THE KINEMATICS AND KINETICS OF JUMPING FOR DISTANCE WITH PARTICULAR REFERENCE TO THE LONG AND TRIPLE JUMPS

PHILIP GRAHAM-SMITH

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THE FOLLOWING PUBLICATIONS, FIGURES AND TABLES HAVE BEEN EXCLUDED ON INSTRUCTION FROM THE UNIVERSITY

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LIST OF PUBLICATIONS

Publications:

First author

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Graham-Smith, P. (1994). Long and triple jump approach velocities. *Athletics Coach*, volume 28(4), Winter 1994, pp. 13-15.

Graham-Smith, P. and Lees, A. (1997). A comparison of the information quality between cinematography and videography for long jump technique analysis. *Biology Of Sport*, 14(3), pp. 213-225.

Second author

Lees, A., Graham-Smith, P. and Fowler, N. (1994). A Biomechanical Analysis of the Last Stride, Touchdown, and Takeoff Characteristics of the Men's Long Jump. *Journal of Applied Biomechanics*. 10(1). pp. 61-78.

Lees, A. and Graham-Smith, P. (1996). Plyometric training: a review of principles and practice. *Sports Exercise and Injury*, 2, pp. 24-30.

Conference Presentations:

First Author

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Graham-Smith, P. and Lees, A. (1994). British Triple Jumpers 1993: Approach Speeds, Phase Distances and Phase Ratios. Presented to The British Association of Sport and Exercise Sciences annual conference, University of Aberdeen, 18th-21st July, 1994.

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Graham-Smith, P. and Lees, A. (1996). The compression phase in the long jump take-off. Presented to The British Association of Sport and Exercise Sciences annual conference, Lilleshall, 7th-9th September, 1996.

Second Author

Lees, A. Smith, P. and Doggart, L. (1993). Running Jumpers and Jumping Jumpers in the Long Jump. Presented to the Sports Biomechanics Section of The British Association of Sports Sciences, Easter Meeting, Crewe and Alsager Faculty, Manchester Metropolitan University, 19th March, 1993.

Lees, A. and Smith, P. (1993). Generating vertical velocity in the long jump. EACA Congress, Berlin, January 1993.

Lees, A. and Graham-Smith, P. (1994). The biomechanics of the horizontal jumps. Scottish Athletic Federation Conference, December, 1994.

Lees, A. and Graham-Smith, P. (1994). The role of the arms in the long jump. Presented to the Sports Biomechanics Section of the British Association of Sport and Exercise Sciences Easter Meeting, West London Institute, 14th-15th April, 1994.

Lees, A., and Graham-Smith, P. (1995). Touch-down and take-off characteristics of the hop phase in the triple jump. In, Abstracts of the International Society of Biomechanics, XVth Congress, Jyväskylä, 2nd - 6th July, 1995, pp. 540-541.

ABSTRACT

The common aim of the long and triple jumps is to attain maximum horizontal distance from the front of the take-off board. This is achieved by converting some of the horizontal velocity developed in the approach run into vertical velocity at take-off. The aim of this thesis was to examine a theoretical model and to identify kinematic and kinetic factors that facilitate the generation of vertical velocity in the long and triple jump take-offs.

A pivot mechanism was defined to act between touch-down and the instant the centre of mass was directly above the toe of the support foot. This mechanism was found to be the largest contributor to the gain in vertical velocity in all take-offs, accounting for 83.0% in the long jump and 63.7%, 69.8% and 70.7% in the hop, step and jump take-offs. The contribution of the pivot to the gain in vertical velocity at take-off in the long jump was significantly greater than in each of the triple jump take-offs, (all $P<0.002$).

A relative momentum approach was used to determine the contribution of the free limbs to the generation of vertical velocity. In the long jump, the free limbs made a 10.8% contribution to the gain in vertical velocity, compared to 12.2%, 19.0% and 19.0% in the triple jump take-offs. Multiple regression analyses were used to identify factors relating to the generation of vertical velocity in the long jump (n=14).

The greatest gains in vertical velocity were associated with techniques that emphasised a low centre of mass and extended knee joint at touch-down and the ability to resist knee flexion in the compression phase, R^2=72.7%. The greatest losses in horizontal velocity were associated with excessive hip adduction, less hip extension and greater increases in height from touch-down to take-off, R^2=84.5%.

Ground reaction forces and net joint moments were measured during short approach running jump tests. Peak vertical impact forces were greater in simulated 'drop' take-offs, 5080 N, compared to those experienced in 'flat' approach take-offs, 3250 N, (P=0.002). Peak horizontal braking forces were 1800 N in both types of take-off. However, the peak net joint moments about the ankle, (403 N.m and 387 N.m), knee (233 N.m and 296 N.m) and hip (292 N.m and 249 N.m) were similar between the 'flat' and 'drop' take-offs. This suggests that athletes adapt their technique in the 'drop' take-off to distribute the larger forces effectively and to keep the net joint moments within controllable limits. Results indicated that strength about the ankle joint was particularly important in both types of take-off, but depending on the athlete's technique strength about the knee and hip are also vital. Greater flexion of the knee joint at touch-down and maximum knee flexion were found to be associated with greater average knee moments, R^2=30.8% and 75.5% respectively, and greater angles of leg placement were moderately associated with greater average hip moments, R^2=23.5%.

In conclusion, this thesis has provided a greater insight into the kinetics and kinematics of jumping for distance. It has quantified the contribution made by the pivot mechanism and the free limbs to the generation of vertical velocity, and has assessed the demands on the musculo-skeletal system in terms of ground reaction forces and net joint moments. The results indicate that elite performers cannot rely on speed alone, and that strength and technique are major factors of successful performance.

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1.0 Introduction

1.0 Introduction

The aim of both the long and triple jump is to gain as much horizontal displacement from the take-off board as possible. The difference between the long and triple jump is that the distance gained in the long jump is the result of one maximal effort, whereas the distance gained in the triple jump is the sum of the 3 consecutive sub-maximal efforts, the hop, step and jump distances.

For the ease of analysis, Hay (1986) broke the long jump down into 4 distinct phases, the approach, the take-off, the flight and the landing. The triple jump has also been divided into similar parts, incorporating an approach run, 3 take-offs, and 3 flight and landing phases (Hay, 1992). In the approach phase athletes aim to generate high speed on the runway before they take-off on the board. In the take-off phase athletes aim to project themselves into the air by converting some of the horizontal velocity attained in the approach into vertical velocity. Once the athlete has left the ground the maximum jump distance has been largely predetermined by the take-off parameters, (height, speed and projection angle of the centre of mass at take-off - the latter two being functions of the horizontal and vertical velocities). However the maximum 'flight' distance may not be attained if the flight and landing techniques are poor (Palermo, 1980). The take-off phase can therefore be viewed as the most critical phase in the horizontal jumps, (Unger, 1980; Stewart, 1981).

The importance of the take-off parameters and their influence on the jump distance can be seen in the deterministic model, figure 1.1. Long and triple jumpers should strive to develop a technique that optimises the take-off parameters mentioned above. The speed and projection angle of the centre of mass at take-off are dependent on the interaction between the horizontal and vertical velocities at touch-down and their changes during the take-off. As the horizontal velocity is developed sufficiently in the approach, the production of vertical velocity in the take-off phase can be regarded as the most important aspect of these jumps.

It has been well documented in the literature that athletes make several adjustments in body position as they reach the take-off board. These include changes in stride length and frequency, the lowering of the centre of mass over the last few strides of the approach and the placement of the leg in front of the centre of mass at touch-down. The lowering of the centre of mass allows the leg to be extended further in front of the body at touch-down and also provides a greater vertical range in which the athlete can work through. These adjustments are said to facilitate the development of vertical velocity.

Figure 1.1. Deterministic model of the long jump. (Hay and Reid, 1988)
(Note, the same factors determine the each flight distance in the triple jump)

However, upward vertical velocity can only be generated when the touch-down leg is in contact with the board, i.e. during the take-off phase. Although the changes in body position are said to put the athlete in a favourable position, the underlying mechanisms that operate between touch-down and take-off have received very little attention.

Lees et al. (1993, 1994) addressed this issue and concluded that there was evidence for two mechanical, one muscular and one biomechanical mechanism acting throughout the take-off phase. The term 'mechanical' was used to describe any effect that could also be produced by an inanimate object, e.g. a wooden stick. With reference to jumping this referred to a pivoting action of the body over the base of support in the compression phase and the lift associated with upward movements of the arms and lead leg during the extension phase. The term 'muscular' mechanism was used to describe the effect produced by the contractile properties of muscle. Such effects cannot be produced by inanimate objects. This mechanism referred to the contribution made by concentric muscular contractions of the support leg in the extension phase of the take-off. The term 'biomechanical' was used to describe the mechanical behaviour of a biological structure, for example the storage and re-utilisation of elastic energy, (enhancement through the stretch-shorten cycle). This resulted in four mechanisms being identified that contribute to the generation of vertical velocity in the long jump take-off: a pivot; the upward movements of the free limbs; the enhancement through the stretch-shortening cycle, and the contribution made by concentric muscular contractions of the support leg.

Lees et al. (1993, 1994) quantified the pivot mechanism as the gain in vertical velocity from the instant of touch-down to the end of the compression phase (expressed as a percentage of the total gain from touch-down to take-off). They observed that the pivot mechanism accounted for 66% and 64.4% of the total gain in vertical velocity in female and male athletes respectively. In their studies, the end of the compression phase (also the beginning of the extension phase) was denoted by the instant of maximum knee flexion. A similar result was found by Bosco et al. (1976) who observed that 60% of the vertical velocity at take-off had been attained by the end of the compression phase. In their study, the end of the compression phase was defined as 'the instant that an imaginary line from the point of force application to the centre of mass reached a vertical position'.

In the model proposed by Lees et al. (1994) the effectiveness of the pivot mechanism was expected to be influenced by the resistance of the touch-down leg to flex at the knee. i.e. a straighter leg should produce a better pivot. However, no significant relationship was found between the gain in vertical velocity from touch-down to maximum knee flexion and the change in knee joint angle. They concluded that the lack of an expected relationship might indicate that other mechanisms, for example actions at the hip, might operate and that these could only be quantified following a full three-dimensional analysis.

Although three-dimensional data acquisition techniques are often reported for kinematic analyses of the long and triple jump take-offs, there have been only two studies that have presented kinematic information out of the sagittal plane. A study by Bober (1974) examined lateral deviations of the centre of mass in the triple jump take-offs and presented limited results of the trunk and the support leg angles in the frontal plane. Unfortunately, combined data was reported for the hop, step and jump take-offs, but a significant relationship was found between the inclination of the trunk and that of the leg in the 'middle phase' of support. The only other study that has reported anything other than the medio-lateral component of velocity was conducted by Fukashiro et al. (1993). They examined movements of the hips and shoulders in the transverse plane, relating it to trunk rotation and the techniques of Mike Powell and Carl Lewis. While the long and triple jumps are generally two-dimensional in nature, it is apparent that movements do occur in the transverse and frontal planes and these need to be examined for their effect on performance (Yeadon and Challis, 1994). Not only do the kinematics of the take-off leg and the trunk need to be examined, but also the movement patterns of the free limbs. The movement patterns of the free limbs have not been examined in the literature and these need to be examined for their role in the generation of vertical velocity and preservation of balance.

An appreciation of the physical demands placed on athletes as they perform long and triple jump take-offs can be obtained from kinetic analyses. The magnitude of ground reaction forces have been found to be very large even in sub-maximal jumps. Vertical impact forces have been reported to be as great as 12.6 times body weight in the step take-off (Ramey and Williams, 1985). Considering these large forces, it was very surprising that only a few studies have reported ground reaction forces in the long and triple jumps. Even fewer have examined how athletes distribute these forces about the joints of the support leg. Net joint moment analyses can provide this information, which is essential if the specific strength requirements of each joint are to be identified. With respect to the objective of generating vertical velocity, it is particularly important to identify how aspects of technique that are associated with the generation of vertical velocity affect the distribution of joint moments. This information will ensure that athletes will have informed advice on the preparation of specific muscle groups if they need to modify their technique. However, to date this information is lacking in the literature.

Finally, considering that the long and triple jumps are regarded as power events, it is very surprising that no studies have profiled the concentric and eccentric strength characteristics of these athletes. Eccentric strength is believed to be essential during the compression phase, to resist knee flexion and to enhance concentric force production through the stretch-shorten cycle in the extension phase. From a practical perspective, this information is essential for identifying normative data and for diagnosing muscle weaknesses and imbalances.

1.1 The theoretical model

Based on the observations made from reviewing the literature a theoretical model is proposed that outlines factors that may influence the generation of vertical velocity. The mechanisms outlined in figure 1.2 apply to both the long and triple jumps, although some of the initial touch-down conditions will inevitably differ between the two events.

The theoretical model identifies four mechanisms that operate to generate vertical velocity in the take-off phase. The pivot describes a 'lever' effect that operates in the compression phase and is the result of a fast approach coupled with an extended leg in front of the centre of mass at touch-down. A low centre of mass at touch-down is thought to facilitate leg extension in front of the centre of mass and also provides a greater vertical range to work through. A more rigid 'pivot' will be produced if the knee and hip joints are extended at touch-down, but this will be negated by knee flexion, hip flexion and hip adduction.

The free limbs are thought to operate in the extension phase and their contribution is determined by the vertical momentum the arms and lead leg generate relative to the shoulder and hip joints that they are attached. The stretch-shorten cycle enhancement relates to the additional force that muscles can generate following an initial pre-stretch. Pre-activation of muscles prior to a short and fast eccentric phase and a fast transition into a concentric contraction are thought to enhance this mechanism. Concentric contractions of the support leg muscles generate more vertical velocity through extension of the hip, knee and ankle joints. The ability to generate maximum force or torque at fast movement speeds is beneficial.

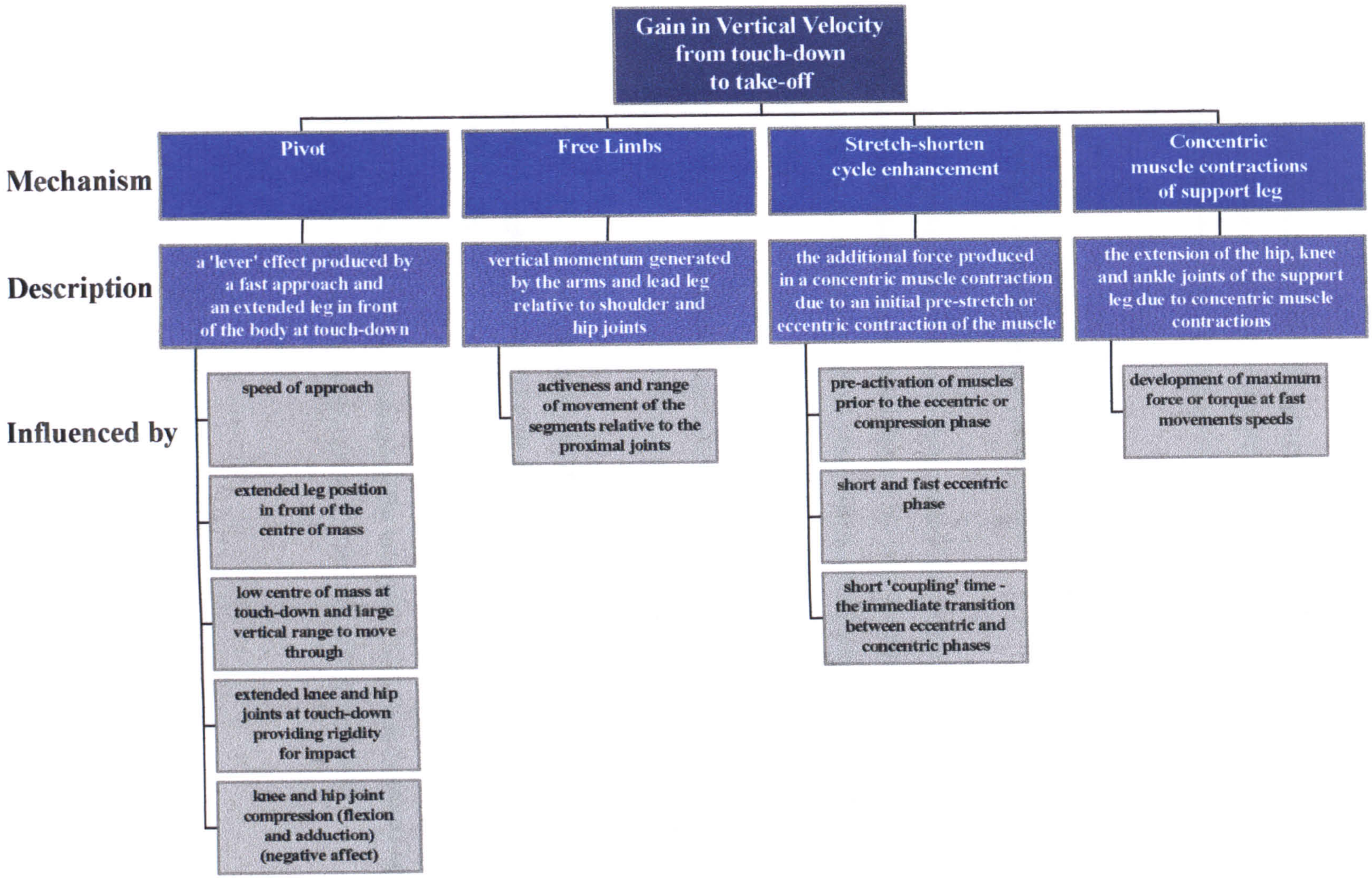


Figure 1.2. Theoretical model for the generation of vertical velocity in the long and triple jump take-offs

A programme of research was formulated to address the following aim and objectives.

1.2 Aim

The aim of this research is to identify factors that influence the generation of vertical velocity in the long and triple jump take-offs. This will be achieved by examining the three-dimensional kinematics and kinetics of the take-offs and meeting the following objectives:

1. To address methodological issues related to the collection of kinematic data and to assess systematic and random errors in digitised data.

2. To establish the three dimensional (3D) kinematic characteristics of the long and triple jump take-offs, to identify factors that influence the effectiveness of the pivot mechanism and to quantify the contribution made by the pivot mechanism in the generation of vertical velocity.

3. To identify the 3D kinematic characteristics of the arms and lead leg and to establish their role in the generation of vertical velocity in the long and triple jump take-offs.

4. To determine the demands placed on the musculo skeletal system in simulated take-offs in terms of the ground reaction forces and net joint moments generated at the hip, knee and ankle joints.

5. To profile the isokinetic muscle function of the knee joint in to obtain a greater insight into the specific muscle strength requirements of elite long and triple jumpers.

1.3 List of abbreviations

Abbreviation	Definition
Key instants	
TOLS	Take-off last stride - the instant of foot leaves the track in the last stride
TD	Touch-down - the instant the foot makes contact with the track
MKF	Maximum knee flexion - marking the end of the compression phase
Tx=0	End of the pivot action - the instant the centre of mass is directly above the toe
TO	Take-off - the instant the foot leaves the track
TD-TO	The change from touch-down to take-off
Velocity measures	
VX	Horizontal (sagittal) velocity of the centre of mass
VY	Vertical velocity of the centre of mass
VZ	Medio-lateral velocity of the centre of mass
Kinematic measures	
Ax	Touch-down angle of the support leg in the sagittal plane - angle between the line connecting the centre of mass to the ankle joint relative to the downward vertical
Az	Touch-down angle of the support leg in the frontal plane - angle between the line connecting the centre of mass to the ankle joint relative to the downward vertical
Dx	Touch-down distance of the support leg in the sagittal plane - horizontal distance between the centre of mass and the ankle joint
Dz	Touch-down distance of the support leg in the frontal plane – horizontal distance between the centre of mass and the ankle joint
Tx	Horizontal distance between the centre of mass and the toe in the sagittal plane

General terms

2D	Two-dimensional
3D	Three-dimensional

2.0 Literature Review

2.0 Literature Review

Most biomechanical analyses investigating the kinematics of jumping for distance have focused on the long jump, mainly because of its relative simplicity compared to the triple jump. The main emphasis of this literature review is therefore on the kinematics of the long jump take-off, particularly in the early sections. The first two sections begin by identifying why speed, and in particular the vertical velocity component, are important when jumping for distance. Section 2.3 examines the kinematics of the approach phase and identifies aspects of long jump technique that facilitate the development of vertical velocity. The focus then moves to the take-off phase in section 2.4, and reviews how the take-off can be divided into sub phases and pays particular attention to the underlying mechanisms that enable vertical velocity to be generated. In an attempt to associate the theories of the long jump with the triple jump, kinematic comparisons of the long and triple jump take-offs are the basis for section 2.5. The limited amount of research that has examined the three-dimensional kinematics of the long and triple jump is reviewed in section 2.6, and the final section examines the kinetic aspects of the jumps. A summary of the current state of research into the horizontal jumps is presented at the end.

2.1 The relationship between approach speed and jump distance.

Research into the long jump has shown that the speed of approach is probably the determinant of how far an athlete is likely to jump. Strong linear correlations between the horizontal velocity of the centre of mass (CM) at the instant of touch-down (TD) on the board and the official jump distance have consistently reported coefficients in the order of 0.7 and greater, (Hay et al., 1986; Hay and Nohara, 1990; Nixdorf and Bruggemann, 1990). The linear relationship between the horizontal velocity of approach and the official jump distance can be seen in figure 2.1.1. The strength of this relationship has been reported to decrease as the level of performance increases and when the athletes are of similar ability (Lukin, 1949, cited by Hay 1986). Lukin (1949) interpreted his findings to indicate that 'as strength and overall fitness increase, good technique becomes more important than running speed'.

Figure 2.1.1. Relationship between the horizontal velocity at touch-down and the official distance of the long jump. ($r=0.95$; 306 jumps by 39 males and 28 females - (Hay, 1993).

The high correlation coefficients obtained in the above studies are not surprising considering that the speed at take-off is probably the most critical of the three projectile parameters. This is because the range of a projectile (i.e. the athlete) is proportional to the square of the speed of the centre of mass at the instant of take-off (Townend, 1984).

2.2 The relationships between loss of horizontal and gain in vertical velocity in the long jump take-off.

The speed of the athlete at the instant of take-off is the resultant of the horizontal and vertical velocities, which in turn define the angle of projection. The interaction of the horizontal and vertical velocities throughout the contact phase therefore play a vital role in the determination of the jump distance. Palermo (1980) stated that the optimum angle of take-off for a projectile (at ground level) is 45°, but to attain such an angle in the long jump the horizontal and vertical velocities would have to be equal. As long jumpers typically generate vertical velocities of approximately 3.0 $m.s^{-1}$ to 3.7 $m.s^{-1}$ (table 2.1.1), this would mean reducing the horizontal velocity to a similar magnitude. Therefore, the resultant speed would not optimise the performance. Long jumpers take-off with angles significantly less, typically between 18° and 24° as reported from recent major championships, illustrated in table 2.2.1.

Table 2.2.1. Typical kinematic data of the long jump take-off from recent major championships.

