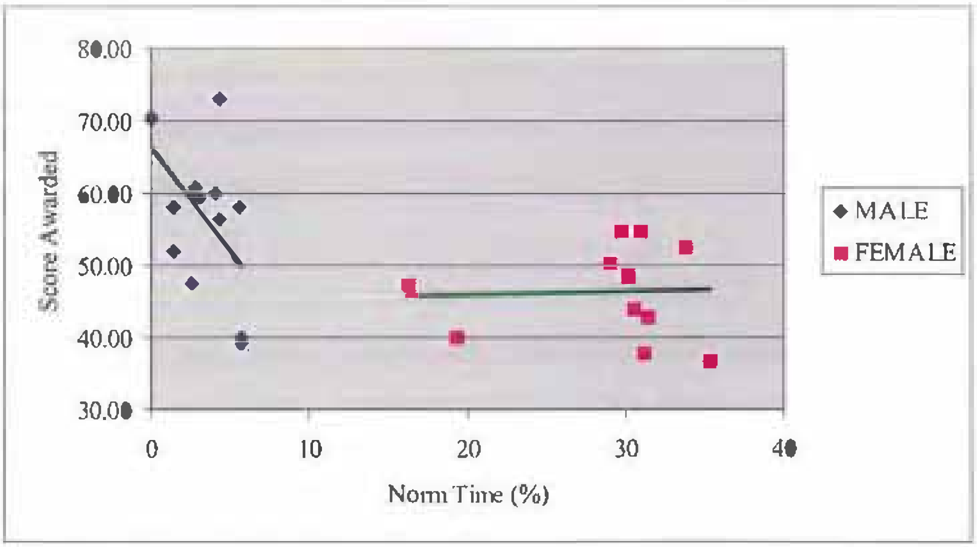

Figure 10. Scatterplot showing the relationship between the normalised times of peak hip flexion torque in relation to last contact and the final score given by the judges for the male and female divers.

With the earlier timing of peak hip flexion torque and the lower mean magnitude of peak hip flexion torque exhibited by the female divers, compared to the male divers, the resulting absence of a significant relationship between the timing and magnitude of peak hip flexion torque may be due to other variables not related to the timing of peak hip flexion torque.

5.3 The Relationship Between Dive Score and Vertical Velocity at Take-off

The difference in the dive scores between the male and female subjects was due in part to the higher degree of difficulty associated with the 107B dive completed by the male group (DD=3.1) than the degree of difficulty of the 105B dive performed by the female group (DD=2.4) (La Federation Internationale de Natation, 2002b). Miller and Sprigings (2001) outlined the effect that degree of difficulty can have on the outcome of a score, and the result this has on the competition. They highlighted that when a diver performs an average dive with a high degree of difficulty, the score often outweighs that which is given for a 'very good' dive from a lesser degree of difficulty dive (Miller & Sprigings, 2001).

One interesting finding of the study was the relationship between the score awarded and vertical velocity at last contact (Figure 11). Both the female and male divers showed a significant ($p<0.05$) relationship between both variables, with the female divers presenting a stronger relationship (r=0.748) than the male divers (r=0.476). The results were similar to those studies by Miller and Munro (1984) and Sanders and Wilson (1988). These findings suggest that vertical velocity is related to a higher score being awarded by the judges.

This study showed similar results to those of previous studies reporting the vertical velocities at last contact, of both the male and female divers. The male divers in this study recorded a mean vertical velocity at last contact of $4.7 m.s^{-1}$ (Table 3) for a forward three and one-half somersault dive in the pike position. This value is similar to Miller and Munro (1985b) who recorded a value of $5.04 m.s^{-1}$ for the same dive. However, these results were found to be less than those reported by Miller and Sprigings (2001) for the forward three and one-half somersault dive of $5.4 m.s^{-1}$. The major difference in 107B vertical velocity values at last contact between Miller and Sprigings (2001) and the present study can likely be attributed to the fact that Miller and Sprigings averaged only the vertical velocities of the top three divers (medal winners) whereas values from 14 divers were averaged in the present study.