A typical profile of the changes in horizontal (VX) and vertical (VY) velocities during the long jump take-off was presented by Lees et al. (1994), figure 2.2.1. This graph shows that when the touch-down leg makes contact with the take-off board, long jumpers experience a characteristic horizontal braking force, which is complemented by a rapid increase in vertical velocity. The relationship between the amount of vertical velocity gained and the magnitude of the horizontal velocity loss in the take-off has been the focus of much attention.

Figure 2.2.1. Horizontal and vertical velocity profiles of a typical long jump.
- (Lees et al., 1994)

Ramey (1970) examined the horizontal force-time relationship in the long jump take-off and confirmed that a braking force is experienced that serves to slow down the athlete. Unger (1980) stated that this braking force is responsible for a loss in horizontal velocity of around 0.8 $m.s^{-1}$ to 1.0 $m.s^{-1}$ in the 'amortisation', or compression phase of the jump. Ramey (1970) stated that a more efficient take-off is obtained by maximising the net vertical impulse while minimising the net horizontal impulse. Bosco et al. (1976) supported this view and added that the take-off in the long jump is a movement in which the athlete tries to develop as much vertical velocity as possible without an appreciable loss of horizontal velocity developed during the approach run.

Tiupa et al. (1982), cited by Hay (1986), analysed the jumps of 113 males, from 'novice to international master' and found a correlation of 0.66 between the magnitude of the vertical velocity gained to the magnitude of horizontal velocity lost in the compression phase. This indicates that the greater the increase in vertical velocity (in the compression phase) and the greater the loss in horizontal velocity, then the greater the effective distance, (the effective distance being the sum of the official distance and the toe to board distance). They concluded that an increase in vertical velocity is almost twice as beneficial as an increase in horizontal velocity and rejected the view that 'increased take-off effectiveness must result from minimising the loss in horizontal speed'. They added that not only is braking important, but 'it is impossible to complete a good jump without a loss of speed'. This view was supported by the data presented by Nixdorf and Bruggemann (1990) and Koh and Hay (1990a).

Nixdorf and Bruggemann (1990) analysed 8 male athletes in the 1988 Olympic long jump final and observed average losses of 1.45 $m.s^{-1}$ and 0.86 $m.s^{-1}$ in the horizontal and resultant velocities and a mean vertical velocity at take-off of 3.2 $m.s^{-1}$. They found a correlation coefficient of $r=0.67$ between the loss in horizontal velocity and the vertical velocity at take-off, indicating that greater losses in horizontal velocity lead to greater vertical velocities.

In relation to actual jump performance, Koh and Hay (1990a) found a correlation coefficient of $r=-0.59$ between the change in horizontal velocity in the last stride and the effective distance jumped. They suggested that large jump distances may be the result of larger losses in horizontal velocity, adding that the function of the last stride landing (touch-down into the jump) did not appear to be for maintaining horizontal velocity.

The literature has clearly shown that the generation of vertical velocity in the long jump take-off occurs at the expense of a loss in horizontal velocity. It is not clear whether there is an optimum loss of horizontal velocity in the long jump take-off, or indeed if the athlete should be trying to minimise the losses in horizontal velocity. It is apparent that the development of vertical velocity is the most critical aspect of the take-off phase in the long jump. The next sections of this review examine the approach and take-off techniques of long jumpers to determine how athletes can facilitate and generate vertical velocity.

2.3 The approach

It has been shown that the long jumper makes several adjustments in body position in the latter stages of the approach run. These are thought to bring the athlete to the take-off board in a favourable position to facilitate the development of vertical velocity during the contact phase of the jump. Such adjustments refer to changes in stride length and frequency, the lowering of the athlete's centre of mass during the last few strides of the approach, and the placement of the touch-down leg well in front of the centre of mass at touch-down on the board (Hay, 1986; Hay and Nohara, 1990; Lees et al., 1993; 1994).

2.3.1 Changes in stride length and stride frequency

It was originally thought that long jumpers should reach maximum horizontal velocity with 4 - 5 steps of the approach still remaining, and then to maintain this speed through to take-off. However, experimental evidence has shown this to be incorrect (Hay, 1993). Data from scientific investigations suggest that there are changes in stride characteristics such as length, frequency, speed, time of support and time of flight (Bruggemann and Susanka, 1987; Nixdorf and Bruggemann, 1990; Hay, 1993).

The lengths of the last four strides tend to vary according to the foot from which the athlete takes off into the stride. Those in which the athlete takes off from the take-off foot (4th and 2nd last strides) tend to be longer than those from the leading foot (3rd last stride). The steps from the take-off foot also become slower and those from the leading foot faster during the last 3-4 strides. This can be seen in table 2.3.1.

Table 2.3.1. Stride length and stride frequency during the last four strides of the approach (Popov, 1969, cited by Hay, 1986)

2.3.2. Changes in height of the centre of mass

Nixdorf and Bruggemann (1983), cited by Hay and Nohara (1990), reported that athletes lowered the height of their centre of mass by 10% from its height at the take-off into the 3rd last stride. Figure 2.3.1 shows a gradual reduction in the height of the athlete's centre of mass through the support phase preceding the 2nd last stride, followed by a large reduction of 7% in the flight phase of the 2nd last stride. The centre of mass was observed to lower slightly more during the contact and flight phases of the last stride until at touch-down on the board the centre of mass was approximately 11 cm lower than its original approach height.

Figure 2.3.1. Changes in height of the centre of mass in the last few strides of the long jump approach - (Nixdorf and Bruggemann, 1983, cited by Hay, 1986).

Hay and Nohara (1990) found a similar trend, revealing that the height of the athlete's centre of mass was significantly lowered during the flight phase of the 2nd last stride by an average of 6 cm (1.07 m to 1.01 m). The centre of mass then remained low during the support phase of the last stride and for the first part of the jump take-off. During the support phase of the jump take-off, the centre of mass was raised through an average of 26 cm, to leave the board at an average height of 1.27m.

Lees et al. (1994) who analysed the performances of the 12 finalists in the men's long jump at the 1991 World Student Games (WSG), and a total of 27 jumps observed that the centre of mass described an exceptionally flat trajectory over the flight phase of the last stride (from take-off last stride, TOLS, to touch-down, TD on figure 2.3.2). The centre of mass was seen to reach its lowest point at the instant of touch-down, dropping approximately 2 cm from its position at take-off last stride. The corresponding vertical velocity at the instant of touch-down reflected this almost flat trajectory, providing a small negative value of -0.04 $m.s^{-1}$.

Figure 2.3.2. Profile of the centre of mass during the last stride and take-off (TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion, TO = take-off). - (Lees et al., 1994)

Lees et al. (1993) stated that the lowering of the centre of mass is thought to have two purposes: first it ensures that the centre of mass has minimal negative vertical velocity at foot contact and , second, it provides the opportunity to work it through as large a vertical range as possible. If the centre of mass arrives at the board with a low, almost horizontal trajectory, it will have an almost zero vertical velocity. The benefit of such a contact with the board is that the vertical impulse imparted to the contact foot will eliminate the need for a negative vertical velocity to be reversed. Therefore the take-off will be more effective as all the vertical velocity generated in the jump take-off will be positive.

The first three images in Figure 2.3.3 show that the knee angle of the support leg is highly flexed and is less than fully extended at take-off into the last stride. This is likely to help the athlete adopt a low flat trajectory of the centre of mass in the last stride of the approach. A low position of the centre of mass throughout the last stride also enables the support leg to be placed well in front of the body at touch-down, (Dapena and Chung, 1988; Lees et al., 1994). This characteristic of long jumping technique can also be seen in figure 2.3.3, (image 5).

Figure 2.3.3. Representation of the last stride highlighting the extended leg at touch-down. - (Tidow, 1989)

2.3.3. Leg placement at touch-down.

Characteristics of the support leg are examined in this section. The touch-down distance - a measure of the extension of the support leg in front of the body at touch-down, and other kinematic variables that describe the landing leg motion before touch-down on the board are considered.

The touch-down distance has been defined in several ways, but all relate to the extension of the touch-down leg in front of the body. The various definitions are illustrated in figure 2.3.4. Hay and Nohara (1990) defined the touch-down distance as the horizontal distance of the athlete's centre of mass relative to the toe of the support foot. They reported a mean value of 0.77 ± 0.08 m for the 20 male long jumpers they analysed. The maximum and minimum values were 0.95 m and 0.65 m respectively. They observed that the touch-down distance was on average 30 cm greater for the touch-down into the jump take-off than for the touch-down into the preceding stride, suggesting that it had some significance in the take-off.

Koh and Hay (1990a) examined the landing leg motions of 19 elite male long jumpers who competed in the 1986 and 1987 TAC (US national) championships. They defined the touch-down distance as the horizontal distance between the hip and the centre of mass of the landing foot at touch-down. Significant increases in the mean touch-down distances from the 3rd, 2nd and last stride landings of 0.36 m, 0.44 m and 0.60 m respectively were found.

Figure 2.3.4. Various definitions of the touch-down distance and touch-down angle.

Lees et al. (1993; 1994) defined the touch-down distance as the horizontal distance between the athlete's centre of mass and the ankle joint of the touch-down leg. The average touch-down distance for elite male long jumpers was found to be 0.45 m (± 0.06). These studies also provided an alternative measure of leg extension, the angle of touch-down, A_{TD}, which was defined by the angle made by a line connecting the centre of mass to the ankle joint of the touch-down leg relative to the downward vertical. This variable, which was found to have a mean value of 24.7° ± 3.7, takes into account differences in body height and leg length and therefore provides a better measure of leg extension when comparing between individuals. This variable was found to be significantly correlated with the vertical velocity at the instant of take-off ($r=0.62$, $P<0.05$) and with the gain in vertical velocity from touch-down to take-off ($r=0.77$, $P<0.05$).

Fischer (1975), cited by Hay (1986), described leg extension as the angle made between the line connecting the centre of mass to heel relative to the backward horizontal. He found that in 72 % of the trials analysed trials, the centre of mass to heel angle fell within the range of 64° to 69°, (21° to 26° for comparison with Lees et al, 1994). No good jump distances were observed when this angle was extremely large or small.

Nixdorf and Bruggemann (1990) used the same definition as Fischer (1975) but referred to this measure as the angle of body lean at touch-down. An average angle of 61.1° was found with a range of 63.4° to 58.5°. For comparison with Lees et al. (1993, 1994) these correspond to angles of 29.9°, 26.6° and 31.5° to the downward vertical.

Although the definitions and measures of the leg extension in the above studies differed, all have identified the importance of an outstretched landing leg upon impact with the take-off board. Koh and Hay (1990a) stated that a large touch-down distance may be important for the last stride landing, as it was greater than the two preceding landings. The loss in horizontal velocity during this landing was also found to be greater than the preceding support phase, (-1.20 $m.s^{-1}$ compared to -0.47 $m.s^{-1}$ and +0.1 $m.s^{-1}$ for the 2nd and 3rd last strides respectively). A correlation coefficient value of $r = -0.61$ between the touch-down distance and the loss in horizontal velocity suggested that large touch-down distances may be associated with large losses in horizontal velocity. In addition, a correlation coefficient value of $r = 0.44$ was observed between the touch-down distance and the effective jump distance, suggesting that large touch-down distances may also have some association with large effective distances, despite the possible association with the loss in horizontal velocity.

The greater extension of the leg in front of the body in the touch-down into the jump has also been proposed to facilitate the production of vertical velocity. This was observed by Dapena and Chung (1988) who examined the take-off in the high jump. Koh and Hay (1990a) added that if the foot is placed far enough ahead of the body and the leg doesn't flex too deeply, the centre of mass can actually be raised while the leg is still flexing. A large touch-down distance was also said to promote a longer duration of the support phase. This provides a longer interval in which the athlete can generate vertical velocity. Compared to a smaller TD distance, Koh and Hay (1990a) stated that a large TD distance:

a) increases the horizontal displacement of the centre of mass during the support phase of the jump;

b) decreases the horizontal velocity of the centre of mass during the braking part of the support phase, and

c) increases the duration of the support phase, enabling greater vertical impulse to be generated.

Lees et al. (1994) added that a large touch-down distance also:

i) increases the range of movement through which the hip extensor muscles may work, and

ii) places the leg in a position that enables muscles and tendons to be stretched and store elastic energy.

Another factor concerning the touch-down leg is the manner in which the foot is placed on the board. Hay (1986) stated that there are two schools of thought as to what type of foot placement (or landing leg motion) should be used. One advocates a pawing, or backward sweeping motion of the landing leg (an active landing) as the foot is brought into contact with the ground; the other advocates a 'locking' placement of the foot where it is assumed that the foot is neither moving forward nor backward relative to the centre of mass.

An active landing reduces the forward horizontal velocity of the foot at touch-down, thereby reducing the opposing braking ground reaction force at impact, compared to a landing that is not active. Hence a smaller braking force is applied to the athlete's centre of mass, and the loss in the horizontal velocity of the centre of mass is minimised during the initial part of the following contact phase. Advocates of the active landing believe that minimising the loss of horizontal velocity in the initial phase of the touch-down is an important determinant of the distance of the jump.

The characteristics of the locking placement are a large forward horizontal velocity of the landing leg with little relative motion to the athlete's centre of mass. This results in a large horizontal braking force in the initial phase of the touch-down and a large reduction in the horizontal velocity of the centre of mass. The locking technique is believed to promote the development of vertical velocity during the support phase of the jump and this is thought to be more important than aiming to limit the loss in horizontal velocity.

Koh and Hay (1990a) examined the landing leg motions of 19 elite male long jumpers during the last 3 strides of the approach. They analysed 'activeness' and 'touch-down' measures of the leg and the changes in horizontal velocity during each of the contact phases. The results revealed that the foot moved backward relative to the centre of mass at TD in each landing, and therefore each landing could be described as 'active'. However, the relative velocity of the foot decreased from -9.02 $m.s^{-1}$ in the 3rd last landing to -6.46$m.s^{-1}$ in the landing of the last stride. The last stride landing was shown to be significantly less active than the two preceding landings, striking the board with a forward velocity of 3.79 $m.s^{-1}$. The larger forward or absolute velocity of the foot was said to lead to a greater horizontal braking force upon impact with the board than the previous two landings.

The literature has shown that athletes makes several adjustments in body position during the last few strides of the approach. The most significant of these are a lowering of the centre of mass from the take-off into the 3rd last stride, maintaining a low flat trajectory through the last stride and then 'actively' or 'inactively' placing the leg in an extended position in front of the centre of mass at touch-down on the board. The benefits of these adjustments have been described as placing the athlete in a favourable position to facilitate the production of vertical velocity in the take-off phase. The next section will look at the take-off phase and examine what mechanisms operate to generate vertical velocity.

2.4 The touch-down (TD) to take-off (TO) phase.

This section begins by describing how the touch-down to take-off phase has been divided into smaller phases and then examines the mechanisms that contribute to the generation of vertical velocity.

2.4.1. Division of the touch-down - take-off phase

Hay (1986) stated that the take-off phase may divided into 3 parts: an initial (or isometric) phase during which the angle of the knee joint remains practically unchanged; a middle phase (variously described as eccentric, yielding, compression or amortisation) in which the knee joint angle decreases, and a final phase (also described as concentric, extension, lift or surmounting) in which the knee joint angle increases. However, the more detailed biomechanical investigations have divided the touch-down to take-off phase into the latter two components and these can be clearly seen in figure 2.4.1. The instant at which this transition point occurs, however, has various definitions.

Figure 2.4.1. The touch-down to take-off phase showing the compression and extension phases - (Tidow, 1989).

Ramey (1970) separated the vertical force-time relationship into 2 primary regions; an impact region and a thrust region. The impact region was defined from the instant the foot first struck the platform to a minimum trough in the vertical force curve, figure

2.4.2. This period, which was observed to last between 0.03 s and 0.05 s, was said to encompass the initial impact of the foot and the onset of knee flexion. The thrust region was taken to act from the trough in the curve to the instant the foot left the platform, and was observed to last between 0.12 s and 0.17 s. The thrust region was said to represent the major portion of the force that is used to propel the jumper upwards. It is apparent that this transition point does not adequately represent the effects of joint compression as the knee continued to flex in the early part of the thrust region.

Figure 2.4.2. Division of the force-time curve into impact and thrust regions - (Ramey, 1970).

Using force platform and cinematography techniques, Bosco et al. (1976) defined the transition from yielding to surmounting to be the moment when an imaginary line, 'point of application to centre of mass', reached the vertical position. This definition seems valid as Unger (1980) stated that 'during the yielding phase the load on the take-off leg increases considerably as it bends at the hip and knee joints, while the jumper's centre of mass moves closer to the supporting point'.

Studies by Lees et al. (1993; 1994) and Aura and Viitasalo (1989) divided the take-off phase into compression and extension phases, denoted by the minimum knee angle of the support leg. The compression phase was therefore defined as the time period between touch-down to the instant of maximum knee flexion and the extension phase from the instant of maximum knee flexion to the point where the foot left the board. Lees et al. (1993; 1994) observed that the instant of maximum knee flexion typically occurred around 45% to 50% into the contact phase of the long jump when the knee angle had decreased to an average angle of 146°.

Dapena and Chung (1988) analysed the take-off phase of the high jump and used the minimum 'radial distance' to distinguish between compression and lift phases. The radial distance was defined as the distance between the centre of mass of the athlete and the hinge point. They observed the radial distance to decrease by an average of 0.19 m in the early phase of the take-off before increasing 0.32 m by the instant of take-off. The radial distance therefore measures the amount of compression experienced by the body as a whole, and does not isolate the compression in the knee joint.

It is clear that each one of these transition points has valid rationale, but all refer to different instants in time within the take-off phase. The instant of maximum knee flexion is the only one that totally separates the effect of joint compression and extension; the others take into account the behaviour of the centre of mass.

However, the division of the touch-down to take-off phase into two major parts has helped to identify mechanisms acting during the touch-down to take-off phase which are responsible for the generation of vertical velocity. Lees et al.(1994) concluded that there is evidence for mechanical, biomechanical and muscular mechanisms acting throughout this phase. The definition of a 'mechanical' mechanism was any effect that could also be produced by an inanimate object, e.g. a wooden stick. With reference to jumping an outstretched support leg at touch-down acts as a lever which helps to rotate the athlete's body over the base of support. This 'lever' effect has been termed the pivot action and is believed to act in the compression phase of the take-off. Another mechanical mechanism is the effect produced by a swinging mass relative to its point of attachment on another object. Upward movements of the swinging mass create a reactive impulse from the surface and this helps to drive the system (both objects) in a vertical direction. This can be applied to the movements of the free limbs in jumping. The 'muscular' mechanism was defined as the effect produced by the contractile properties of muscle and these cannot be produced by inanimate objects. In jumping, concentric muscular contractions extend the hip, knee and ankle joints and this increases in height and vertical velocity of the centre of mass. The 'biomechanical' mechanism was defined as a mechanical effect on a biological structure. In actions that involve a rapid transition from eccentric to concentric muscular contraction, elastic energy is believed to be stored in muscle and tendon and re-utilised to enhance the concentric contraction.

2.4.2 Mechanisms for the generation of vertical velocity.

a) The Pivot

The 'pivot' is a term used to address the role of the support leg as it controls the movement of the body during the first part of the take-off, i.e. the compression phase described above. The effectiveness of the 'pivot' has been described by the movement of the centre of mass and the magnitude of vertical velocity during the compression phase. This section examines how different researchers have assessed the action of the pivot mechanism and identifies factors relating to its effectiveness.

Bosco et al.(1976) studied 4 male Finnish national level long jumpers, and a total of 8 jumps. The vertical velocity of the centre of mass at the time when the imaginary line from the point of force application to the centre of mass reached a vertical position was found to account for 60% of the total vertical velocity gained at take-off. They observed that in the good performances 'the centre of mass began to rise immediately after the first touch on the force platform, but in poorer jumps the centre of mass remained at about the same height during the early contact phase'. The results indicated that a strong emphasis should be placed on the early phase of support.

Lees et al. (1993) examined the centre of mass height and horizontal and vertical velocity profiles of 6 female long jumpers, (a total of 22 jumps) at the World Student Games, 1991. They observed that the centre of mass rose by an average of 4 cm by the end of the compression phase, and rose by a further 20 cm in the extension phase. However, after inspection of the vertical velocity - time curve they observed that 66% of the total vertical velocity gained throughout the support phase had been attained by maximum knee flexion.

A further study by Lees et al. (1994) presented data on the 12 male finalists at the 1991 World Student Games found similar results. From an average height of the centre of mass at touch-down of 1.10 m, the centre of mass was found to rise through 4.4 cm. during the knee compression phase, and then through 18.8 cm in the knee extension phase. In contrast, the vertical velocity of the centre of mass increased from -0.11 $m.s^{-1}$ at touch-down to 2.06 $m.s^{-1}$ at maximum knee flexion to 3.26 $m.s^{-1}$ at take-off. Of the total vertical velocity gained from touch-down to take-off, 64.4% was attained in the compression phase and the remaining 35.6% was gained in the extension phase. The results of the study supported the findings of Bosco et al. (1976), highlighting the importance of the compression phase.

Strong positive relationships between the angle of touch-down, A_{TD} (see figure 2.3.4) and the vertical velocity at take-off ($r = 0.62$) and the total gain in vertical velocity ($r = 0.71$) suggested that the angle of leg extension could be a critical factor in the development of vertical velocity. Lees et al. (1993) stated that a fast approach speed coupled with a leg angle at touch-down of approximately 26° allows the centre of mass to ride over the foot creating vertical velocity. They added that the benefits of what they later termed the 'pivot' may be reduced if the leg is not placed far enough in front of the body and if the athlete does not have sufficient eccentric strength to resist the flexion at the knee joint. They also stressed that if the leg is placed too far in front of the body then a larger braking effect is likely to be produced, leading to a greater reduction in horizontal velocity. This view was also given by Fischer (1975), cited by Hay (1986).

In an attempt to investigate factors relating to the effectiveness of the pivot, Lees et al. (1994) theorised that the ability of the athlete to withstand knee flexion would enhance the effectiveness of the pivot. However, the relationship between the amount of knee flexion and the gain in vertical velocity from touch-down to maximum knee flexion was not significant. Although the rationale for this theory is sound, it is clear that other factors may influence the generation of vertical velocity and these need to be identified.

Alexander (1990) proposed a simple mathematical model of the athlete to identify the principles that govern optimum speed and leg placement angle at touch-down in the high and long jump take-offs. The model comprised a rigid trunk and a leg formed from two rigid segments of equal length. The mass of the athlete was concentrated in the trunk and the centre of mass was located at the hip joint. The foot was treated as a point at the distal end of the lower leg segment. The model also incorporated properties of the leg muscles, changes in knee angle, the torque generated in the extensor muscles, changes in the contractile component and angular compliance. After entering reasonable estimates of the various parameters, the model proposed that the longest long jump distance would be achieved following the fastest possible run-up (approximately 11 $m.s^{-1}$) with the leg planted at an angle of 70° to the horizontal upon impact. This corresponds to an angle of 20° by the definition of Lees et al. (1993, 1994). In contrast, for optimal performance in the high jump, the optimal speed of approach was estimated to be about 7 $m.s^{-1}$ with a leg placement angle of 45° to the horizontal.

The pivot action essentially describes a rotation effect about the ankle and foot. The cause of the rotation is a fast approach speed coupled with an extended leg in front of the centre of mass at touch-down which acts as a lever. However, upon impact with the take-off board, horizontal and vertical ground reaction forces act about the athlete's centre of mass creating a resultant moment. The resultant moment will serve to rotate the athlete forwards or backwards about the transverse (somersault) axis depending whether the line of action of the resultant force passes in front or behind the centre of mass. From the angular impulse – change in angular momentum relationship, the resultant moment acting throughout the support phase causes a change in angular momentum. The angular momentum possessed by the athlete in the flight phase is therefore the sum of the angular momentum of the athlete in the preceding flight (of the last stride) and the change developed during the support. Studies by Ramey (1974) and Bedi and Cooper (1977) assumed that the athlete entered the take-off with zero angular momentum and the flight angular momentum was determined by the angular impulse generated in the take-off. This has later been shown to be incorrect and that approximately half of the flight angular momentum is developed in the approach (Hinrichs et al., 1989).

In a highly complex optimisation model of the long jump take-off Hatze (1981) included the magnitude of the athlete's forward angular momentum for the calculation of jump distance. He stated that the forward angular momentum must be large enough to prevent the athlete falling back upon landing in the pit, and thereby losing distance. Unfortunately no angular momenta data were presented in the paper, but judging by the exaggerated forward inclination of the hominoid's trunk at take-off, approximately 40°, it would appear that angular momentum was over emphasised. Hay (1993) commented that too much forward angular momentum can also be detrimental to performance, as over-rotation will not allow the athlete to extend the legs in front of the body at touch-down. If angular momentum is not controlled during the flight, the legs will land beneath the body rather than in front, and consequently distance will be lost in the landing. The same problem would apply equally to the landing into the pit from the jump phase in the triple jump. However, effective use of the 'sail', 'hang' or 'hitch-kick' flight techniques can overcome the potential detrimental effects of over-rotation. Indeed, Ramey (1974) reported that the three techniques required significantly different magnitudes of forward angular momentum to produce equally successful performances. These were 5.4 $kg.m^2.s^{-1}$, 14.2 $kg.m^2.s^{-1}$ and 20.3 $kg.m^2.s^{-1}$ for the sail, hang and 3.5 hitch-kick respectively. In the triple jump Yu and Hay (1995) reported that some forward angular momentum is required in the preceding flight phases to allow for active landings of the touch-down leg. They suggested that the activeness of the landing leg, which is thought to reduce the horizontal braking effect on the athlete (and enhance performance), is dependent on the magnitude of the somersaulting angular momentum during the preceding flight. Mean angular momenta in the flight phases of the last stride, hop, step and jump were 6.37 $kg.m^2.s^{-1}$, 8.27 $kg.m^2.s^{-1}$, 2.16 $kg.m^2.s^{-1}$ and 5.63 $kg.m^2.s^{-1}$ respectively.

Although forward angular momentum can be regarded as a by-product of the take-off, possible detrimental effects of over rotation can be overcome by flight technique and the movement of body segments to accommodate a good landing position. Athletes should primarily focus on generating vertical velocity, as this will give them time in the air (prolonging the flight distance), rather than be too concerned about the possible loss of distance due to over-rotation.

In summary, there is strong evidence in the literature that the centre of mass can actually be raised in the compression phase of the long jump take-off, even when the knee joint is flexing. Relationships have been reported between the angle of leg extension at touch-down and the amount of vertical velocity generated in the take-off, suggesting that leg extension in front of the body is a vital part of the pivot mechanism. However, factors relating to the effectiveness of the pivot action in the compression phase are not yet clear. Considering that the pivot mechanism accounts for over 60% of the total gain in vertical velocity a thorough understanding of how the pivot operates is required. Aspects of technique and strength need to be investigated for their influence on the pivots effectiveness if specific advice is to be given to athletes.

b) The upward movements of the lead leg and arms

The role of the free limbs is strongly emphasised in long jumping technique (Tidow, 1989) and it is a clearly observable feature of performance, see figure 2.4.1. The supporting movements of the arms and lead leg have been reported to have a considerable influence on the take-off, increasing the effectiveness up to 25%, Unger (1980). A common explanation for the effect of the free limbs is that as they are thrown upwards into the air, they pull the remainder of the body with them, raising the height of the jumper's centre of mass by the end of the extension phase.

The mechanism which operates when a limb is moved upwards to gain vertical velocity is one where the downward reaction is transferred to the ground creating a reactive impulse that drives the system's centre of mass in the direction of the segment, Lees and Barton (1996). This works effectively providing that there is a firm surface on which to generate the reactive impulse.

The effectiveness of the supporting movements of the limbs depend on the speed and amplitude of the acceleration phase, as well as the length and time of the deceleration phase. From a theoretical point of view, straight arm and leg movements are more efficient because the centre of mass is further away from the turning axis, increasing angular momentum. However, this is not practical in the long and triple jump take-offs as the forward speed of the athlete doesn't allow time to perform a straight leg swing. Long and triple jumpers therefore perform the swinging movements with flexed arms and lead leg. This decreases the moments of inertia about the shoulder and hip joints, and allows the arms and leg to develop greater speeds. Lukman (1974), cited by Hay (1986), reported that the maximum velocity of the centre of mass of the lead leg was 13.5 $m.s^{-1}$ and this occurred when the centre of mass of the lead leg was almost directly below the hip joint. It would appear that the effectiveness of the free limbs are dependent on a trade off between joint angle and speed of movement. Presently no studies have described the movement patterns of the free limbs, and until this is done the relationship between optimal joint angles and speed of movement will remain unresolved.

Several studies have examined the relative contribution of body segments to the generation of vertical velocity in the long jump take-off. Luhtanen and Komi (1979) evaluated segmental contributions during the touch-down to take-off phase using the impulse - change of linear momentum relationship. Ground reaction forces were measured using a force platform, while body movements were analysed using cinematography. During the contact phase, which was observed to last an average of 0.11 s, all the body segments analysed recorded positive vertical impulses. The trunk and head recorded the greatest vertical impulse of 111.8 Ns, whilst the arms, support leg and lead leg recorded similar values of 34.6 Ns, 33.6 Ns and 32.6 Ns respectively.

Stewart (1981) analysed the jumps of 2 elite Australian male long jumpers, who attained distances of 7.53 m and 7.37 m. He used a linked system model to estimate the forces generated by particular body segments. The peak forces generated by the swinging leg were 733 N and 800 N, compared to the peak forces generated by the take-off leg of 3586 and 3432 N respectively. The take-off leg was reported to contribute 49.5% of the total force, the lead leg approximately 11.5%, both arms 12.5% and the remaining 26.5% from the trunk, and in particular its extension during the take-off phase.

The contribution made by the free limbs in running and jumping activities have been determined from kinematic data using the relative momentum approach proposed by Ae and Shibukawa (1980). In this method, the total vertical momentum of the limb is the sum of the transfer momentum and the relative momentum. For example, for the arm segment

$$
\begin{array}{llll}
m_a V_a & = & m_a V_s & + & m_a V_{a/s} \\
\text{total momentum} & = & \text{transfer momentum} & + & \text{relative momentum}
\end{array}
$$

where 'm' is the mass, 'V' is the vertical velocity and subscripts 'a' and 's' refer to the arm segment and shoulder joint respectively. The transfer momentum accounts for the momentum transferred through the proximal joint and the relative momentum reflects the active use of the limb.

However, several interpretations of relative momentum data have been offered in the literature. The interpretations of Ae and Shibukawa, (1980) and Hinrichs et al., (1987) are inconsistent with each other and not compatible with studies that calculated the effects of the free limbs direct from force platform measurements. Lees and Barton (1996) provided a summary of their limitations and offered their own interpretation which is summarised below:

i) the contribution of a single limb to the vertical velocity at take-off is determined by the positive increase in the relative momentum value from the beginning (touch-down) to the end of the action (take-off).

ii) when considering a single limb, the negative relative momentum can be ignored as it makes no direct contribution to upward movement.

iii) the combined effects of several limbs together can be determined by the increase in the positive value of the sum of the relative momentum for all limbs between the start and the end of the action.

The results of Lees and Barton (1996) compared favourably with the studies by Shetty and Etnyre (1987) and Harmen et al. (1990) which both used a direct method (force platform) to determine the contribution of free limbs during vertical jumping.

Using the same interpretation of Lees and Barton (1996), Lees and Graham-Smith (1994) analysed the best jump of 10 male and 6 female long jumpers in the finals at the 1991 World Student Games. The free limbs were found to contribute 11% (female) and 13% (male) to the vertical velocity of the centre of mass at take-off. Of this, the lead leg was shown to produce the greatest contribution to the free limb total with over 70% for females and 67% for males. This was attributed to the greater mass of the leg compared to the arms, and the greater percentage found for the female athletes was attributed to their larger proportion of body mass concentrated in the leg. The co-lateral arm (same side as take-off leg) was found to contribute 26%, while the contra-lateral arm (same side as lead leg) contributed only 7% to the vertical velocity at take-off. This indicates that the arm action is asymmetrical.

Lees and Barton (1996) also concluded that the effectiveness of the total free limb contribution is affected by the co-ordination and timing of limb movements. Unger (1980) stated that the acceleration of the swinging movements should occur during the amortisation phase and deceleration during the drive phase. During the acceleration of the swinging mass the forces on the take-off leg are increased, the extensor muscles are completely stretched and a favourable condition is created for the following contraction. As the deceleration begins the forces on the take-off leg decrease and the driving action of the take-off becomes faster. The co-ordination between the swinging movements and the take-off action secures an explosive take-off, provided the jumper performs the swinging movements as fast as possible and co-ordinates it well with the acceleration of the drive.

Research has shown that the movement of the free limbs is an important characteristic of long jump performance, but this aspect of technique is not fully understood. Various methods have been adopted to evaluate the contribution of the free limbs to the generation of vertical momentum and these range from 11% to 24%. The movement patterns of the free limbs have not been quantified, and these need to be analysed if the role of the free limbs in the generation of vertical momentum and the maintenance of balance are to be evaluated. Whilst the arm action in the long jump is described as asymmetrical and a continuation of a running style, various arm techniques have been reported for the triple jump, Hay (1992). These refer to the single arm techniques similar to the long jump, double arm shifts where both arms are moved upwards in a symmetrical manner, and a combination of the two termed the 'arm and a half' technique. The effectiveness of these different techniques also need to be investigated.

c) Storage and re-utilisation of elastic energy

Cavagna et al., (1968), cited by Shorten (1987) stated that 'when a concentric muscle contraction is preceded by a stretching eccentric phase, the force, power and work produced are greater than for a contraction without pre-stretch'. The combination of an eccentric contraction followed rapidly by a concentric contraction forms a natural type of muscle action called the 'stretch-shortening cycle'. Since the take-off leg undergoes an eccentric phase prior to a concentric phase then a long or triple jumper can enhance his drive off the board through effective use of a pre-stretch.

The benefits of a pre-stretch have been demonstrated by comparing two types of vertical jump, one with a pre-stretch (counter movement jump) against one without a pre-stretch (squat jump), (Bosco et al.1982a; Bosco et al. 1982b). Whilst it is generally accepted that performance is enhanced by a pre-stretch the mechanisms surrounding this phenomenon are far from clear. The debate over this topic recently led to a full issue of *Journal of Applied Biomechanics* being devoted solely to collating current views in this area. The target article by Ingen Schenau et al. (1997) identified 4 mechanisms that researchers believe help explain this phenomenon. These are: i) the increased time available for force development, ii) the storage and re-utilisation of elastic energy, iii) potentiation of the contractile machinery, and iv) the contribution of stretch reflexes.

Ingen Schenau and his group of researchers firmly endorsed the argument that enhanced performance is related to the increased time available to develop force. Their view is formulated on the evidence that a muscle undergoing an initial loading or pre-stretch attains a greater level of active state and force prior to the commencement of the concentric phase. In a counter movement jump, for example, the lowering of the centre of mass therefore provides time for the quadriceps and calf muscles to develop force. In a squat jump the movement starts from rest and this takes longer for the subject to reach maximum force. Additionally, Komi (1986) reported that the force and power characteristics of skeletal muscle are greatest in an eccentric mode of contraction and this increases as a function of stretching velocity. Therefore, depending on the rate of stretch it is possible that the initial concentric force at the beginning of the shortening phase can be greater than the maximum force generated without a pre-stretch. This is supported by the early observations of Cavagna et al. (1968).

The second mechanism, which for many years researchers have believed to be the major factor, is the storage and re-utilisation of elastic energy in muscle and tendon. When an active muscle is pre-stretched the series elastic element, which is in series with the contractile element, is believed to store energy. This 'elastic energy' is then returned, in part, to assist in the concentric contraction of the contractile element. Ingen Schenau et al. (1997) did not dispute that muscle and tendon have this ability, but recognised it as a secondary factor and only in fast stretch-shorten movements like in the high jump.

While Ingen Schenau et al. (1997) disagree that potentiation and stretch reflexes contribute to the enhanced force production in stretch-shorten cycle activities, several researchers do (Edman, 1997; Biewener, 1997, Komi and Gollhofer, 1997, Zatsiorsky, 1997). Potentiation refers to an increased neuro-muscular excitability or stimulation of contractile machinery in muscle after a stretch and leads to increased force production due to stretching. The contribution of stretch reflexes relate to the response from muscle spindle receptors and the Golgi-tendon organs located in muscle and tendon which detect changes in length and tension respectively. When these receptors detect large amounts of length change and tension they send neural messages to the brain to initiate a concentric contraction of the muscle. By blocking the action of the stretch reflex in the vastus lateralis by a 1% Novocain (procaine) injection, Kilani et al. (1989) found that performance is significantly reduced in one-legged squat and counter movement jumps. It was concluded that the stretch reflex has a significant contribution to jump performance.

Although the extent to which the above mechanisms are thought to operate is unresolved, it is accepted that effectiveness of a stretch-shorten cycle is related to three main factors. Komi and Gollhofer (1997) report these as: a well timed pre-activation of muscles prior to the eccentric phase, a short and fast eccentric phase, and the immediate transition between the eccentric and concentric phases. The latter has also been termed the 'coupling time' (Aura and Komi, 1987; Goubel, 1997). Luhtanen and Komi, (1979) and Unger (1980) added that a short stretch at a high velocity is more effective than a longer stretch at a lower velocity.

Consequently, with respect to long and triple jump performance, the shorter and the faster the bending action of the take-off leg in the eccentric phase, the greater the reactive contraction will be in the drive phase. Bosco et al. (1976) commented that if the stretching phase is too long, it will lead to a reduction in stored elastic energy and subsequently cause a lowering of the athlete's centre of mass, a characteristic they observed in the poorer performances.

Witters et al. (1992) attempted to estimate the conversion efficiency and importance of elastic energy in the long jump take-off. They adopted a theoretical model which assumed that the take-off leg behaved in a spring-like manner. A 'recovery efficiency factor', α (alpha), was defined as 'the fraction of energy lost in horizontal motion which is regained in vertical motion'. They concluded that elastic effects are important in the long jump take-off, showing a 30% efficient conversion of run-up kinetic energy to energy of vertical motion. When an optimisation model for jump distance was applied to data from the 1987 World Championships (Nixdorf and Bruggemann, 1988), conversion efficiencies fell within the range 0.2 to 0.3. They demonstrated that conversion efficiency decreased with increasing run-up speed and that 'maximal efficiencies are not always realised because the athlete can choose from a certain range of parameters, probably trading-off elastic conversion for heavier impacts'.

The problem with theoretical models is that they are often over simplified, and as previously stated it is not yet clear whether the muscle can be modelled as a spring. A study by Fukashiro et al. (1995) attempted to overcome this by measuring in vivo Achilles tendon loading during jumping activities. The results from the buckle-type transducer found peak Achilles tendon forces of 2233 N, 1895 N and 3786 N in squat, counter movement and hopping type jumps, respectively. An estimate of tendon stiffness, 22 Nmm^{-2}, (assuming a quadratic characteristic of tendon) was made from the cross-sectional area of the subject's tendon, and this enabled an estimation of stored elastic energy. The Achilles tendon was found to store 7.9 J (23% of total calf work) in the squat jump, 6.2 J (17%) in the counter-movement jump and 17.5 J (34%) in hopping. They concluded that the greater contribution to mechanical work in hopping was due to elastic energy as the calf muscles showed a definite change in length during this action (determined from the muscle length equations of Grieve et al, 1978).

To summarise, the role of the stretch-shorten cycle in enhancing performance is generally accepted in the literature. The mechanisms that have been proposed to help explain the enhanced force production in the concentric phase are unresolved and judging by the differing opinions in the literature they will remain unresolved for some time to come. To avoid getting too involved in the debatable issue of stretch-shorten mechanisms, the overall effect of the phenomenon will be referred to as 'stretch-shorten cycle enhancement'.

d) Concentric effort in the extension phase

The final consideration in the generation of vertical velocity is the contribution made by concentric muscle contractions of the leg extensor muscles. Surprisingly this area has received little attention from researchers, but this may be due to the difficulty in separating the role of concentric muscle strength from the effects of the stretch-shorten cycle and the free limbs in the extension phase. The combined effect of these mechanisms has been shown to equate to around 35% of the total gain in vertical velocity generated from touch-down to take-off, (Lees et al., 1993; 1994). These values are supported by findings of Aura and Viitasalo (1989) who measured average eccentric and concentric contact times and forces in a range of jumping exercises. Their data indicated that the average concentric forces in 'high jump', 'running 5 hops' and 'running 5 jumps' exercises were approximately 31% to 33% of the average force of the entire contact. As the concentric contact time was slightly greater than the eccentric contact time in these jumps, the concentric impulse (and velocity) will be similar to the data of Lees et al. (1993; 1994).

Considering that the role of concentric muscle strength has not been isolated during actual performance, an indication of long and triple jumpers' concentric strength can be obtained from resistance training methods. Anecdotal evidence from coaching literature indicates that male triple jumpers who jump over 16 m can 'easily perform squats with a weight of 1.5 to 1.7 times their body mass', (Kreyer, 1993). Johnson (1996) reported that leading up to Jonathan Edwards' world record performances in 1995 he was lifting 132.5 kg in the 'clean', 92.5 kg in the 'snatch' and 'bench pressing' 102.5 kg. While this is interesting, it is of little value to the sports scientist because it often lacks critical information on standardisation. For example, Kreyer (1993) did not state whether the squat exercises were 'half' or 'full' squats or indeed whether it related to a 1 repetition maximum (1RM). In addition, the performance in Olympic type lifts is very much dependent on technique and incorporates multi-joint movement. While the multi-joint nature should be encouraged for training specificity, such exercises cannot identify weaknesses in the musculature surrounding individual joints of the lower extremity. The use of free weights and the Olympic style lifts therefore has limited use from a diagnostic perspective. To overcome this, isokinetic dynamometers can be used to measure the strength of isolated muscle groups in different modes of contraction and through a range of movement speeds, (Perrin, 1993).

Since the long and triple jumps are regarded as power events and strength is considered to be a major factor of performance, it is surprising that the strength characteristics of these athletes have not been profiled. Two studies were found in the literature that have examined track athletes. Appen and Duncan (1986) examined groups of sprinters and endurance athletes and compared their concentric strength of the quadriceps and hamstrings at slow (60°/s) and fast (300°/s) speeds of movement. The second study by Ghena et al. (1991) combined the data of 13 track athletes within the data for 100 male athletes from various sports. However, not only did they adopt the same tests as Appen and Duncan (1986), they also assessed eccentric quadriceps strength at a speed of 120°/s. This mode of contraction is particularly relevant for long and triple jumpers as they experience an initial compression phase in the take-off.

The research has shown a lack of information on the specific muscle function characteristics of long and triple jumpers. Considering the high demands placed on these athletes during the take-off phases, profiling the muscle strength characteristics of elite long and triple jumpers is essential.

This section has shown that between 60 to 66% of the vertical velocity at take-off in the long jump is attained by the end of the compression phase (various definitions). The pivot mechanism operates during the compression phase and therefore it is the single most important factor for the generation of vertical velocity during the take-off. However, the factors that influence the effectiveness of the pivot mechanism have not been clarified. Estimates of the contribution of the arms and lead leg in the long jump have ranged from 11% (Lees et al., 1994) to 24% (Stewart, 1981). This wide range suggests that the contribution of the free limbs is still unclear and may reflect the different methods of calculation and interpretation of body segmental contributions. The movement patterns of the free limbs have not been analysed and their role in maintaining balance has not been evaluated. While the mechanisms relating to the enhanced force production in stretch-shorten cycle activities are unresolved, research indicates that long and triple jumpers will enhance their concentric force production following the eccentric phase. The contribution of the stretch-shorten enhancement in long and triple jumps has not been quantified. Finally, other than anecdotal evidence in the coaching literature there is no indication as to the strength capabilities of elite long and triple jumpers. All these areas require further investigation.

2.5 Kinematic comparisons between the long and triple jump take-offs.

The findings of studies that have compared technical aspects of the long jump with those of the triple jump are reported in this section. It is intended that this section will help to identify differences between the take-offs and to apply the long jump theories to the triple jump.

Verhoshanski (1961), cited by Hay (1992) provided a comparison between the hop, step and jump take-offs and the long jump take-off. At touch-down into the hop, Verhoshanski noted that the triple jumper places the take-off foot closer to the vertical projection of the centre of mass and with greater flexion of the knee than would a long jumper. The knee was noted to flex more during the support phase (135° compared to 146°), and the take-off leg was found to be inclined at a smaller angle to the track at the instant of take-off. In the step take-off a stronger braking resistance and increased load on the support leg causes the knee to flex more deeply than in the hop take-off to approximately 125°. An increase in the duration of the 'cushioning' (compression) phase relative to the total support time was also identified to be different from the hop take-off. The jump take-off was reported to be very similar in nature to the long jump take-off, where the take-off leg is almost completely straight at touch-down. The leg was said to be planted at a similar angle to the track as in the step take-off.

The observations made by Verhoshanski (1961) lacked scientific content and have become very dated. During this period the world record has increased from 17.03 m to 18.29 m and it is likely that techniques have changed. A more recent study by Koh and Hay (1990b) analysed 16 elite male triple jumpers competing in the 1986 and 1987 TAC (US National) Championships and compared the landing leg motion of the hop, step and jump take-offs with that of the long jump. The average effective distance of the triple jump was 16.72 ±0.84 m comprising of a 5.93 m hop, 5.11 m step and a 5.68 m jump. The mean effective distance of the long jump data was 7.98 ±0.44 m. The loss in horizontal velocity and activeness and touch-down measures of the landing leg in the 3 phases of the triple jump and the long jump take-off are presented in table 2.5.1.

Table 2.5.1. Comparison of activeness and touch-down measures and loss of horizontal velocity in the long and triple jump take-offs, (Koh and Hay, 1990b).