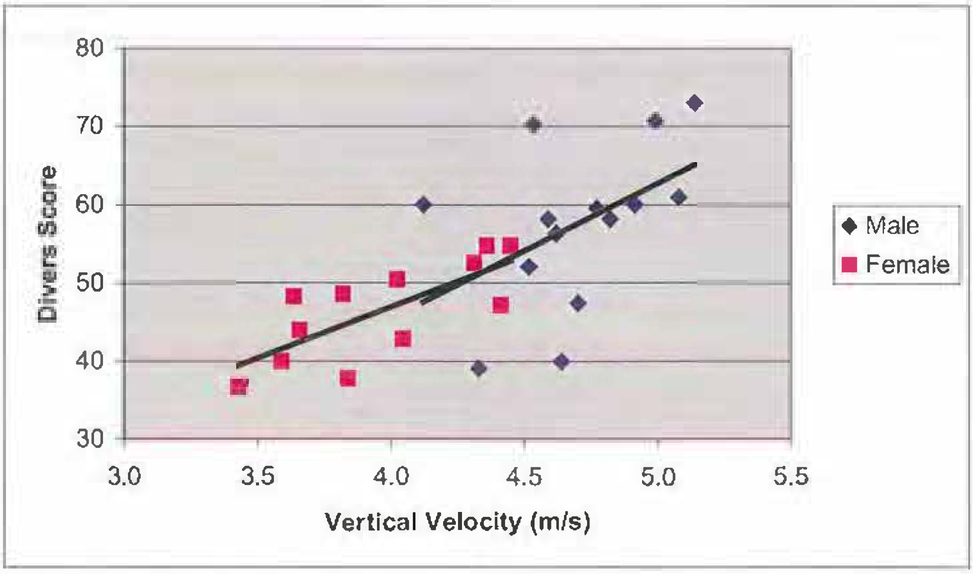

Figure 11. Scatterplot showing the relationship between the score given by the judges and vertical velocity at last contact for the male and female divers.

The female divers in this study also showed similar results to previous studies. In this study, the female divers recorded a mean vertical velocity at last contact of $4.0 m.s^{-1}$ (Table 3) for a forward two and one-half somersault dive in the pike position. This result can be favorably compared to that obtained by Miller and Munro (1984) of $3.81 m.s^{-1}$, Sanders and Wilson (1988) of $3.91 m.s^{-1}$, and Miller and Sprigings (2001), who only reported one result, of $4.7 m.s^{-1}$, for a forward two and one-half somersault dive in the pike position. The results reinforce the importance of achieving good height despite high rotational demands. Thus, the need to develop large angular momentum while minimising losses in height due to energy absorption through early hip flexion is apparent.

5.4 Implications for Training

If future work confirms that large hip torques generated late in the period of springboard contact are beneficial in maximising rotation and maintaining height as close as possible to the height achieved in dives of fewer rotations, then there are important implications for training. These are:

i. Divers can learn to time hip flexion late in the contact phase of a springboard dive to improve their ability to perform high degree of difficulty forward somersault dives.

ii. Divers can also improve hip strength and power to help in the production of greater hip flexion torque required to vigorously "throw" the trunk downwards, to assist in the production of extra rotation.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Conclusions

In conclusion, it was found that the timing and magnitude of normalised peak hip flexion torque did not influence the vertical velocity of the diver at last contact. However, there were several significant findings in this study that may have implications in springboard diving. These findings include:-

i. Male divers generated greater normalised peak hip flexion torque closer to last contact than the female divers.

ii. Males showed a negative relationship between the timing of normalised peak hip flexion torque and the magnitude of peak hip flexion torque.

iii. Females showed a positive relationship between the timing of normalised peak hip flexion torque and the magnitude of peak hip flexion torque.

iv. Males showed a negative relationship between the timing of normalised peak hip flexion torque and the dive score awarded.

v. Both the male and female divers showed a positive relationship between vertical velocity and the dive score awarded.

With this research and future research on hip flexion torque, a greater understanding of the effect that the timing and magnitude of hip flexion torque has on vertical velocity will be gained. It will also give a greater insight into the training methods that may need to be employed by coaches to improve a divers ability to generate greater hip flexion torque later in the take-off which, based on the rationale outlined in the introduction, would improve the diver's ability to generate height and rotation leading to higher scores awarded by the judges.

6.2 Recommendations for Further Research

Future studies should involve divers across a larger ability range. All the divers used in this study were of elite level. If a broader ability range was used, the influence of the timing and magnitudes of peak hip flexion torque on vertical velocity and the score awarded may be more apparent.

The second recommendation for further research would be to use a camera with a faster frame rate. In this study a digital video camera operating at 60 fields per second was used to film the dive. With the camera filming at this speed combined with a modest shutter speed some errors in the digitising process may have occurred during the fast arm actions of springboard depression and recoil. This was the reason for the repeatability study outlined in the methods section. With a relatively slow camera speed there exists larger gaps between frames making it harder to estimate the critical periods of interest exactly. If a higher speed camera were used to film the dive, such as a digital video camera operating at 200 Hz, these errors in estimating the times of key events would be small. This is particularly important because the differences in timing among this group of elite subjects was small. This would make it easier to find the periods of interest in the dive and also a more accurate measurement of when peak hip flexion torque occurred and it's magnitude.

Another recommendation would be to use a more accurate anthropometric database, as the calculations for inverse dynamics are reliant upon accurate anthropometric data. As Dempster's study involved the gathering of anthropometric data from a limited number of cadavers in the 1950's, there are errors when using these data to estimate the anthropometric characteristics of today's athletes. With today's technological advancements, it may be possible to calculate the anthropometric characteristics of each individual using methods such as Jensen's (1986) elliptical zone method, which separates each segment of the body into 2cm elliptical zones, or using Magnetic Resonance Imaging (MRI) scans. With more accurate anthropometric measurements, the calculations for inverse dynamics would represent the individual diver more accurately, instead of adapting the anthropometric data from a different data set.

Further research needs to be conducted to establish what relationship exists between the timing and magnitude of normalised peak hip flexion torque. The study raises an interesting question with the male divers achieving a negative relationship, whereas, the female divers achieved a positive relationship. It would be an interesting study to see exactly why the two genders differ when examining the same two factors, as well as looking more deeply into how the two are linked in competitive springboard diving.

CHAPTER 7. REFERENCES

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