	Relative TD velocity of foot ($m.s^{-1}$)	Touch-down distance (m)	Change in horizontal velocity ($m.s^{-1}$)
Long jump			
Last Stride (Jump take-off)	-6.46	0.60	-1.20
Triple jump			
Last Stride (Hop take-off)	-6.93	0.55	-0.69
Hop landing (Step take-off)	-6.43	0.53	-1.25
Step landing (Jump take-off)	-5.18	0.60	-1.50

The relative touch-down velocity of the foot was found to be greater for the last stride landing (hop take-off) in the triple jump than for the hop and step landings and for the last stride landing in the long jump. This suggests that athletes aim to reduce the braking effect when in contact with the board in preparation for the hop take-off. This is supported by the findings that less horizontal velocity was lost in the hop take-off compared to the step, jump and long jump take-offs. The large touch-down distance (0.55m), however, suggests that the development of vertical velocity is also a main priority. The function of the last stride landing in the triple jump therefore appears to be one of promoting a compromise between the development of vertical velocity and the minimising of the losses in the horizontal velocity during the support phase of the hop take-off, (Koh and Hay, 1990b).

A correlation coefficient of r=-0.62 between the relative touch-down velocity of the foot and the step distance suggested that relatively active hop landings (step take-off) may be associated with large step distances. A correlation between the touch-down distance and the step distance produced a coefficient of r = -0.50, implying that small touch-down distances may also be associated with large step distances. Additionally, Koh and Hay (1990b) observed a relationship between the change in horizontal velocity during the step take-off and the effective triple jump distance, suggesting that large triple jump distances are associated with minimising losses in horizontal velocity in the support phase of the step. They concluded that, 'a relatively active landing, a small touch-down distance and minimising the losses in horizontal velocity seem important for the hop landing, step take-off'.

The landing leg motion in the step landing (jump take-off) was found to be relatively less active compared to the preceding take-offs and the long jump take-off. However, a correlation coefficient value of $r=-0.64$ was found between the relative touch-down velocity of the foot and the jump phase distance, suggesting that relatively active step landings may be associated with longer jump phase distances. Koh and Hay (1990b) reported that a reason for the relatively lower level of activeness than the preceding landings may have been due to the difficulty in achieving higher levels, or the inability to use higher levels of activeness effectively. The touch-down distance in the step landing was larger than the preceding landings, but similar to that of the long jump take-off. The results therefore suggest that in the jump take-off, the generation of vertical velocity is more important than the maintenance of horizontal velocity. The function of the step landing (jump take-off) is therefore similar to that of the long jump take-off.

To summarise, Koh and Hay (1990b) have shown that kinematic differences exist between the landing leg motion in the long and triple jump take-offs. These relate to the touch-down and activeness measures and the amount of horizontal velocity lost during each contact phase. As greater touch-down distances have been reported to facilitate the production of vertical velocity in the long jump take-off, it is likely that the differences in the touch-down distance reported by Koh and Hay (1990b) will influence the amount of vertical velocity generated in each of the four take-offs. The losses in horizontal velocity and the activeness of the landing leg in each take-off were different, indicating that each take-off has its own unique function. The kinematics and the relative contributions made by each of the vertical velocity mechanisms are therefore likely to be different during each of these take-offs. The work of Koh and Hay (1990b) therefore needs to be extended to examine the kinematics of each take-off phase.

2.6 Three-dimensional analyses of the long and triple jump take-offs.

For many years long and triple jump techniques have been considered to be two-dimensional in nature, where movements occur in the sagittal plane. Such analyses ignore movements away from that plane, suggesting that these movements have no significance on the performance. Recently sports biomechanists have called for full three-dimensional analyses of sports techniques to ascertain whether or not such assumptions can be mâde (Yeadon and Challis, 1994). Three-dimensional analyses have been made easier with the Direct Linear Transformation (DLT) technique developed by Abdel-Aziz and Karara (1971). A major benefit of the technique is that cameras do not have to be positioned perpendicular to the direction of movement, as in 2D studies. However, the DLT requires two images to be digitised and is therefore more time consuming.

Kinematic analyses of the long and triple jump take-offs have often reported using 3D data acquisition techniques. Unfortunately, only the sagittal plane kinematics have been presented, in particular the touch-down and take-off parameters. Others have limited their 3D analyses by simply supporting the sagittal plane parameters with the medio-lateral component of velocity (Nixdorf and Bruggemann, 1990, Bruggemann, 1990, Scheirman et al., 1989). The value of the medio-lateral velocity component has been shown to be very close to zero, and therefore provides a negligible contribution to the resultant speed of the athlete. Scheirman et al. (1989) added that although the medio-lateral motions of the long jumper were smaller than the other directions, their results suggested that such motions may have illustrated adjustments needed to complete a legal jump. For example to ensure the foot takes off from behind the board an athlete may make a laterally diverted last stride to maintain the same stride length. It was suggested that possible consequences of performing such a movement would be a change in the action of the lead leg, a loss in balance and a reduction of vertical force production. However, these suggestions were not examined.

To date only two studies have reported kinematic body position data away from the sagittal plane. In the triple jump, Bober (1974) performed a 2D analysis of the frontal plane to investigate how inclination angles of the trunk and take-off leg related to the lateral deviation of the feet throughout the hop, step and jump. A lateral deviation was said to occur when the foot was placed to one side of the axis running through the foot position in the preceding take-off, such that the medio-lateral distance exceeded 2% of the phase distance. Lateral deviations were classified into three types; inside, outside and normal. 'Inside' described movements across the axis, i.e. right foot directed towards the left, or left towards the right. 'Outside' described movements away from the axis, i.e. right foot directed towards the right, left foot towards the left. 'Normal' was when the medio-lateral distance was 2% or less than the phase distance. Trunk and lower leg angles were measured 'in the middle phase of the take-off' and data from all take-offs were combined. When there was no deviation the 'normal' position in the middle phase was described by 6.13° leg inclination and a trunk angle of 8.13°. Results found that the trunk and leg angles became less inclined (more upright) when jumps deviated towards the inside, 3.89° and 2.67° respectively. In jumps where outside deviation occurred the trunk and leg were observed to become more inclined with angles of 8.5° and 9.9°. Bober (1974) also found a significant relationship between the inclination of the trunk and that of the leg, ($r=0.62$). While this study was the first of its kind and actually identified that movements in the frontal plane can have an effect on triple jump performance, it did not examine each take-off separately. The effect of different landing conditions in each take-off are likely to have an affect on the amount of medio-lateral movement of the trunk, support leg, the amount of hip adduction and the movements of the free limbs for balance. Considering that Bober observed these significant findings in 1974 it is surprising that frontal plane kinematics have not been explored further, and in particular their possible effect on maintaining balance and in the generation of vertical velocity.

A study by Fukashiro et al. (1993) is the only study which has attempted to examine motion in the transverse plane in the long jump. They analysed the world record jump of Mike Powell, 8.95 m, and an 8.91 m jump by Carl Lewis and focused on trunk rotation as well as the general sagittal plane kinematics. They revealed that both athletes exhibited similar degrees of trunk rotation from touch-down to take-off, (74° and 70° respectively), but Powell's was mainly supported by rotation of his hips, whereas Lewis' was mainly supported by rotation of his shoulders. Although this study has revealed that elite level long jumpers exhibit considerable amounts of trunk rotation, the study did not attempt to identify the importance of these movements. It is possible that these movements may be related to the action of the free limbs and the ability to extend the support leg in front of the body.

A study by Yu and Hay (1995) examined the three-dimensional angular momentum characteristics of the triple jump take-offs. Their results provided strong evidence that the magnitude of the side-somersaulting angular momentum in particular was very important to successful triple jump performance. Side-somersaulting angular momentum describes the movements and rotations of the athlete about an antero-posterior axis that passes through the centre of mass. Side-somersaulting angular momentum can be detrimental to performance if it causes the athlete to lose balance, but it is also a necessary requirement when the athlete needs to alternate the legs for the following touch-down. This is reflected in larger side-somersaulting angular momenta for the take-offs into the last stride and step, 3.71 $kg.m^2.s^{-1}$ and -3.58 $kg.m^2.s^{-1}$, compared to take-offs into the hop and jump, -0.40 $kg.m^2.s^{-1}$ and 0.70 $kg.m^2.s^{-1}$. A positive value represents rotation of the body towards the side of the hop take-off leg. The magnitude of side-somersaulting angular momentum at take-off into the step was the main focus of their results as it was closely related to the triple jump distance. They noted that the side-somersaulting angular momentum required for the step take-off should be obtained during the hop take-off, and the change during the step take-off should then be minimised because of its potential detrimental effect on the jump take-off. Yu and Hay (1995) proposed that the change in side-somersaulting angular momentum during a support phase may depend on four factors: the lateral placement of the foot relative to the centre of mass; the rotation of the trunk about an antero-posterior axis through the centre of mass; the rotation of the whole body about the subtalar joint; and the movements of the free limbs. These movements have not yet been quantified in the literature.

To summarise, little work has been undertaken to investigate the three-dimensional nature of the long and triple jump take-offs. The work of Bober (1974) and Fukashiro et al. (1993) needs to be extended to further quantify the movements made in the frontal and transverse planes and to investigate their influence in the generation of vertical velocity.

2.7 Kinetic analyses of the long and triple jump take-offs

Kinetics is the branch of mechanics that examines forces. For the long and triple jumps it is particularly useful to measure the ground reaction forces as these help to provide an understanding of the interaction between the athlete and the surface. It is also useful to examine how athletes distribute these forces about the joints of the lower extremity in order to produce a successful take-off and to gain an understanding of the strength requirements of each joint.

Ground reaction forces can be estimated from kinematic data using the impulse - change in momentum relationship. The main disadvantage of using kinematic data is that only the average forces can be determined and the characteristics of impact and drive-off obtained from direct methods, i.e. force platforms, are lacking, (see figure 2.4.2). However, the average force data obtained from high level competition can be useful in providing an indication of the overall demands placed on elite performers. Bruggemann (1990) and Hay and Miller (1985) reported such information from Olympic triple jump finals. They found average horizontal forces to be within -0.5 BW and -1.0 BW (in all take-offs), and vertical forces to be in the ranges of 3.2 BW to 3.8 BW in the hop, 3.8 BW to 4.4 BW in the step and 3.7 BW to 4.2 BW in the jump take-offs.

Considering that peak vertical and horizontal forces derived from direct methods, even in sub-maximal jumping, are very large (table 2.7.1) it is not surprising that athletes are reluctant to perform maximally out of competition. It can be seen that the vertical impact peak is the largest force and this has been found to have values of between 5.6 BW to 8.6 BW in the long jump (Ramey, 1970; Scheirman et al., 1989) and between 7.1 BW to 12.6 BW in the triple jump (Ramey and Williams, 1985). The average forces from the kinematic analyses are therefore particularly useful in gauging how well sub-maximal performances compare to competition performances.

The only study to date that has managed to collect kinetic data on national level triple jumpers performing maximally out of competition was conducted by Kyrolainen et al.

(1997). His five male athletes approached the board with an approach speed of 9.07 ±0.27 $m.s^{-1}$ and attained an average distance of 14.53 ±0.58 m. Using a 13 m long force platform they collected ground reaction forces in the three take-offs during the same performance, the first time such data has been reported. Mean peak vertical impact forces of 10.1 kN, 12.3 kN and 10.9 kN and mean peak horizontal braking forces of 4.3 kN, 6.5 kN and 5.1 kN in the hop, step and jump take-offs were reported. Unfortunately, the study failed to present body mass information and peak vertical drive-off and peak horizontal propulsive forces. These would have been useful for comparison with other data.

Table 2.7.1. Summary of peak vertical and horizontal ground reaction forces obtained during long and triple jump performances.

Author(s) (subject information)	Jump LJ / TJ	Vertical Force Impact (BW)	Vertical Force Drive-off (BW)	Horizontal Force Braking (BW)	Horizontal Force Propulsion (BW)	Contact Time (s)
Ramey (1970) (3 males, 12 m approach, jumps < 4.20 m)	LJ	5.60 - 6.00	2.70 - 4.70	1.75	0.3	-
Scheirman et al. (1989) (6 national decathletes, jumps 6.70 to 7.21 m)	LJ	8.60	-	5.50	0.50	-
Ramey and Williams (1985) (2 males and 2 female triple jumpers, 80 to 90% of competitive best)	TJ					
	Hop	7.90 - 10.12	3.98 - 5.04	2.11 - 3.25	0.34 - 0.52	0.14 - 0.16
	Step	8.19 - 12.62	3.36 - 4.57	1.73 - 3.32	0.43 - 0.57	0.16 - 0.17
	Jump	7.13 - 12.17	3.61 - 3.99	1.68 - 3.35	0.35 - 0.46	0.16 - 0.20
Kyrolainen et al. (1997) 5 male national triple jumpers, average distance 14.53 m, average app. speed 9.07 $m.s^{-1}$)	TJ					
	Hop	10.1 kN	-	4.3 kN	-	0.127
	Step	12.3 kN	-	6.5 kN	-	0.155
	Jump	10.9 kN	-	5.1 kN	-	0.175

Considering the magnitude of these forces, athletes will only be able to complete a successful take-off if the ground reaction force is distributed effectively about the joints of the support leg. This load distribution can be assessed using net joint moment analyses (Winter, 1980). Surprisingly this area of research has until recently been very limited. Several studies have examined the standing long jump, Horita et al (1991), Robertson and Flemming (1987), and Thorpe et al. (1998), but these do not take into account the effect of a fast approach and different landing conditions at touch-down.

A study by Avela et al. (1988) was the first to report joint moments in the long jump. They observed that athletes produced large peak moments about the knee, 488 N.m ±237 and hip joints, 1246 N.m ±433 during maximal long jump take-offs. These moments were 2.7 and 1.5 times greater than peak moments measured in sub-maximal jumps performed at approximately 90% of maximal horizontal running velocity. Their results also found a significant relationship between the mechanical work of the hip joint and the length of the jump, (r=0.89), emphasising the importance of the hip extensor muscles during the take-off. Unfortunately, this study did not provide any information on the ankle moment.

It is only during the last year that more research has been conducted in this area. Stefanyshyn and Nigg (1998) analysed the net joint moments and joint power in running vertical jumps and running long jumps. A group of 5 basketball players performed the vertical jumps and 4 experienced long jumpers, with personal best performances of 7.05 m to 7.53 m, performed the long jumps. The long jumpers had a maximum approach run of 15 m and the average speed over the data collection area ranged from 6.1 $m.s^{-1}$ to 6.6 $m.s^{-1}$. The analysed jumps were therefore of a sub-maximal nature. Their results found peak net joint moments of 100 N.m to 150 N.m about the metatarsophalangeal (MP) joint, 250 N.m to 400 N.m about the ankle, 250 N.m to 300 N.m about the knee and 400 N.m to 650 N.m about the hip joint. From numerical integration of the joint power curves Stefanyshyn and Nigg assessed the amount of energy absorbed and generated by the four joints. The MP, ankle and knee joints all absorbed more energy than they generated, but in most cases the hip generated more energy than it absorbed. However, in relation to the total amount of energy absorbed and generated by the support leg, 284.7 J and 213.5 J respectively, each joint was classified either as a net energy absorber or as a net energy generator. The difference in the percentage contributions indicated that the MP joint (absorbed 15% and generated 0%) and the knee joint (absorbed 28%, generated 25%) were net energy absorbers, while the ankle (absorbed 47%, generated 49%) and hip (absorbed10%, generated 26%) joints were net energy generators. Based on these findings they concluded that the ankle joint was the largest energy absorber and generator in the long jump and advised that training regimens should pay particular attention to the development of the gastrocnemius and soleus muscles. They also stressed the importance of the hip extensor muscles to performance.

In the running vertical jump the peak net joint moments were not too dissimilar to those found in the long jump. These values ranged from 75 N.m to 150 N.m, 250 N.m to 400 N.m, 150 N.m to 300 N.m and 300 N.m to 500 N.m about the MP, ankle, knee and hip joints respectively. As with the long jump, the ankle and hip joints were also found to be net energy generators, but the relative percentage differences in energy absorption and generation indicated the functions of the ankle and hip joints differed. In the running vertical jump the ankle joint absorbed 36% of the total energy lower extremity loss and generated 53%, making the ankle joint a large net energy generator. In contrast, athletes in the long jump absorbed and generated similar relative amounts, 47% and 49% respectively, making the ankle a small energy generator. The hip joint, on the other hand was a large net energy generator in the long jump, absorbing 10% and generating 26%, but only a small net energy generator in the vertical jump, absorbing 16% and generating 21%.

Applied to the long and triple jump, the findings of Stefanyshyn and Nigg (1998) suggest that if an athlete changes his or her technique to emphasise greater gains in vertical velocity then the functions of each joint may change also. This view is supported by the observations of Requejo et al. (1998) who investigated how load distribution and power changed when athletes reduced the net horizontal impulse during the take-off. They reported that a reduction in the net horizontal impulse, along with relatively small modifications in segment kinematics at contact 'dramatically' changed the net joint moments at the knee and hip. Likewise, a study by Costa et al. (1998) noted that differences between subjects can be attributed to variations in foot strike patterns, segment kinematics and the magnitudes of the ground reaction forces. Unfortunately, no detailed information was given in either of these studies to link aspects of technique to changes in ground reaction forces and net joint moments.

The observations made above have suggested that factors relating to body position and technique have a major influence on the magnitudes of ground reaction forces and on the effective distribution of these forces about the joints of the lower extremity. However, no studies have indicated which parameters of technique create these changes. This information is vital if modifications in technique are to be supported with the correct preparation of relevant muscle groups. Additionally, no studies have yet examined the distribution of ground reaction forces in the triple jump take-offs. Considering that triple jumpers experience ground reaction forces in excess of long jumpers (table 2.7.1) the need for net joint moment analyses of triple jump take-offs is paramount.

2.8 Summary

To date, the information concerning the production of vertical velocity has primarily been reflected in the analysis of the sagittal plane kinematics covering the last few strides and the actual support phase of the take-off. It is well established that over this period elite athletes exhibit a continual lowering of the centre of mass and strike the board with an extended take-off leg. Lees et al. (1993) and Koh and Hay (1990) both stressed the importance of such characteristics for successful jumping performance; the latter adding that an 'active' landing was more beneficial than a 'locking' technique. Tiupa et al. (1980, cited by Hay, 1986) observed that the athlete's landing leg undergoes a yielding or eccentric phase upon impact with the take-off board and is succeeded by a surmounting or concentric phase. Lees et al. (1993) reported that the ability to resist knee flexion through good eccentric leg strength is a major determinant of success in jumping, acknowledging that approximately 66% of the total gain in vertical velocity is obtained by the end of the compression phase. However, the role of hip adduction in the frontal plane in contributing to or reducing eccentric strength of the lower body complex is unknown. The remaining 34% of the total vertical velocity is reported to be the result of stretch-shorten cycle enhancement (Shorten, 1986); the athlete's concentric muscle strength in the extension phase, and the upward movements of the free limbs. However, the contributions made by these mechanisms have not been separated.

The criticisms of the current state of research into the long and triple jump take-offs are that the majority of investigations have been concerned with the long jump. Although the same principle of projectile motion exists for each form of jump, be it the long jump or the hop, step and jump phases of the triple jump, the kinematics and kinetics of each may not necessarily be identical. Verhoshanski (1961), cited by Hay (1992) provided evidence of kinematic differences between the four jumps, but that study has become very dated. The work of Koh and Hay (1990), who examined kinematic differences of the landing leg 'swing' prior to touch-down, needs to be extended to analyse the support phases of all four take-offs. An appropriate step forward is to conduct three-dimensional analyses to quantify the actions of the support leg, the hip, the trunk and the free limbs in all three planes of motion. Such studies will build on the limited research conducted by Bober (1974) and Fukashiro et al. (1993). For example in the frontal plane the amount of trunk lean, the amount of hip adduction and the medio-lateral movement of the free limbs is of particular interest, while hip, shoulder and trunk rotation is of interest in the transverse plane.

There is also a lack of information regarding ground reaction forces and the distribution of these forces about the joints of the lower extremity, in both the long and triple jumps. Net joint moment analyses will provide an indication of the physical demands associated with long and triple jumping and will quantify the resultant stresses placed on the muscles around the hip, knee and ankle joints. Changes in technique have been reported to affect the distribution of net joint moments, but they have failed to identify specific variables and their effect, (Requejo et al., 1998; Costa et al., 1998). Therefore, if modifications in technique are necessary, it is important to identify the effect of different kinematic variables on load distribution, so that informed advice can to be given to athletes on the preparation of specific muscle groups. Further, no research into the strength requirements of elite long and triple jumpers has been reported. It is clear that the take-off phases in these events are very explosive and require both eccentric and concentric strength in the compression and extension phases respectively. Normative data on these critical aspects of performance have not been determined.

3.0 Methodological Issues

3.0 Methodological issues.

Quantitative analysis of sports performance requires the biomechanist to follow correct experimental procedures and to develop a number of skills. These experimental procedures are designed to ensure that the data produced is accurate. When conducting kinematic analyses these considerations fall into two main areas: data collection (film recording and digitising) and data processing. To determine the accuracy of the data collected assessments of both the operator and the equipment he or she uses must be performed.

This chapter is therefore devoted to assessing the quality of data collected and examines issues relating to the accuracy of the operator and the experimental techniques adopted. In section 3.1 analyses are conducted to assess the objectivity and reliability of the operator's data in relation to the data of another experienced operator and compared to a second trial of digitisation. With respect to the consideration of equipment, Hay and Nohara (1990) identified the importance of assessing the maximum error due to sampling frequency. The limitations of video-based digitising equipment in terms of its lower sample frequency (50 Hz) and its reduced resolution compared to a cine-based system operating at 100 Hz is the focus of section 3.2. An assessment is made to the viability of using a video-based system for long jump technique analysis. The full paper is presented in the Publications and Conference Communications section of this thesis and an abstract is presented here.

Although the main objectives of this research programme relate to three-dimensional analysis, Bartlett et al. (1992) suggested that sound experience should be gained in all procedures relating to 2D quantitative analyses before attempting 3D analyses. Two-dimensional techniques were adopted in sections 3.1 and 3.2 before moving into the more complicated area of 3D analysis in section 3.3. The focus of section 3.3 is to examine specific experimental procedures relating to 3D reconstruction, and in particular the development of a calibration frame and the assessment of reconstruction errors. A number of studies have indicated that 3D reconstruction accuracy is related to the design criteria of the calibration frame. This study investigates these considerations, (the number and distribution of control points, the shape and size of the calibration frame) prior to developing a frame suitable for the 3D analysis of the long and triple jumps.

The chapter ends with an overview of the methodological findings and provides recommendations for the main studies.

3.1 An assessment of data objectivity and reliability.

3.1.1 Introduction

The aim of this study was to assess data objectivity and reliability by repeating the digitising and analysis procedure for a number of long jump take-offs, comparing the results with another experienced digitiser and against a personal second trial. This study partly fulfils the requirements of aim number 1.

A definition of 'objectivity' is an appraisal of the amount of bias in the measurement process, (Vincent, 1995). Reliability on the other hand refers to a measure of consistency of the data when measured more than once under the same conditions, (Vincent, 1995). The former therefore relates to a comparison between two or more individuals and the bias they enter into the data. The latter relates to an operator's ability to reproduce the data and measures their level of consistency between trials.

3.1.2 Method

Before this study commenced a 20 hour familiarisation period was completed, allowing time for the operator to become competent with correct digitising techniques.

The take-off phase of the men's long jump was captured on film during the AAA National Championships in 1992. A Locam 16 mm high speed cine camera recorded at 100 Hz and was positioned perpendicular to the runway, approximately 7 m from the take-off board, figure 3.1.1. The field of view allowed the touch-down into the last stride and approximately 1 m following the take-off from the board to be captured on the film. This ensured that sufficient film frames were available for analysis after take-off into the jump to calculate projection parameters adequately.

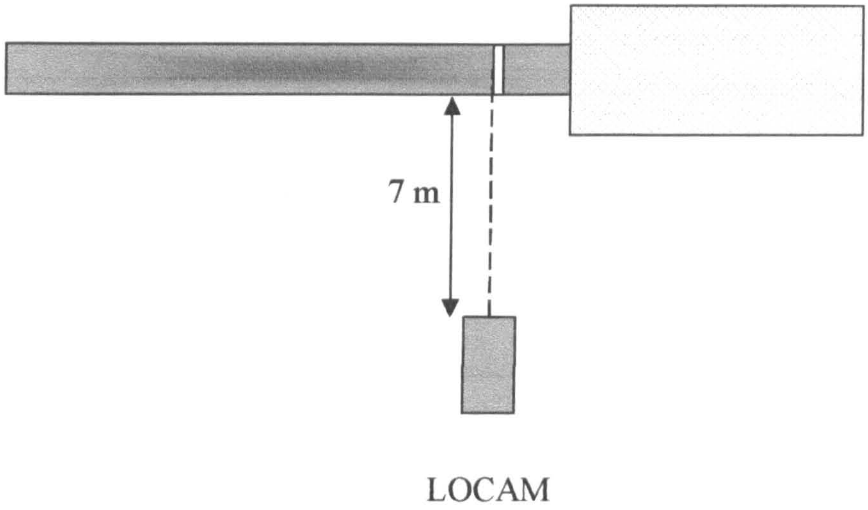


Figure 3.1.1. Camera set-up for 2D analysis.

The best recorded performance of 8 athletes were digitised twice by myself and once by another experienced digitiser. The digitising system incorporated an NAC analysis projector and a TDS digitising tablet operating through an Archimedes 32 bit computer. The reference origin was located at the front of the take-off board through a level corresponding to the mid line of the take-off foot.

An eleven segment model defined by eighteen points and segmental data proposed by Dempster (1955) were used to determine the whole body centre of mass. Details of body landmarks and segments are presented in Appendix I. Ideally each athlete would have a personal set of body segment parameters, but their accuracy relies on expensive equipment and a lengthy assessment protocol. As performances were recorded during a major national competition it was not possible to collect anthropometric information on athletes. All athletes were assumed to have a body mass of 80 kg, although this value did not contribute to any calculations of mass centre location.

Although a segmental data set derived from cadavers is not specific to the athletic population under investigation, comparisons between different data sets have found segmental centre of mass locations to be similar. Mungiole and Martin (1990) examined differences in the centre of mass location of the lower leg segment using different methods. They found that their magnetic resonance imaging technique provided similar locations to those determined by a gamma-scanner method (Zatsiorsky and Selyunanov,

1983) and studies on cadavers (Dempster and Gaughran, 1967; Clauser et al., 1969). The location of the lower leg centre of mass determined by Dempster (1955) was 43.3% of segment length from the proximal joint, compared to 41.6% determined by Mungiole and Martin (1990). A difference of 1.7% of segment length between the two methods equates to an absolute difference in location of less than 1 cm for a typical segment of length 45 cm. In terms of segmental mass ratios, expressed as a percentage of whole body mass, the ratios of Dempster (1955) compare favourably with those of Zatsiorsky and Seluyanov (1983) who examined 100 young adult males using a gamma-scanner method. The main differences between the data sets were an underestimation of the thigh mass ratio by 4.5% and an overestimation of the trunk mass ratio by 6.1% in the data of Dempster (1955). The whole body centre of mass would therefore be located slightly higher for Dempster's (1955) data than for that of Zatsiorsky and Seluyanov (1983).

The data were processed using a Butterworth 4th order zero lag digital filter with padded end points (Smith, 1989). An appropriate cut-off frequency of 8.33 Hz was determined following a residual analysis where the amounts of noise and signal distortion are balanced, Winter (1990). The same cut-off frequency was applied to all variables. Velocities and accelerations were calculated by direct differentiation, Lees (1980).

The events of touch-down (TD), maximum knee flexion (MKF) and take-off (TO) were recorded. Touch-down was defined as the first frame in which there was clear contact between the foot and the ground. Take-off was defined as the first frame in which the foot had clearly left the ground. A selection of key variables (Table 3.1.1) which have been identified as characteristics of long jump performance were measured. Objectivity between the first trial of the current data and the same data of another experienced digitiser was assessed through limits of agreement. Reliability was assessed between two repeated trials of the same digitiser and this also used limits of agreement. Limits of agreement are expressed by two terms, 'difference' and 'random error'. The 'difference' term refers to the mean difference between corresponding data items in the two data sets. The 'random error' term measures the variance between data items. This term is calculated by multiplying the standard deviation of the differences between corresponding data items by 1.96 to obtain the 95% random error component, (Atkinson and Nevill, 1998). Paired t-tests were used to identify any significant differences between the two data sets and significance was set at the $P<0.05$ level.

Table 3.1.1. Selected variables and their definitions.

$Height_{TD}$; $Height_{TO}$	Height of the athlete's centre of mass at touch-down and take-off respectively
D_{TD}	Touch-down distance - horizontal distance between the centre of mass and the ankle joint;
A_{TD}	Touch-down angle - angle between the line joining the centre of mass to the ankle joint and the downward vertical,
Knee angle MKF	Maximum knee flexion angle,
VX_{TD} ; VX_{TO}	Horizontal velocity of the athlete's centre of mass at touch-down and take-off respectively;
VY_{TD} ; VY_{TO}	Vertical velocity of the athlete's centre of mass at touch-down and take-off respectively;
$Speed_{TO}$	Speed of the athlete's centre of mass at take-off;
Projection $angle_{TO}$	Projection angle of the centre of mass at the instant of take-off.

3.1.3 Results.

Tables 3.1.2 and 3.1.3 show the mean and standard deviation of the selected variables and the results of the statistical tests.

Table 3.1.2. Limits of agreement and t-tests between Trial 1 data set and the same data set from previously digitised data of a second experienced operator. (subjects, n=8).

Variable	(Trial 1)		Previous data from experienced operator				Limits of Agreement		
	Mean	SD	Mean	SD	t	sig.	Difference		Random Error
Height $_{TD}$ (m)	1.02	0.03	1.03	0.03	-0.527	NS	-0.01	±	0.03
D_{TD} (m)	0.50	0.08	0.50	0.08	0.143	NS	0.00	±	0.06
A_{TD} (°)	28.2	3.7	27.8	3.7	0.265	NS	0.4	±	3.4
VX_{TD} ($m.s^{-1}$)	9.28	0.42	9.64	0.44	-2.370	*	-0.36	±	0.37
VY_{TD} ($m.s^{-1}$)	0.12	0.13	-0.06	0.22	-2.888	*	0.18	±	0.38
Knee angle MKF (°)	143.7	6.8	141.2	7.8	0.979	NS	2.5	±	5.9
Height $_{TO}$ (m)	1.29	0.05	1.29	0.06	-0.088	NS	0.00	±	0.05
VX_{TO} ($m.s^{-1}$)	8.28	0.30	8.21	0.35	0.633	NS	0.07	±	0.33
VY_{TO} ($m.s^{-1}$)	3.17	0.30	3.21	0.38	-0.296	NS	-0.04	±	0.40
Speed $_{TO}$ ($m.s^{-1}$)	8.88	0.27	8.82	0.31	0.501	NS	0.05	±	0.39
Projection angle $_{TO}$ (°)	21.0	2.1	21.4	2.6	-0.463	NS	-0.4	±	2.2

* $P<0.05$; NS = Non-Significant

Table 3.1.3. Limits of agreement and t-tests between Trial 1 and Trial 2 (subjects, n=8).

Variable	(Trial 1) Mean	(Trial 1) SD	(Trial 2) Mean	(Trial 2) SD	t	sig.	Limits of Agreement Difference		Random Error
$Height_{TD}$ (m)	1.02	0.03	1.02	0.03	-0.099	NS	0.00	±	0.02
D_{TD} (m)	0.50	0.08	0.51	0.07	-0.099	NS	0.00	±	0.02
A_{TD} (°)	28.2	3.7	28.4	3.6	-0.160	NS	-0.2	±	1.0
VX_{TD} ($m.s^{-1}$)	9.28	0.42	9.21	0.39	-0.458	NS	0.07	±	0.23
VY_{TD} ($m.s^{-1}$)	0.12	0.13	0.20	0.09	-2.087	*	-0.08	±	0.19
Knee angle MKF (°)	143.7	6.8	143.0	7.0	0.278	NS	0.7	±	1.9
$Height_{TO}$ (m)	1.29	0.05	1.30	0.06	-0.309	NS	-0.01	±	0.02
VX_{TO} ($m.s^{-1}$)	8.28	0.30	8.26	0.30	0.191	NS	0.02	±	0.17
VY_{TO} ($m.s^{-1}$)	3.17	0.30	3.22	0.34	-0.412	NS	-0.05	±	0.18
$Speed_{TO}$ ($m.s^{-1}$)	8.88	0.27	8.87	0.25	0.005	NS	0.00	±	0.20
Projection angle $_{TO}$ (°)	21.0	2.1	21.3	2.5	-0.411	NS	-0.3	±	0.9

* $P<0.05$; NS = Non-Significant

3.1.4 Discussion

The results of the t-tests in table 3.1.1 indicate that for 9 of the 11 variables analysed the means of the Trial 1 data and the data of another experienced operator are similar, i.e. NS. The differences between the data sets are generally within 1 cm for the displacement measures $Height_{TD}$, $Height_{TO}$ and D_{TD}. Although the difference for the angular measure of A_{TD} was within 0.5°, the results showed a slightly greater difference in the knee extension angle at maximum knee flexion, 2.5°. The velocity measures at take-off (VX_{TO}, VY_{TO}, $Speed_{TO}$) and the projection angle of the centre of mass, Projection $angle_{TO}$ were similar, within 0.07 $m.s^{-1}$ and 0.4° respectively. However it can be seen that the horizontal and vertical velocities of the centre of mass at touch-down, VX_{TD} and VY_{TD}, were significantly different to those of the previously digitised data, (both $P<0.05$). In these variables greater differences of -0.36 and 0.18 $m.s^{-1}$ were found respectively.

Although the majority of variables are similar in magnitude, it is also important to evaluate how well individual data items correspond to each other. This is assessed through the random error term in the limits of agreement. Atkinson and Nevill (1998) stated that the greater the random error component of the limits of agreement then the larger the minimal detectable change needs to be for a given sample size. This means that the spread of data in the population must be greater than the random error between tests to detect meaningful differences in the data. Clearly, it is best to have as little random error as possible. It can be seen in table 3.1.1 that the random error component ranged from 3 cm ($Height_{TD}$) to 6 cm (D_{TD}) for displacements measures, 3.4° (A_{TD}) to 5.9° (knee angle maximum knee flexion) for angular measures, and 0.37 $m.s^{-1}$ (VX_{TD}) to 0.40 $m.s^{-1}$ (VY_{TO}) for velocity variables.

While the magnitudes of the random error components are quite small they are large enough to require investigation. The explanation for them may be attributed to several factors. The estimation of joint centre location is likely to be the main influencing factor on the error in the displacement and angular measures. For the knee angle at maximum knee flexion this is likely to be due to the location of the hip joint in particular which is not easily identifiable. The correct identification of the critical frames of touch-down and take-off are also likely to be large factors, and the errors associated with this will be more pronounced in the velocity variables. The significant differences found in the horizontal and vertical velocities at touch-down are also likely to be a result of data smoothing in relation to the number of frames of movement digitised before contact with the board.

In terms of the reliability in digitising, the limits of agreement for the trial 1 to trial 2 analysis revealed virtually zero difference in every variable and all the random error components were found to be very small, table 3.1.3. These results indicate that the operator has achieved a good level of consistency in the digitising process and can reproduce the data within relatively small margins of error. The displacements measures were found to have a random error of 2 cm, angular measures to within 2°, velocity variables to around 0.2 $m.s^{-1}$ and the projection angle to within 1°. The narrower limits of agreement found for the reliability check (compared to the those obtained against another operator), suggest that factors such as joint centre location and the selection of critical frames appear to have been controlled successfully.

In conclusion, the results of this study have found that the operator's data is both objective and a highly reliabile. Objectivity was found for 9 of the 11 variables which exhibited no significant differences between the means and minimal bias between the two data sets. The random error was small, but was large enough to warrant concern. Possible explanations for the random error were in the assessment of joint centres and the identification of the critical frames of touch-down and take-off. However, considering that this thesis will be the work of one digitiser only, it is important that the operator is consistent in his work. The limits of agreement found between 2 repeated trials of digitisation found almost zero difference and much lower random errors. The results obtained therefore indicate that the operator has a high reliability or consistency. However, to reduce the error further it is recommended that the mean data of several repeated digitisations on each jump be used in the main studies.

3.2 A comparison of the information quality between cinematography and videography for long jump technique analysis.

This study was published in *Biology of Sport* 14(3) and to avoid replication only the abstract is presented here. For the full published version please refer to the Publications and Conference Communications section of this thesis.

3.2.1 Abstract

The aim of this study was to compare the information quality of specific long jump performance variables produced from cine and video based digitising systems in order to establish whether video based systems were adequate for the production of quantitative feedback information to athletes. Previous comparisons of cinematography and videography have concentrated on the accuracy of reproducing specific points in two or three dimensions or the accuracy of digitising a standard length. The literature has not examined how sport specific performance variables are influenced by the choice of medium. The quality of information produced from a digitising system is related to sample frequency, resolution of the recording medium and the choice of data processing routines. Eight long jump take-offs were recorded simultaneously by a cine camera (at 100 Hz) and a video camera (at 50 Hz). Each jump was digitised twice on both systems to assess possible trial effects on the data produced. All data was processed using a Butterworth 4th order zero lag routine thereby controlling data processing as an influencing factor. Residual analyses were performed on the raw data to identify appropriate cut-off frequencies, Winter (1990). For sample frequencies of 100 Hz and 50 Hz, the cut-off frequencies were 8.33 Hz and 6.25 Hz respectively, and these were applied to all variables. Cine at 100 Hz was taken as the preferred data set as most scientific investigations into the long jump indicate this choice. The effect of sample frequency was examined by comparing the information produced from cine at 100 Hz with two segmented 50 Hz cine data sets (derived from the 100 Hz cine data). The effects of the recording medium were examined by comparing two different 50 Hz cine data sets with the video data sets. A further analysis directly compared cine at 100 Hz with the video data to assess the combined effects of a lower sample frequency and a reduced resolution. The results of the three analyses suggested that sample frequency and

recording medium resolution do influence the quality of information produced. The data suggested that the accuracy of velocity variables are likely to be significantly effected by a sample frequency of 50 Hz ($P<0.05$). Displacement and angular measures were influenced more by the resolution of the recording medium. It was concluded that in an event, such as the long jump, where velocity characteristics are of the utmost importance, data from video based systems with a reduced sample frequency and inferior resolution capacities are unacceptable.

3.3 3D reconstruction: The development of a 3D calibration frame and assessment of reconstruction errors.

3.3.1 Introduction

The aim of this study was to develop a 3D calibration frame and to assess the accuracy of the 3D reconstruction. This study therefore addresses further methodological issues and attempts to fulfil the requirements of objective number one.

The progression from 2D analysis to 3D analysis involves a significant increase in complexity to derive positional data (Yeadon and Challis, 1994). The most commonly used method of obtaining 3D coordinates of a point is the Direct Linear Transformation (DLT) developed by Abdel-Aziz and Karara (1971). In contrast to other methods for obtaining 3D coordinates, the DLT technique has the advantages of being relatively simple and accurate, permitting great flexibility in the camera setup, (Chen et al. ,1994). Another advantage of the DLT procedure compared to other methods is that the internal parameters and orientation of the camera do not need to be measured directly. The DLT procedure represents these by 11 coefficients which define the linear transformation between the 3D object space and the 2D image planes. These coefficients are determined by the use of a calibration procedure where control points of known positions in 3D space (generally on a frame) are filmed simultaneously by two (or more) arbitrarily placed cameras. The calibration frame is then removed and the subject is filmed in the same object space with the same camera set-up. The two camera views are then digitised to reconstruct the volume described by the calibration frame.

Although the 3D reconstruction process requires two camera views and therefore twice as much digitising, the restrictions to the camera location associated with 2D analyses are lifted. This is especially important in sports biomechanics where camera location during competition is further restricted by stadia personnel and television crews. In addition, long and triple jump judges often occupy positions that are essential for 2D analyses, (Lees et al., 1993; Lees et al., 1994).

The calibration frame is an essential component of 3D analysis when using the DLT procedure. The accuracy of the 3D reconstruction has been shown to be related to characteristics of the calibration frame such as the number and distribution of control points, the shape and the size.

Number of control points

Chen et al. (1994) stated that 'as long as there are at least 6 control points, the least squares method can be used to determine the 11 standard DLT parameters'. However, studies by Wood and Marshall (1986), Challis and Kerwin (1992) and Chen et al. (1994) have all demonstrated that the accuracy of the DLT increases with an increase in the number of control points. Chen et al. (1994) examined the accuracies of 8, 12, 16, 20 and 24 control point structures. They observed that the accuracy improved when the number of control points increased from 8 to 24, but there was no significant difference between the 16, 20 and 24 control point groups. They suggested that, when a minimum number of control points are used, the DLT parameters are vulnerable to the individual random error of the control points. As more points is used the least squares algorithm reduces the influence of random errors when it determines the DLT parameters. Beyond a certain number the inclusion of more control points does not improve the calibration accuracy significantly, as systematic errors, e.g. system set-up and lens distortions, account for a major part of the total error.

Distribution of control points

The above studies also investigated the distribution of the control points in the control volume. Analyses have shown that the most accurate calibrations are obtained when the control points are evenly distributed throughout the control volume, avoiding clustering in particular regions. If clustering was to occur, Yeadon and Challis (1994) stated that the DLT parameters will produce an increased reconstruction accuracy in the clustered region at the expense of poorer reconstruction accuracy elsewhere.

Calibration frame shape

Another characteristic of the calibration frame that has been investigated is its shape. Several designs have been reported in the literature. Van Gheluwe (1978) developed a simple structure that has since become known as the 'Christmas tree' design. It consisted of six steel tubes fitted together perpendicularly. Wood and Marshall (1986) constructed their 43 point calibration frame into a wedge shape out of 50 mm square aluminium tubing. The dimensions were 3.5 m long, 2.5 m high with a base of 1.5 m. The control points were measured to be accurate to ± 1 mm. The structure was welded together with diagonal struts to ensure stability. Chen et al. (1994) produced a rectangular aluminium frame with dimensions 2.1 m long, 1.35 m high and 1.0 m wide, incorporating 32 control markers. The locations of these control points were accurate to 0.5 mm. Challis and Kerwin's (1992) design was a rectangular structure (length 1.0 m, height 1.0 m and base 0.6 m), with internal control points. The internal points were incorporated to simulate the 'Christmas tree' effect of van Gheluwe (1978). The frame was constructed of 12 mm steel tubing and provided a total of 51 control points accurate to ± 0.0008 mm. Using a portion of these 51 control points Challis and Kerwin (1992) were able to assess 6 different configurations. The results of the study concluded that the 'Christmas tree' design was much less accurate than a configuration in which the control points surrounded the calibration space (rectangular designs). They concluded that it was more important to surround the space in which the activity is to take place than to have control points inside the space.

Calibration frame size

One further criterion that one must consider in the development of a calibration frame is its size. Challis and Kerwin (1992) added that the shape and size of the calibration structure is dependent on the activity being studied. The calibration frame of Wood and Marshall (1986) was built to be sufficiently large enough to encompass one full stride of a sprinter, hence the longer length of 3.5 m. Wood and Marshall (1986) indicated that significant inaccuracies in 3D reconstruction are likely to occur if the target points lie outside the calibrated volume. The size of the calibration frame must therefore assume extreme importance and must encompass the movement being analysed.

Assessment of accuracy

A procedure for the assessment of calibration accuracy was proposed by Challis and Kerwin (1992). They stated that often the set of control points used to test the reconstruction accuracy has been the same points as those employed to determine the calibration coefficients of the DLT. This, they say, is not an independent measure and therefore cannot be considered a true test of accuracy. They suggested the use of another set of control points with known 3D coordinates, not used in the calibration procedure, to assess the accuracy of the system in locating points in space. This view was also expressed by Allard et al. (1995) who also recommended that the accuracy should be stated as the root mean square (RMS) error as opposed to the mean error.

3.3.2 Method

To attain the most accurate 3D data, the findings of previous studies suggested that the design of the 3D calibration frame must fulfil the following criteria:
i) the dimensions of the frame must be large enough to include the entire movement sequence to be studied;
ii) the calibration frame must have at least 16 control points evenly distributed about the volume, avoiding clustering;
iii) be of a rectangular design with control points surrounding the structure, as opposed to having 'internal' reference points.

In addition, the design of the calibration frame must also fulfil the following criteria:
i) be cheap to produce;
ii) be portable, to transport to various competitions;
iii) be able to be quickly constructed;
iv) to be reproducible, avoiding long calibration procedures on site; and
v) when digitised, the mean and maximum calibration errors should be less than 15 mm and 30 mm respectively. These limits were suggested as 'general guidelines' by the 3D software being used to be of an 'acceptable level' (Bartlett and Bowen, 1993). It is left to the user to determine acceptable reconstruction accuracy.
vi) have additional control points to test reconstruction accuracy.

3.3.3 Pilot study

A rectangular prototype was constructed from 25 mm square tubing with dimensions 1650 mm x 735 mm x 585 mm. All joints were welded together at right angles to ensure stability. Using insulation tape, sixteen markers were placed on the structure at equal intervals along each side of the frame. Each marker was approximately 25 mm wide and was easily visible through both cameras. The origin was located at the rear bottom left corner of the structure. The three positive axes were therefore described by the tubes leaving this corner, see figure 3.3.1. The Y axis defined the vertical axis and the X and Z axes defined the longitudinal and medio-lateral axes respectively. The 3D coordinates of each of the 16 points were measured assuming that the structure had perfect right angles. The two views of the calibration frame were filmed and then digitised. After reconstruction, using the software of Bartlett and Bowen (1993), the mean and maximum reconstruction errors between the true and computed test point coordinates were evaluated. Bartlett and Bowen (1993) suggested that the mean errors should be less than 15 mm and maximum errors to be less than 30 mm. The reconstruction process was repeated 5 times. The mean (and maximum) reconstruction errors obtained for the prototype calibration frame were 3.65 mm (10.01 mm); 3.85 mm (9.63 mm); and 5.64 mm (13.18 mm) for the X, Y and Z directions respectively. This analysis showed that it was possible to obtain good reconstruction errors well within the above error limits as suggested by Bartlett and Bowen (1993).

3.3.4 Design one

Following this successful pilot study, a calibration frame with more appropriate dimensions for studying the long jump take-off (2.5 m long, 2.5 m high and 1.25 m wide) was constructed from 25 mm square steel tubing. The joints were not welded as the frame was required to be portable. Again, 16 markers were taped at equal intervals about the structure and the coordinates were determined assuming joint angles of 90°. The frame was filmed from two views and digitised. Reconstruction errors greater than the suggested limits were observed. As the joints were not rigid, the frame became distorted and therefore the joint angles could not be assumed to be 90°. Further analyses revealed that the frame distortion was dependent on where in the laboratory the frame was positioned. Therefore the frame was not reproducible and meant that a full calibration procedure would be necessary wherever the frame was constructed. This was initially overcome by incorporating adjustable feet in the design, allowing the base of the frame to be 'levelled' with the use of a spirit level. This meant that all points on the base of the frame lay in the same plane. Knowing that the joint angles were not 90°, the 3D coordinates of the 16 control points had to be measured with greater care. The distances between the centres of each point to all other points had to be measured. This was done using a steel measuring tape with the distances measured to the nearest millimetre. This process was repeated several times and the average distance was recorded. The 3D coordinates of each point were then determined using a trigonometrical solution.

Each corner of the frame was colour coded to ensure that the same pieces were positioned in the correct places following reconstruction. To test whether the frame distortion was reproducible, only the long diagonals needed to be re-measured, the lengths between points 0-13; 2-15; 3-10 and 5-12, (see figure 3.3.1).

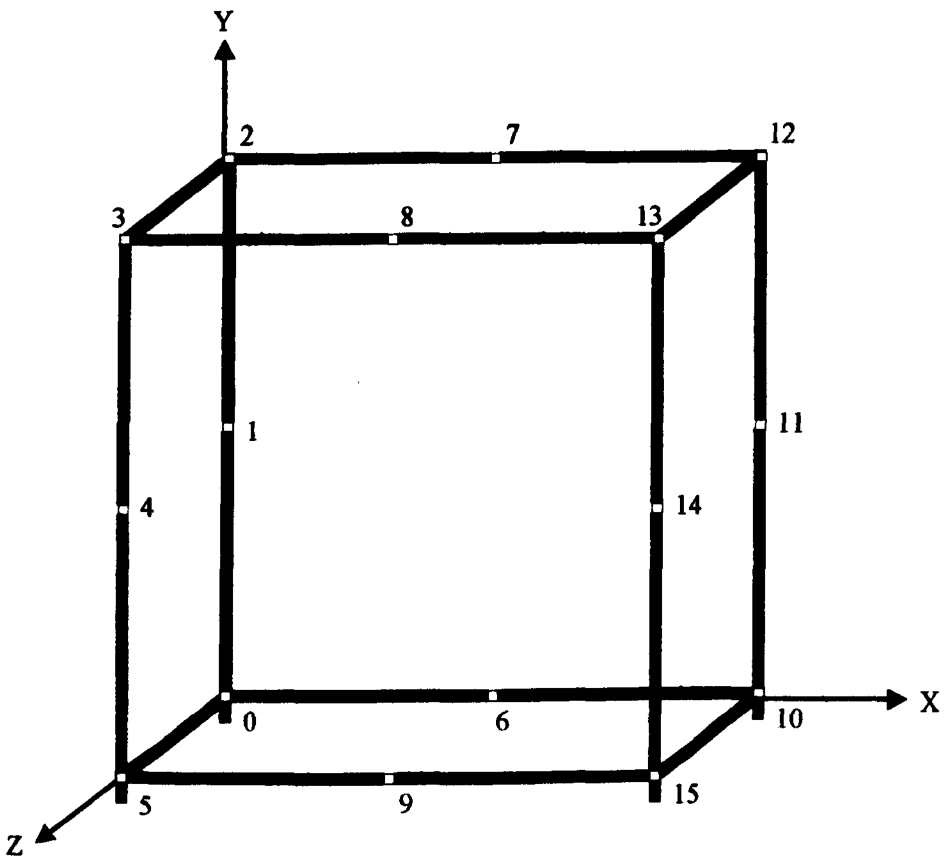


Figure 3.3.1. Diagrammatic representation of the 3D calibration frame identifying calibration points.

Due to time and cost factors the accuracy of the 3D reconstruction was initially tested using video digitising equipment. The mean and maximum errors were found to fall within the limits set out by Bartlett and Bowen (1993). The practicality of this method was then tested during competition at the AAA National Championships at Sheffield in 1994. The calibration frame was recorded on 16 mm cine-film by two high speed cine cameras. The angle between the optical axes of the cameras was approximately 120°. One camera was in the stand and was elevated by approximately 10 m, whilst the other was at ground level. Following 10 repeated calibrations, the mean and standard deviation reconstruction errors were 7.38 ±1.08 mm, 4.62 ±0.41 mm and 5.23 ±0.71 mm for the X, Y and Z directions respectively. Likewise, the maximum errors were found to be 18.41 ±2.18 mm, 14.14 ±1.4 mm and 12.05 ±2.21 mm. Again the calibration errors were found to fall well within the acceptable limits proposed by Bartlett and Bowen (1993).

3.3.5 Design two

Although the construction and calibration procedure had been successful the design had two disadvantages. Firstly the frame needed re-calibrating periodically. This required the full measurement protocol to be completed again, a process that took over three hours. The second problem was the time which it took to get the frame level and to complete a few 'check' measurements during actual competitions. To combat both these problems the frame needed to be reproducible without having to do any checks. The only way to solve this was to make the frame rigid, but as mentioned earlier it also had to be transportable.

This was achieved with the use of wire cable. The eight corner joints were drilled and tapped in the centre of the three faces. A bolt was screwed into the hole, enabling the cable to be attached to the frame. The eight long lengths of the frame were precision cut to the same size, (2455 mm) as were the four small lengths (1229 mm). Pythagoras' theorem was used to calculate the lengths of the diagonals and hence the exact length that the wire cables needed to be. Two cables were made for each face of the frame, except the base, figure 3.3.2. In total there were 10 cables, 6 of length 2745 mm and 4 of length 3472 mm. After construction the frame was rigid and all the cables were taut, indicating that the structure had been pulled into shape. The coordinates of the frame were therefore calculated very quickly knowing that the frame was not distorted and each corner could be assumed to be a right angle. The frame was recorded on video tape from two views and digitised. The mean reconstruction errors were 5.04 mm, 6.98 mm and 12.35 mm for the X, Y and Z directions respectively.

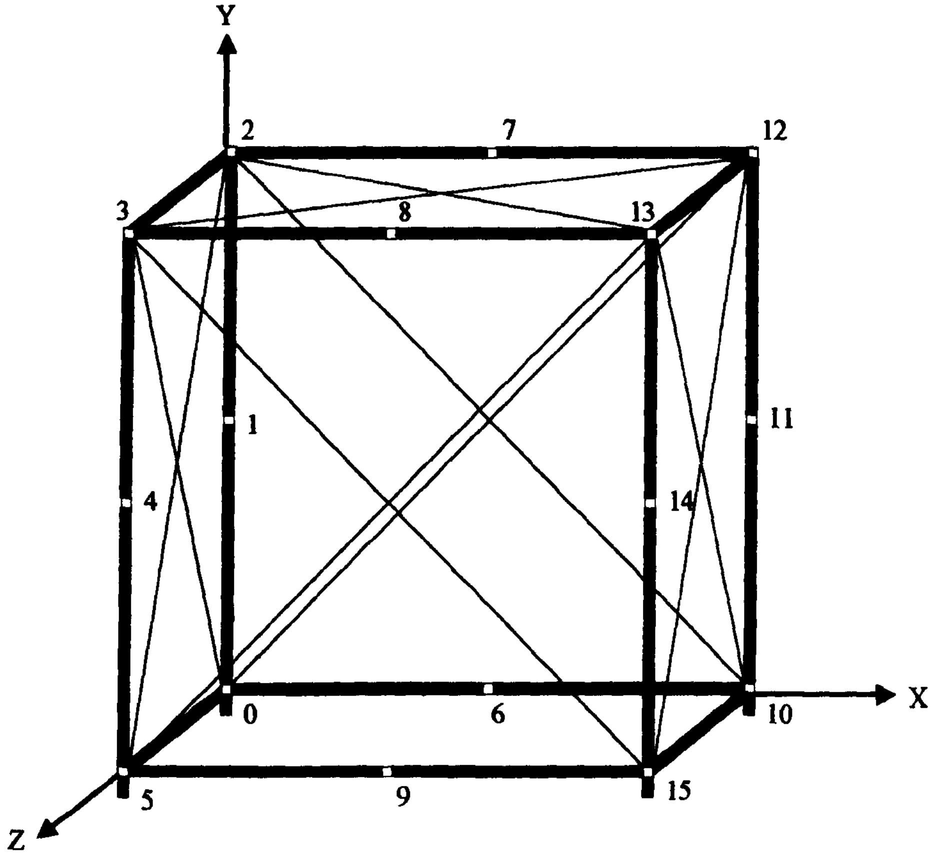


Figure 3.3.2. Design two of the calibration frame showing the cross-wires.

The new calibration frame was taken to the AAA national championships at Birmingham in 1995 and filmed by two high speed cine cameras. These calibration errors were similar to the ones obtained from the previous year's competition, showing mean calibration errors of 3.89mm, 5.26 mm and 5.72 mm for the X, Y and Z directions respectively. Maximum errors were found to be 9.25 mm, 14.15 mm and 15.24 mm. The new design of the calibration frame not only provided a successful reconstruction, it was also less time consuming during filming and less of an inconvenience to TV personnel, officials, athletes and spectators.

3.3.6 Assessment of reconstruction errors.

Although the reconstruction errors were initially assessed using the mean and maximum errors provided by the 3D software, it is acknowledged that more independent estimates of accuracy are determined using markers which were not used in the derivation of the DLT parameters (Allard et al., 1995). This was examined by placing 6 extra markers of known location onto the frame. Two Panasonic video cameras were positioned such that the angle between the optical axes was approximately 90°. The calibration frame was then recorded and digitised. After the 3D reconstruction, the 6 new reference markers were digitised. The accuracy of the calibration was assessed by comparing the root mean square (RMS) error of the digitised points to their actual known location. The RMS error, E_{RMS}, was calculated using the following equation:

$$E_{RMS} = \frac{\sqrt{\sum(x_R - x_i)^2}}{N}$$

where x_R corresponds to the reference values, x_i corresponds to the measured values and N is the number of observations.

The mean and RMS errors for these points are presented in table 3.3.1.

Table 3.3.1. Differences between reference and measured coordinates and estimates of the mean and RMS errors.

Marker	Differences (mm) (Reference - Measured)		
	X	Y	Z
1	-0.60	-0.80	5.00
2	2.00	0.20	17.00
3	2.00	-0.80	-0.14
4	-19.00	-8.00	0.14
5	3.00	2.00	-25.00
6	-6.00	8.00	6.00
Mean Error	-3.10	0.10	0.50
SD	8.45	5.16	13.95
RMS error	3.39	1.92	5.20

Allard et al.(1995) stated that the mean error is inappropriate for expressing the instrument accuracy because the negative errors are cancelled by the positive ones. They added that the RMS error is a conservative estimate of instrument accuracy. Table 3.3.1 confirms their findings, showing the mean errors to be lower than the RMS error, especially in the Y and Z directions. The results indicate the reconstruction to be accurate to 3.39 mm in the X direction, 1.92 mm in the Y direction and 5.20 mm in the Z direction. The resultant RMS error, an overall measure of the X, Y and Z components, was calculated to be 6.49 mm. Considering the dimensions of the calibration frame, (2455 mm long by 2455 mm high and 1229 mm wide), the percentage errors are 0.138%, 0.078% and 0.423 % in the X, Y and Z directions respectively.

The accuracy of the 3D reconstruction compares well with other studies. Kennedy et al. (1989) found a resultant mean error of 5.8 mm in the reconstruction of their 2 m cube, 20 point calibration object. The field of view in their study was approximately 3.5 m in the horizontal direction, compared to 4.5 m in the present study. The resultant mean error of the present study was 3.14 mm, less than 5.8 mm reported by Kennedy et al. (1989). Angulo and Dapena (1992) examined 3D reconstruction accuracies in a wider field of view, approximately 8 m, and found the RMS error of 62 points to be 7 mm, 5 mm and 4 mm in the X, Y and Z directions respectively. The resultant of these errors was 10 mm and the maximum errors were 17 mm, 13 mm and 11 mm in the X, Y and Z directions. The RMS errors obtained in the present study were generally less than those found by Angulo and Dapena (1992) and would be expected considering the smaller field of view in this study.

Depending on the size of the field of view, the use of a cine digitising system may reduce these errors. Kennedy et al. (1989) found the resultant mean error of their video system to be 1 mm greater than their cine system. Angulo and Dapena (1992) also found their cine system to be more accurate than their video system, finding resultant RMS errors of 4 mm and 5 mm for large and small film images respectively.

3.3.7 Summary and Conclusion

It has been shown that the calibration frames developed have provided reconstruction errors less than those recommended by Bartlett and Bowen (1993). Although the first full size design gave low reconstruction errors, the design meant that full calibration procedures had to be carried out periodically and a few 'on-site' checks had to be made. The latter caused minor inconveniences to TV personnel and officials in particular. A less time consuming calibration procedure was developed by making the frame rigid, yet transportable. This was achieved by attaching wire cables of known length to each corner of the frame. Reconstruction errors fell well within the limits proposed by Bartlett and Bowen (1993). A more independent test of reconstruction accuracy was carried out using 6 points that were not used to determine the DLT parameters. The RMS errors between the reference and measured coordinates of the 6 additional points gave accuracies of 3.39 mm, 1.92 mm and 5.20 mm for the X, Y and Z directions respectively. These values were found to compare well with the results of Kennedy et al. (1989) and Angulo and Dapena (1992).

3.4 Overview of methodological issues

The three sections in this Chapter collectively fulfil the requirements of objective 1 of this thesis - to address various methodological issues relating to data collection and in particular an examination of the errors and the limitations of biomechanical techniques. Following the recommendations of Bartlett et al. (1992) the studies progressed from 2D analysis into the more complicated area of 3D analysis. Skills have been developed along the way which have led to a thorough understanding of the data collection procedure. Specifically, an appreciation of both the quality of the data generated and the considerations and limitations associated with different methods has been gained.

To summarise, the results of section 3.1 found that the operator was reliable or consistent in his digitising, and the data were objective when compared to another experienced operator. The data were objective in the sense that there were no significant differences between the mean data for 9 of the 11 variables analysed. However, the relatively large 'random error' component of the limits of agreement indicated that the judgement of joint centre locations and the correct identification of the critical frames of touch-down and take-off are potential sources of error. The recommendation was that specific attention be paid to the above, and that the average data of several repeated digitisations of a jump be used to reduce digitising error further.

The results of section 3.2 indicated that video-based digitising systems are currently not acceptable for the quantitative analysis of the long jump. A lower sample frequency of 50 Hz was found to have a major affect on velocity measures in particular. For an event like the long jump such information is vital. Inferior resolution was also found have a detrimental affect on the quality of displacement data produced by the video system. The recommendation from this study was that a cine-based digitising system operating at no less than 100 Hz should be used in the main studies.

The development of a three-dimensional calibration frame was the focus of section 3.3. After following design recommendations set out by several main authors a frame has now been constructed that performs as well as others reported in the literature in terms of its reconstruction accuracy. The true reconstruction capability of the calibration frame was assessed by the RMS error of 6 new reference points (not used in the derivation of the DLT parameters) as suggested by Allard et al. (1995). The results indicated that points could be digitised to an accuracy of 3.39 mm, 1.92 mm and 5.20 mm in the X, Y and Z directions respectively.

The methodological issues relating to 2D and 3D data collection have now been reviewed sufficiently to progress into full three-dimensional analyses of the long and triple jump take-offs.

4.0 Three-Dimensional Kinematic Analyses of Long and Triple Jump Take-offs

4.0 Three-dimensional kinematic analyses of the long and triple jump take-offs

This chapter is divided into two parts. Section 4.1 examines the three-dimensional kinematics of the long jump take-off and section 4.2 examines the hop, step and jump take-offs in the triple jump. Both sections have common objectives and these are:

i) to quantify the three-dimensional kinematics of the support leg, trunk and the free limbs in each of the take-off phases;

ii) to quantify the contributions made by the pivot mechanism and the free limbs during each take-off.

These studies build on the research of Bober (1974) and Fukashiro et al. (1993) and collectively fulfil the requirements of objectives 2 and 3 in section 1.2.

In section 4.1 an additional objective is to assess the theoretical model by relating characteristic movements to the gain in vertical velocity and the loss horizontal velocity of the centre of mass during the long jump take-off. This builds on the work of Lees et al. (1994). A further objective is to examine whether the relationship between approach speed and long jump distance can be improved upon by taking into account aspects of technique during the take-off phase.

An investigation into the kinematic differences between the long and triple jump take-offs is an additional objective in section 4.2. This uses the results of the theoretical model in section 4.1 as a basis to assess the function of each take-off. This study builds on the work of Verhoshanski (1961), cited by Hay (1992) and Koh and Hay (1990).

4.1 A three dimensional kinematic analysis of the long jump take-off.

4.1.1 Introduction

It was noted in section 2.6 that only one study has attempted to describe the movement of long jumpers outside of the sagittal plane. While most researchers regard the long jump to be a two-dimensional sagittal plane activity, such assumptions cannot be made without first investigating the characteristics of movement in the frontal and transverse planes (Yeadon and Challis, 1994). The study by Fukashiro et al. (1993) noted some interesting characteristics in the transverse plane, but this now needs to be expanded into the frontal plane. Attempts must also be made to relate the full three-dimensional characteristics to the changes in height and the gains and losses in vertical and horizontal velocities of the centre of mass.

4.1.2 Method

Fourteen male long jumpers were assessed for approach speed and technique during the finals of the 1994 (n=8) and 1995 (n=6) U.K. Championships. Approach speed was determined via photoelectronic timing devices positioned at 11, 6 and 1 m from the front of the take-off board. Technique was assessed through analysis of film records obtained from two high speed 16mm cine-cameras (Locam and Photosonics). One camera (Photosonics) was placed in the stand, approximately 20 m from the runway and about 10 m behind the take-off board (see figure 4.1.1). The stand produced an elevation of about 10 m. The second camera (Locam) was placed about 40 m in front and slightly to one side of the landing pit so that a head on view was obtained. This camera was positioned higher in the stand providing an elevation of approximately 15 m. The optical axes of the two cameras were approximately 120° apart. Both cameras were set to record at a frequency of 100 Hz and were checked by recording a millisecond timer. The calibration frame and several control markers were recorded on both cameras. Digitising equipment included a NAC cine projector and a TDS digitising tablet operating through an Acorn A3000 computer. The film was digitised using the software developed by Bartlett and Bowen (1993). The 3D volume was reconstructed using the DLT technique and the centre of mass was calculated using a 14 segment model defined by 18 points and segmental data proposed by Dempster (1955). The origin was taken to be the front left hand corner of the take-off board. Data were smoothed using a Butterworth 4th order zero lag filter with padded end points and a cut-off frequency of 8.33 Hz. Each jump was digitised three times and the average of the processed data taken to reduce errors.

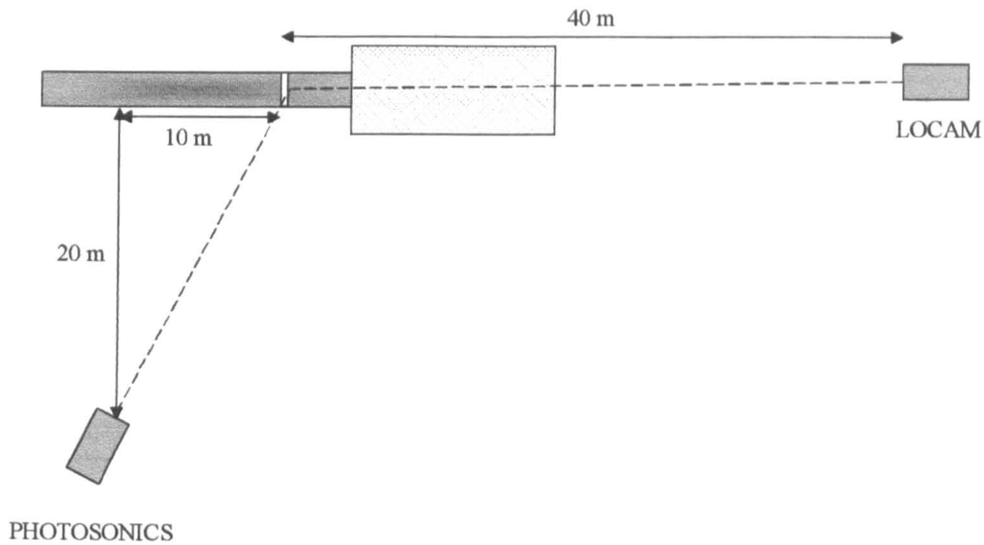


Figure 4.1.1. Camera set-up for 3D analysis.

The accuracy of the 3D reconstruction was determined by the RMS error of the digitised coordinates and the measured coordinates. Systematic errors of 3.39, 1.92 and 5.20 mm were found for the X, Y and Z directions respectively. The precision of the digitisation was assessed on 3 repetitions of one randomly selected jump using the mean deviation from the mean of each variable assessed. Estimates of precision for a selection of variables are presented in Appendix III. Typically, displacement measures were precise to 0.4 mm, angles to 1°, and velocities to less than 0.1 $m.s^{-1}$.

To estimate the contribution made by the arms and the lead leg, the relative momentum approach proposed by Ae and Shibukawa (1980) and the interpretation offered by Lees and Barton (1996) was adopted, (see section 2.4.2 b). This calculates the vertical momentum of the limb as the sum of the vertical transfer momentum and the vertical relative momentum. The transfer momentum accounts for the momentum transferred through the proximal joint and the relative momentum reflects the active use of the limb. As anthropometric measurements could not be taken during competition all athletes were assumed to have a body mass of 85 kg. Assuming a constant body mass will affect the accuracy of the absolute values of relative momentum, but it will not affect the percentage contribution of the free limbs as body mass is cancelled out.

Statistical tests were performed to assess the theoretical model outlined in section 1.1. Normality of data was first examined using the skewness and kurtosis measures outlined by Vincent (1995). All data were found to have a normal distribution. Relationships were tested using the Pearson Product Moment Correlation Coefficient, coefficient of determination and the 'best subsets' multiple regression analysis (Minitab for Windows, version 11, 1996). After entering 10 variables relating to the theoretical model, the 'best subset' option was used to determine the best combination of predictor variables. However, considering that the ratio of subjects to independent variables should be no less than 5:1 (Vincent, 1995) a maximum of 3 predictors was permitted. The coefficient of determination (R^2) was used to assess the association between variables.

4.1.3 Results

The results presented in this section refer to the mean and standard deviation of the 14 subjects analysed. The mean effective distance of the jumps was 7.44 ± 0.18 m with a range of 7.14 to 7.84 m. Data are presented at the instants of take-off last stride (TOLS), touch-down (TD), maximum knee flexion (MKF) and take-off (TO). These can be seen clearly in figure 4.1.2. Touch-down was defined as the first frame in which the foot had made clear contact with the ground and take-off was defined as the first frame in which the foot had clearly left the ground. The instant of maximum knee flexion was taken to represent the point at which the compression phase ended and the extension phase began, (Lees et al. 1993, 1994).

As the time of contact differed by only 1 frame (0.01 s) between the subjects the graphs have not been normalised. The line depicting the instant of touch-down is correct for all 14 athletes, but the lines of take-off last stride, maximum knee flexion and take-off are representative of average positions. In any single jump it is unlikely that these lines will deviate by more than one frame either way.

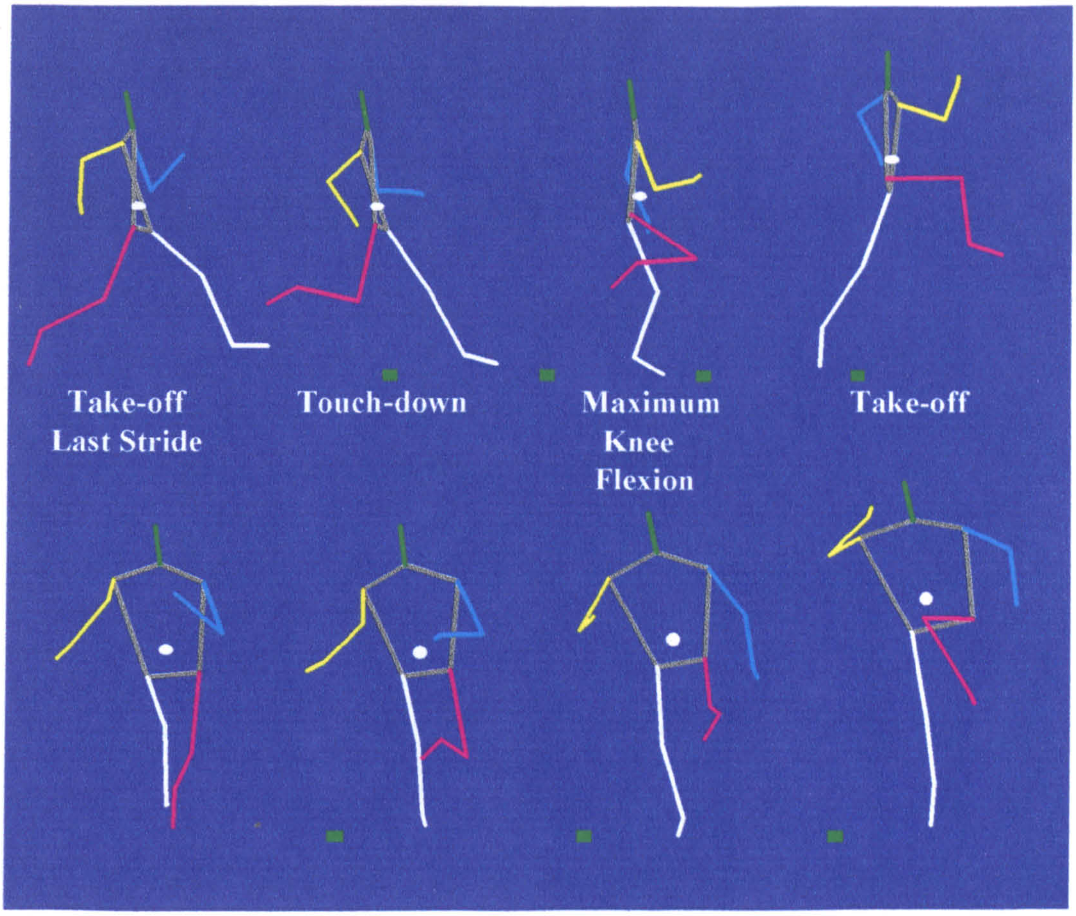


Figure 4.1.2. Kinetograms depicting the instants of 'take-off last stride', 'touch-down', 'maximum knee flexion' and 'take-off', (subject N3).

<u>Temporal characteristics</u>

4.1.3.1. Kinematics of the centre of mass.

Height of the centre of mass

Table 4.1.1 shows the changes in the mean vertical displacement of the athletes' centre of mass between take-off last stride and take-off. Figure 4.1.3 shows the mean (n=14) profile of the change in the height of the centre of mass. The graph depicts an almost flat trajectory between take-off last stride and touch-down, decreasing by only 1 cm, a small increase of 6 cm during the compression phase and the greatest gain in height of 23 cm occurring during the extension phase. This led to a total gain in height of 29 cm between touch-down and take-off.

Table 4.1.1. Mean (±SD) vertical displacement of the centre of mass at the instants of take-off last stride, touch-down, maximum knee flexion and take-off.

	Take-off Last Stride		Touch-down		Maximum Knee Flexion		Take-off	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Height (m)	0.99	0.04	0.98	0.04	1.04	0.04	1.27	0.04

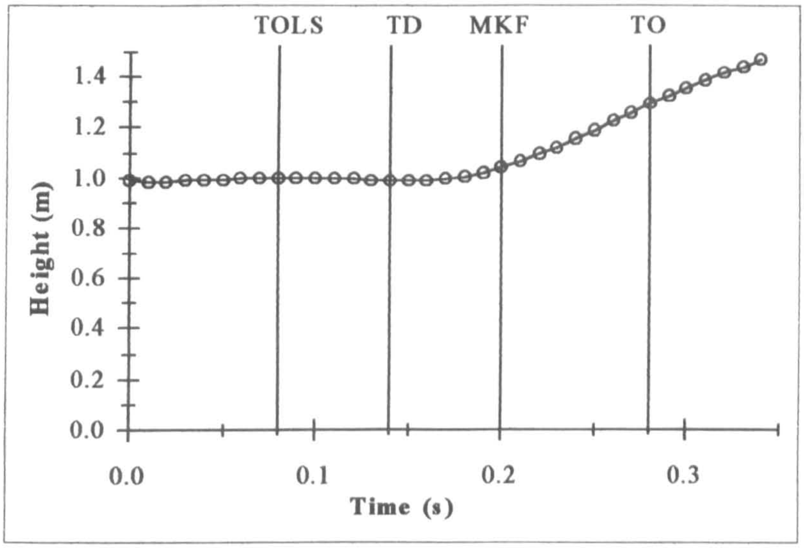


Figure 4.1.3. Profile of the mean centre of mass height during the long jump take-off (n=14). (TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion and TO = take-off).

Horizontal and vertical velocity profiles of the centre of mass

The results found that athletes approached the board with an average approach speed of 9.95 ± 0.34 m.s^{-1} over 11 m to 1 m from the board. The instantaneous value of horizontal velocity at touch-down, VX_{TD}, was found to be almost identical, 9.93 ± 0.37 m.s^{-1}, table 4.1.2 . Following impact with the board a substantial amount of horizontal velocity was lost between touch-down and maximum knee flexion, 1.30 m.s^{-1}, and a further loss of 0.09 m.s^{-1}occurred in the extension phase. The vertical velocity at touch-down was slightly negative, -0.18 m.s^{-1}, which reflects the almost flat trajectory of the centre of mass between take-off last stride and touch-down described previously. In contrast to VX, the vertical velocity VY showed a dramatic increase during the compression phase. The relationship between the loss in VX and the gain in VY can be seen in figure 4.1.4. By the instant of maximum knee flexion the athletes attained 2.29

m.s^{-1}, a gain of 2.47 m.s^{-1} from the instant of touch-down. The extension phase accounted for a further 1.08 m.s^{-1} of vertical velocity with a mean VY $_{TO}$ of 3.37 m.s^{-1}. The total gain in vertical velocity between touch-down and take-off was 3.54 m.s^{-1}, of which 69.8 % was gained by the end of the compression phase. It can be seen in figure 4.1.4 that the vertical velocity actually reaches a peak slightly before the instant of take-off and decreases as the athlete enters the flight phase. The medio-lateral velocity (VZ) of the centre of mass produced the smallest values of the three velocity components and these were very close to zero. The contribution of VZ to the resultant speed (S) of the athlete was therefore minimal. Very small changes of -0.04 m.s^{-1} and 0.09 m.s^{-1} were observed for VZ during the compression and extension phases respectively.

Table 4.1.2. Mean (±SD) horizontal and vertical velocity changes of the centre of mass at the instants of take-off last stride, touch-down, maximum knee flexion and take-off.

	Take-off Last Stride		Take-off		Maximum Knee Flexion		Take-off	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
VX (m.s^{-1})	10.01	0.27	9.93	0.37	8.64	0.35	8.55	0.35
VY (m.s^{-1})	0.12	0.16	-0.18	0.21	2.29	0.32	3.37	0.32
VZ (m.s^{-1})	-0.01	0.36	0.13	0.24	0.10	0.29	0.18	0.32
Speed (m.s^{-1})	10.02	0.27	9.94	0.37	8.95	0.28	9.20	0.25

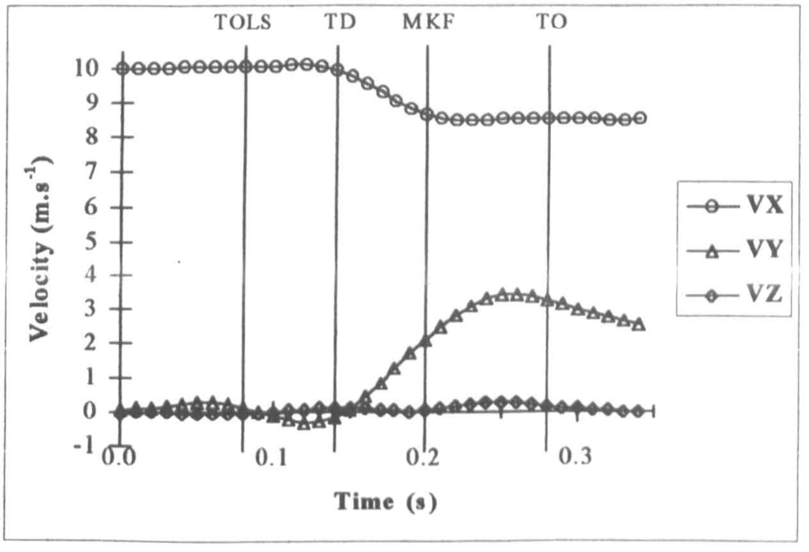


Figure 4.1.4. Mean centre of mass velocity profiles (n=14). (TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion and TO = take-off).

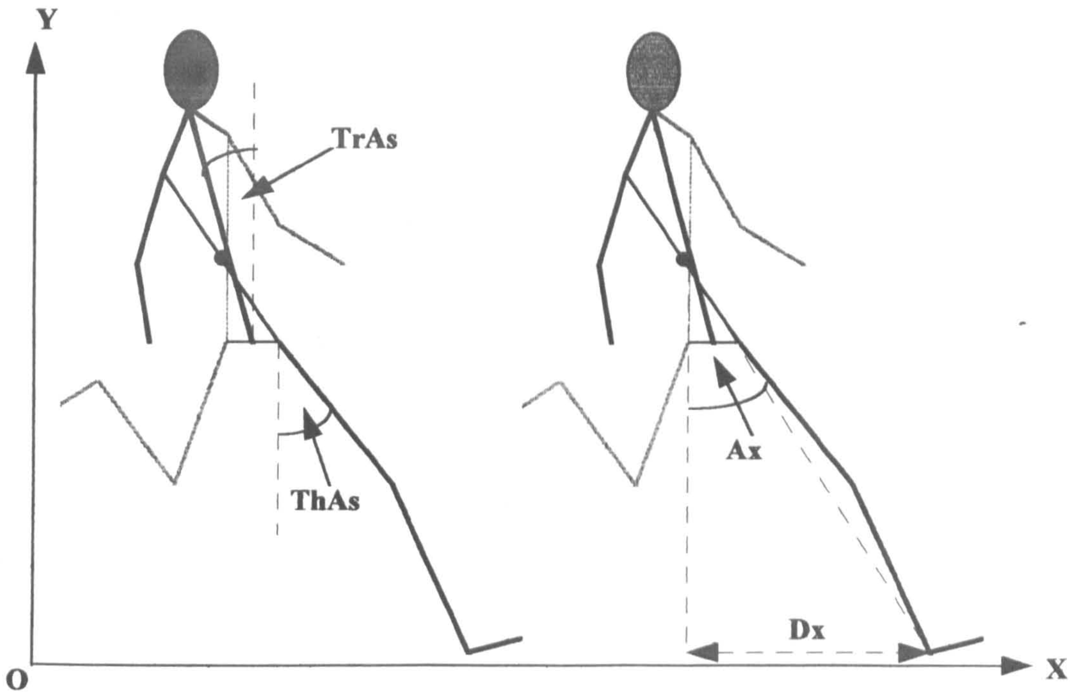
4.1.3.2. Kinematics of the trunk, support leg and free limbs

The trunk and support leg

Sagittal plane kinematics

Figure 4.1.5 and table 4.1.3 represent important kinematic characteristics of the trunk and touch-down leg in the sagittal plane. The extension of the leg in front of the centre of mass at touch-down has been associated with the development of vertical velocity. The touch-down distance (Dx_{TD}) is defined as the horizontal distance between the centre of mass and the ankle joint of the touch-down leg (Lees et al., 1993 and 1994). The average touch-down distance was found to be 0.55 m. At maximum knee flexion the centre of mass is slightly behind the ankle by 0.03 ± 0.05 m and at take-off the centre of mass has moved into a position 0.44 ± 0.06 m in front of the ankle. The corresponding angle (Ax) values are $32.2 \pm 2.2°$ at touch-down and $-23.6 \pm 3.1°$ at take-off. The manner in which the foot strikes the board has also been the focus of several investigations. In this study the average velocity of the ankle relative to the horizontal velocity of the centre of mass at touch-down was -5.56 $m.s^{-1}$. The negative sign representing backwards movement of the ankle relative to the centre of mass. Such a value indicates an 'active' landing, characterised by a backward sweeping, or 'pawing' action of the leg at touch-down which is thought to reduce the loss in horizontal velocity.

The trunk angle, (TrAs) was observed to be inclined backwards throughout the support. Following impact with the board the trunk angle moved forwards from -7.5 to -1.3° at the point of maximum knee flexion. Little movement was observed from maximum knee flexion to take-off and the trunk remained in an almost vertical position. The thigh was observed to move through a range of 15.7° backwards and downwards from touch-down to maximum knee flexion (ThAs). Ultimately this resulted in a net extension of the hip joint by an average of 11.0°. In none of the jumps did hip flexion occur between touch-down and maximum knee flexion. At take-off, the thigh was in a position to the rear of the centre of mass at -21.7° to the downward vertical and the hip joint was a state of hyper-extension denoted by an angle of 201.0°. As the thigh moved through a range of 62.1° between touch-down and take-off compared to only 6.7° by the trunk, it can be said that the movement of the thigh had a greater influence on hip extension than movement of the trunk.



<u>Legend and conventions</u>

Dx Horizontal distance between the centre of mass and ankle joint of take-off leg, (positive when the centre of mass is behind the ankle joint).

Ax Angle made by line joining the centre of mass to ankle joint and the downward vertical, (positive when centre of mass is behind the ankle joint).

TrAs Trunk angle sagittal plane (negative when the trunk is inclined behind the upward vertical, as shown).

ThAs Thigh angle sagittal plane to downward vertical (positive when knee joint is in front of the hip joint).

Figure 4.1.5. Stick figure representation of selected sagittal plane kinematic variables.

Table 4.1.3. Mean (±SD) of selected sagittal plane kinematic variables of the trunk and take-off leg.

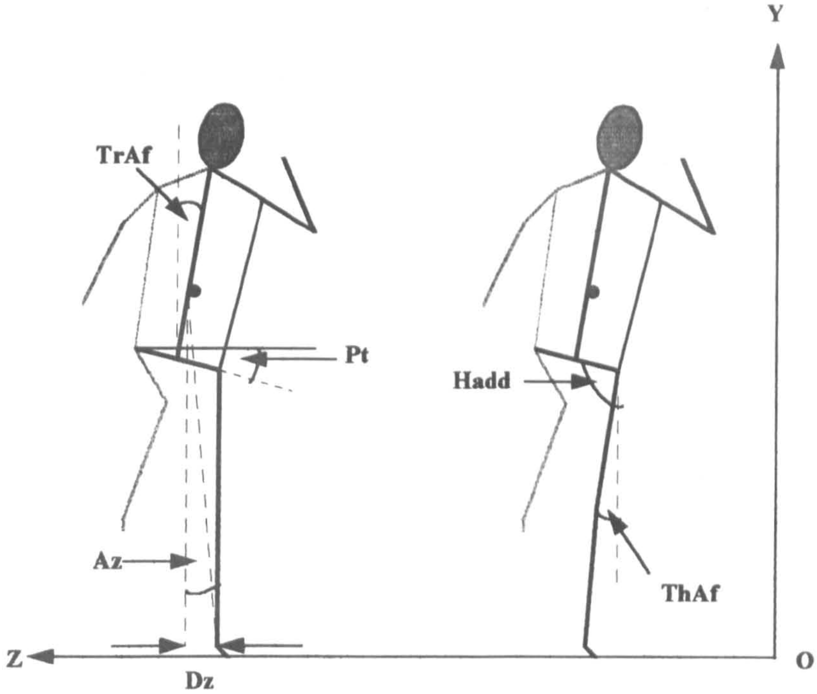
	Touch-down		Maximum Knee Flexion		Take-off	
	Mean	SD	Mean	SD	Mean	SD
Dx (m)	0.55	0.04	0.03	0.05	-0.44	0.06
Ax (°)	32.2	2.2	1.8	3.2	-23.6	3.1
Rel. ankle vel ($m.s^{-1}$)	-5.56	1.07	-8.28	0.43	-4.85	0.80
Trunk angle (sagittal) (°)	-7.5	3.3	-1.3	3.4	-0.8	5.3
Thigh angle (sagittal) (°)	40.6	3.3	24.9	3.3	-21.1	2.8
Hip flexion angle (°)	146.0	5.9	157.0	5.9	201.0	6.2

Note: Hip flexion angle is calculated from the trunk and thigh angles, (180° - Trunk angle (sagittal) - Thigh angle (sagittal)).

Frontal plane kinematics

Figure 4.1.6 shows the angles and distances describing movements of the trunk, pelvis and touch-down leg in the frontal plane. The distance Dz, the horizontal distance between the centre of mass and the ankle joint in the medio-lateral direction, gives an indication as to where the point of support is relative to the athlete's centre of mass. The average data of the group suggests that the ankle is placed more or less directly under the centre of mass at touch-down and little change occurs throughout the support phase, (table 4.1.4). The corresponding angle, Az, is also very small. At touch-down this angle is close to zero, -0.3°, and increases to -1.8° at maximum knee flexion. Values greater than zero are likely to create a turning moment of the centre of mass about the point of support. This might cause the athlete to adduct more at the hip or in extreme cases to lose balance.

The trunk was found to be inclined towards the side of support throughout the whole of the take-off phase. The trunk angle in the frontal plane, (TrAf), was seen to decrease from touch-down to take-off by an average of 2.4°, indicating that the trunk moves into a slightly more vertical position at take-off. The angle of the pelvis, Pt, indicated that the hip joint of the lead leg was always in a higher position than the hip joint of the touch-down leg. The pelvis was observed to move through a range of 13.9° from touch-down to take-off, leaving the board at approximately 19.3° to the horizontal. The thigh angle, ThAf, showed only a small change, 2.4° between touch-down and take-off. The hip joint was observed to adduct by an average of 3.9° following impact with the board. The minimum hip adduction angle was 87.1° ± 6.2 and this generally occurred before the end of the compression phase, (see figure 4.1.9). The hip then abducted through a range of 15.4° by the time of take-off.



Legend and conventions

Dz	Horizontal distance between centre of mass and ankle joint (positive as shown, negative when ankle joint crosses the downward vertical).
Az	Angle made by line joining the centre of mass to the ankle joint and the downward vertical (same convention as Dz).
TrAf	Trunk angle frontal plane (negative when trunk leans towards the side of support, as shown).
Pt	Pelvic tilt (positive when hip joint of the support leg is below the hip joint of the free leg, as in the diagram).
ThAf	Thigh angle frontal plane (positive when the thigh is inclined towards the midline of the body, as shown in the diagram).
Hadd	Hip adduction angle.

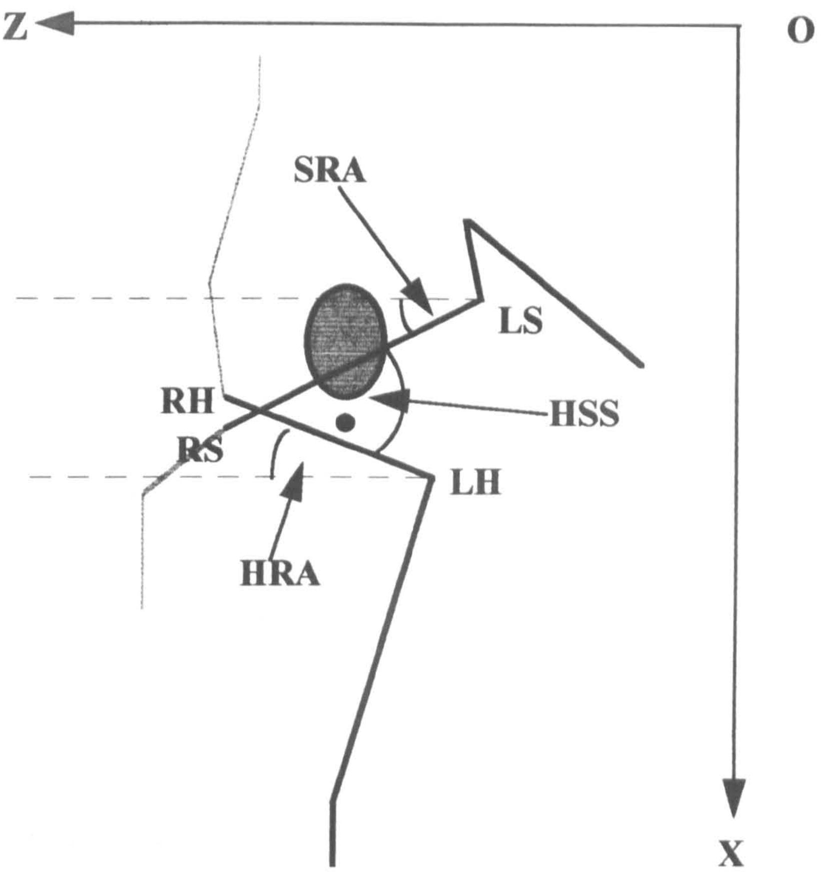
Figure 4.1.6. Stick figure representation of selected frontal plane kinematic variables.

Table 4.1.4. Mean (±SD) frontal plane kinematics of the trunk and take-off leg.

	Touch-down		Maximum Knee Flexion		Take-off	
	Mean	SD	Mean	SD	Mean	SD
Dz(m)	0.00	0.03	-0.03	0.04	-0.02	0.05
Az (°)	-0.3	1.9	-1.8	2.5	-1.4	2.7
Trunk angle (frontal) (°)	-9.4	2.8	-9.5	3.0	-7.0	3.5
Pelvic tilt (°)	5.4	5.7	5.1	4.2	19.3	8.3
Thigh angle (frontal) (°)	4.5	4.2	3.3	6.0	6.8	3.6
Hip adduction angle (°)	91.0	5.4	91.8	6.1	103.0	8.2

Transverse plane kinematics

Figure 4.1.7 shows the hip and shoulder rotation angles in the transverse plane. RH, LH, RS and LS refer to the right and left hip and shoulder joints respectively. The difference between these two angles describes the amount of trunk rotation, which is commonly referred to as the hip-shoulder separation angle, (HSS). It can be seen that between touch-down and take-off the trunk rotates through a range of 74.7°. The hips and shoulders rotate through similar ranges (35.7 and -39.0° respectively) and therefore they contribute almost equally to the total amount of trunk rotation. The negative sign indicates that the shoulders rotate in the opposite direction to the hips. However, in the compression phase the hips rotate through a greater range than the shoulders and the shoulders through a greater range than the hips in the extension phase.



Legend and conventions

HRA Hip rotation angle to positive Z axis (negative when hip joint of support leg is in front of hip joint of the free leg, i.e. negative in the diagram).

SRA Shoulder rotation angle to positive Z axis (negative if shoulder on same side as the support leg is in front of the opposite shoulder, i.e. positive in the diagram)

HSS Hip - Shoulder separation angle (negative when hip joint of the support leg is in front of the shoulder joint, i.e. negative in the diagram).

Figure 4.1.7. Stick figure representation of selected transverse plane kinematic variables.

Table 4.1.5. Mean (±SD) transverse plane kinematics of the trunk.

	Touch-down		Maximum Knee Flexion		Take-off		Touch-down to Take-off	
Angle	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Hip rotation angle (°)	-15.6	7.2	9.7	8.5	20.1	15.1	35.7	17.2
Shoulder rotation angle (°)	21.6	6.0	4.9	9.0	-17.4	8.4	-39.0	9.0
Hip-Shoulder Separation Angle (°)	-37.2	8.4	4.8	8.7	37.5	19.7	74.7	24.9

Three-dimensional movement

Figure 4.1.8 shows the 3D angles of the hip and knee joints. The 3D hip joint angle was measured in the plane defined by both hip joints and the knee joint centre. This angle can be described as a complex of hip abduction / adduction, flexion / extension, hip rotation and pelvic tilt. The 3D knee joint angle essentially describes flexion and extension. Figure 4.1.9 shows typical profiles of a) the 3D knee and ankle angles, and b) the 3D hip angle, the hip adduction angle and the hip flexion angle. It can be seen that all angles, with the exception of the hip flexion angle decrease following touch-down on the board and increase during the extension phase. Throughout the touch-down to take-off period the profile of the hip adduction angle closely resembles the 3D hip joint angle and both reach a minimum value before the instant of maximum knee flexion. The minimum 3D hip angle and the minimum hip adduction angle were correlated ($r = 0.937$, $P<0.01$) with average values of 86.4° ± 6.8 and 87.1° ± 6.2 respectively. The knee joint flexed through an average range of 26.5° prior to maximum knee flexion and extended through 29.1° to the instant of take-off. The ankle dorsi-flexed following touch-down until just after maximum knee flexion where it reached a minimum angle of 97.9° ± 6.1. The ankle then plantar-flexed through 41.4° ± 7.0 to the point of take-off. The minimum angles were all found to be significantly smaller than the values at touch-down, ($P<0.01$).

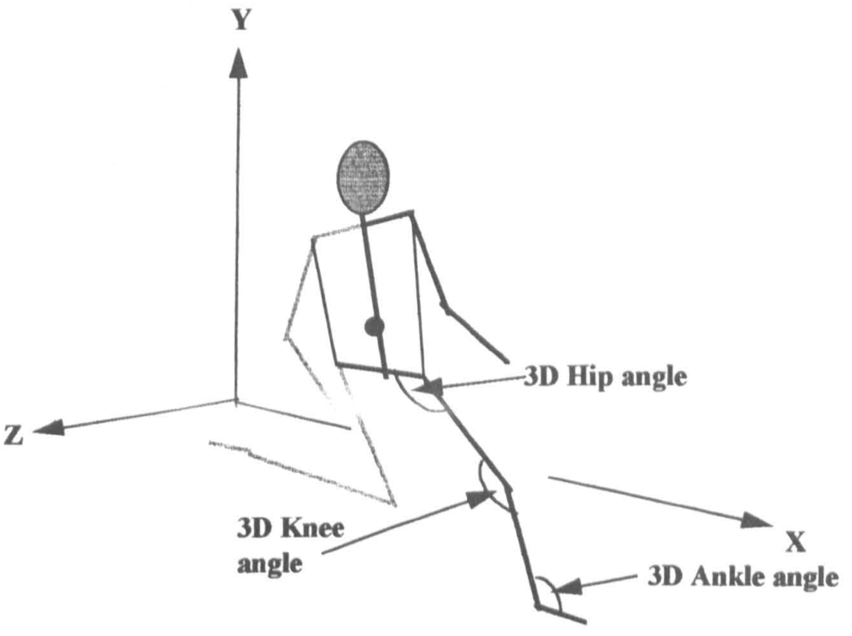
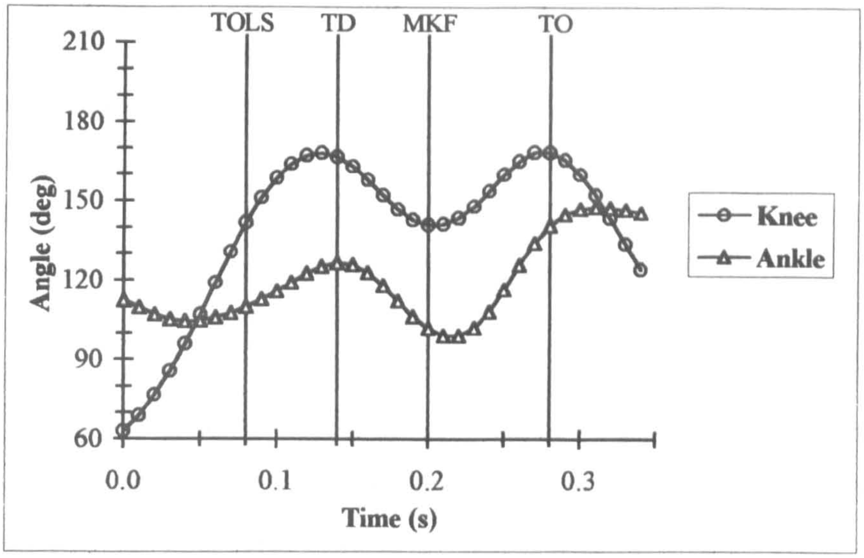


Figure 4.1.8. 3D representation of the hip and knee joint angles.

a)



b)

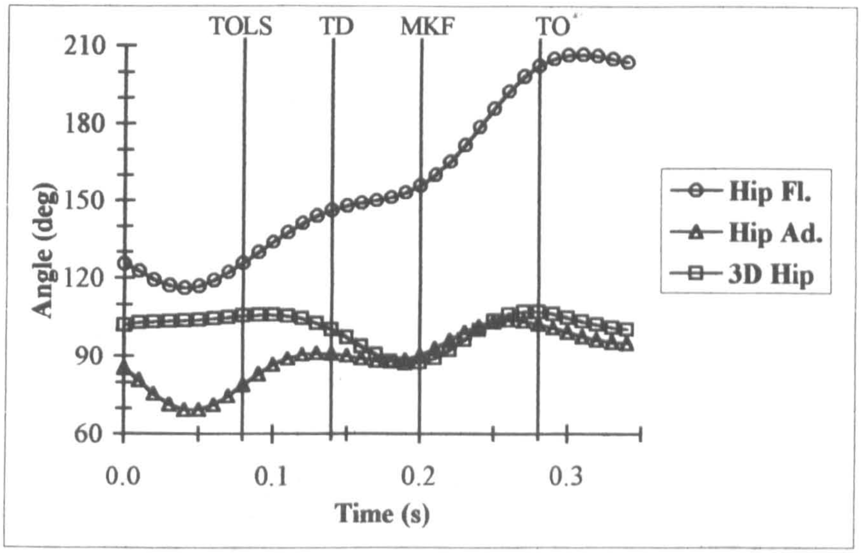


Figure 4.1.9. Mean profiles of a) 3D knee and ankle joint angles, and b) hip flexion, hip adduction and 3D hip angle in the long jump take-off (n=14). (TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion and TO = take-off).

Table 4.1.6. Three-dimensional activity of the hip and knee joints of the take-off leg.

	Touch-down		Maximum Knee Flexion		Take-off	
	Mean	SD	Mean	SD	Mean	SD
3D Hip angle (°)	100.0	7.1	88.3	6.7	107.0	9.8
3D Knee angle (°)	167.0	4.7	140.0	4.5	169.0	3.0
3D Ankle angle (°)	127.0	5.2	99.8	5.9	139.0	6.5

The free limbs

The term 'free limbs' is taken to represent the combined action of the lead leg; the co-lateral arm (the arm on the same side of the body as the support leg) and the contra-lateral arm (the arm on the same side of the body as the lead leg).

This section is divided into two parts, the first examines the relative momentum of the free limbs and the second examines their individual movement patterns.

i) *Relative momentum*

Figure 4.1.10 shows the relative momentum profiles of the co-lateral and contra-lateral arms, the lead leg and the combined free limbs. The combined free limb profile is calculated as the sum of the individual limbs from the start of the action (touch-down) to the end (take-off). The contribution of each limb (and combined limbs) to the take-off vertical velocity of the centre of mass is calculated by the positive increase (ignoring negative values) in the relative momentum from touch-down to take-off, (Lees and Barton, 1996).

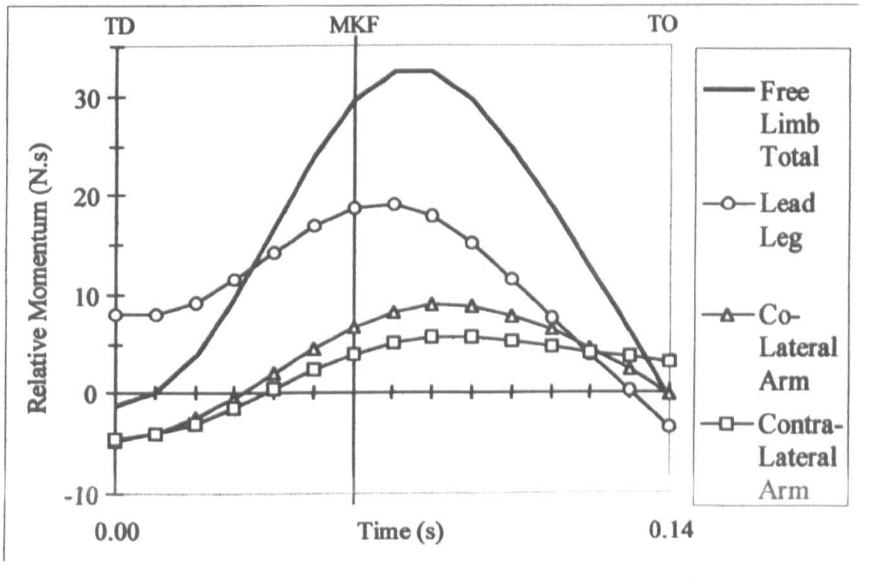


Figure 4.1.10. Mean relative momentum profile of individual and combined free limbs in the long jump take-off, (n=14). (TD = touch-down, MKF = maximum knee flexion and TO = take-off).

It can be seen in figure 4.1.10 that the free limbs (total) begin to develop positive relative momentum shortly after touch-down and reach a peak (32.1 N.s) shortly after the instant of maximum knee flexion. The lead leg appears to be the main cause of this as it already has positive relative momentum at touch-down, (8 N.s), which increases to 20 N.s around maximum knee flexion. This gives an average peak positive increase of 12 N.s from touch-down to take-off. The relative momentum of the lead leg then returns to zero by take-off. Both arms have negative relative momentum values at touch-down which become positive in the mid part of the compression phase and peak in the early to mid part of the extension phase. The average peak positive increases in relative momentum of the co-lateral and contra-lateral arms were measured as 9.4 N.s and 6.4 N.s respectively. The relative momentum values for individual and combined free limbs are summarised in table 4.1.7. The contribution of the free limbs to the vertical momentum of the centre of mass was determined by expressing the free limbs total as a percentage of the peak vertical momentum of the centre of mass, see table 4.1.7. The results show that free limbs account for 10.8 % of the peak centre of mass vertical momentum.

The fact that the combined free limbs generated an average of 29.4 N.s (± 8.2) in the compression phase, or 91.6% ± 11.2 of the peak positive increase, suggests that the free limbs may assist the pivot mechanism in the generation of vertical velocity.

Table 4.1.7. Gain in positive relative momentum of the free limbs in the long jump take-off.

Relative Momentum (N.s)	Mean	SD
Co-Lateral Arm	9.4	2.2
Contra-Lateral Arm	6.4	3.1
Lead Leg	12.0	5.0
Free Limbs Total	32.1	7.6
Pk CM Momentum	297.6	23.8
FL Contribution (%)	10.8	2.3

ii) *Movement patterns*

The kinetograms in figures 4.1.11-13 show the average positions of the elbow and wrist (or knee and ankle) joint centres relative to the shoulder (or hip) joint in the sagittal and frontal planes. To aid understanding the contra-lateral arm and the lead leg have been plotted to represent the right hand side of the body and the co-lateral arm is the left side. Positive positions of the limb in the sagittal plane indicate that the segment is in front of the shoulder / hip joint. In the frontal plane positive positions indicate that the segment has moved across the body (adduction) and negative values indicate movement away from the body (abduction). Positions have been plotted at the instants of touch-down, maximum knee flexion (of the support leg), PEAK relative momentum and take-off. The angles of the upper arm and upper leg in the sagittal and frontal planes (measured to the downward vertical) and the elbow and knee angles have been presented at each of these instants in the accompanying tables.

Co-lateral arm

During the take-off phase the co-lateral arm moved in a back-to-front direction with marginal movement in the medio-lateral direction (figure 4.1.11) The upper arm moved forward through a range of 89.9° in the sagittal plane and abducted through 25.4°. Throughout the take-off the elbow remained flexed moving through a range of 17.6° from 97.6 to 80.0° (table 4.1.8).

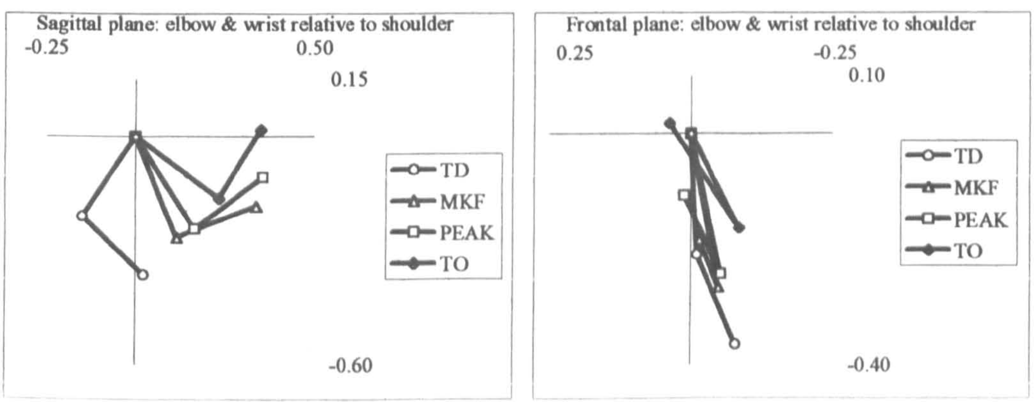


Figure 4.1.11. Mean co-lateral arm action in the sagittal and frontal planes (n=14). (TD = touch-down, MKF = maximum knee flexion, PEAK relative momentum and TO = take-off).

Table 4.1.8 Mean (±SD) upper arm and elbow angles of the co-lateral arm. (Upper Arm angles measured to the downward vertical)

Co-lateral Arm		Upper Arm angles (°)		Elbow
		Sagittal	Frontal	angle (°)
Touch-down	Mean	-36.1	-2.1	97.6
	SD	12.2	13.9	16.2
Maximum Knee Flexion	Mean	22.9	-10.5	90.4
	SD	13.8	7.6	14.7
PEAK relative momentum	Mean	34.5	-12.9	85.4
	SD	9.7	10.0	14.1
Take-off	Mean	53.9	-27.5	80.0
	SD	13.3	13.6	14.1
Touch-down to Takeoff	Mean	89.9	-25.4	-17.6
	SD	11.8	22.7	19.6

Contra-lateral arm

The action of the contra-lateral arm is very different to that of the co-lateral arm, figure 4.1.12. In the sagittal plane the arm moved in a front-to-back direction with the upper arm moving through a relatively smaller range of 62.4°. Although the upper arm abducted through a similar range to the co-lateral arm, 23.4°, it was in a far more abducted position at the instants of touch-down and take-off. Throughout the take-off phase the arm was straighter than the co-lateral arm. The elbow extended to 132.5° in the compression phase and then flexed through 18.4° to take-off with an elbow angle of 114.1°. A more pronounced displacement away from the body in the frontal plane with little vertical movement suggests that the contra-lateral arm has a function in maintaining balance. All athletes demonstrated this movement pattern which indicates that the arm action can be classified as single / arm and a half depending on the relative degrees of backward and lateral movement.

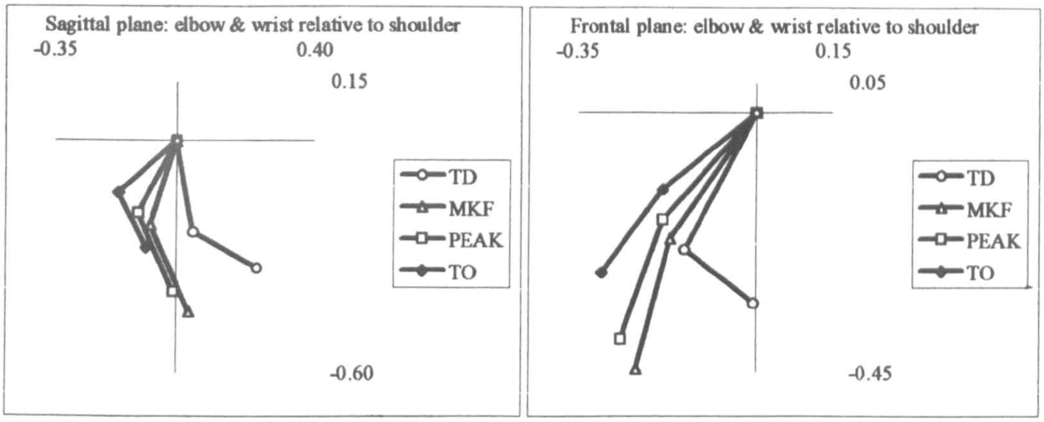


Figure 4.1.12. Mean contra-lateral arm action in the sagittal and frontal planes (n=14). (TD = touch-down, MKF = maximum knee flexion, PEAK relative momentum and TO = take-off).

Table 4.1.9. Mean (±SD) upper arm and elbow angles of the contra-lateral arm.

Contra-lateral Arm		Upper Arm angles (°) Sagittal	Frontal	Elbow angle (°)
Touch-down	Mean	11.3	-30.6	99.1
	SD	15.6	9.3	20.1
Maximum Knee Flexion	Mean	-19.4	-37.9	132.5
	SD	13.2	8.5	28.2
PEAK relative momentum	Mean	-30.8	-45.0	124.8
	SD	15.4	7.9	31.8
Take-off	Mean	-51.1	-54.0	114.1
	SD	17.4	14.2	38.1
Touch-down to Takeoff	Mean	-62.4	-23.4	14.9
	SD	24.0	15.9	33.1

Lead leg

The lead leg can be seen to move in a back-to-front direction adducting across the body in the extension phase. The upper leg rotated through a range of 100.1° between touch-down and take-off, starting slightly behind the body, -18.4°, and finishing in an almost horizontal position, 81.7°, (figure 4.1.13). By maximum knee flexion the knee joint is positioned well in front of the body, 42.5°, having flexed through 57.3° from 94.0° to 40.3°. Throughout the take-off the upper leg adducted through 67.2°, the majority of which occurred in the extension phase.

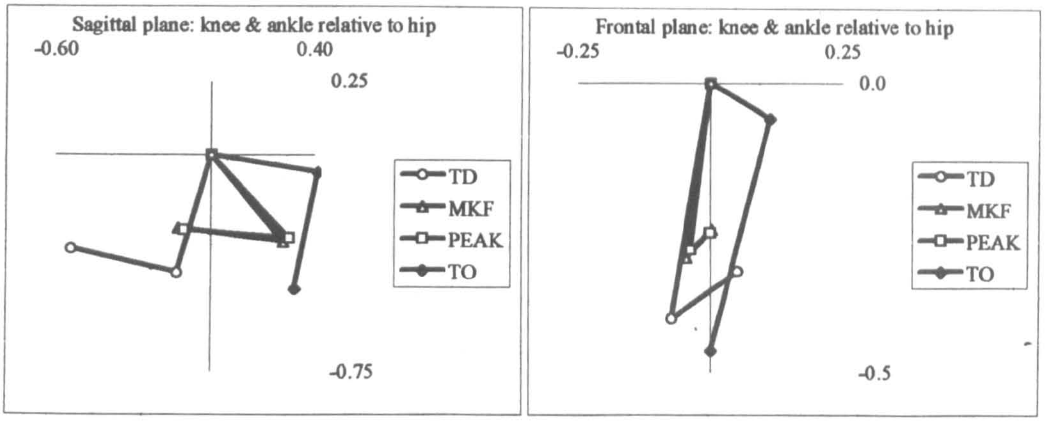


Figure 4.1.13. Mean lead leg action in the sagittal and frontal planes (n=14). (TD = touch-down, MKF = maximum knee flexion, PEAK relative momentum and TO = take-off).

Table 4.1.10. Mean (±SD) upper leg and knee angles of the lead leg.

Lead Leg		Upper Leg angles (°) Sagittal	Frontal	Knee angle (°)
Touch-down	Mean	-18.4	-10.2	94.0
	SD	7.3	5.2	14.1
Maximum Knee Flexion	Mean	42.5	-6.4	40.3
	SD	10.8	7.3	10.3
PEAK relative momentum	Mean	46.1	-4.6	39.7
	SD	6.9	7.9	8.9
Take-off	Mean	81.7	57.0	82.4
	SD	6.8	24.6	10.2
Touch-down to Takeoff	Mean	100.1	67.2	-11.6
	SD	8.8	24.1	17.5

4.1.3.3 Statistical analysis

An additional objective of this study was to assess the theoretical model (section 1.1) and relate important kinematic variables of leg placement, joint angle changes and the free limbs to the gain in vertical velocity during the long jump take-off. As vertical velocity is reported to be generated at the expense of a loss in horizontal velocity, (section 2.2), the same variables were examined for their association with the loss in horizontal velocity.

Relationships between selected kinematic variables and the gain in vertical velocity, $VY_{TD\text{-}TO}$, and the loss in horizontal velocity, $VX_{TD\text{-}TO}$.

The previous sections described the three-dimensional behaviour of the trunk, support leg, hip, knee and ankle joints and the kinematics of the free limbs. With the intention of relating such movements to the theoretical model described in section 1.1, and described elsewhere by Lees et al. (1993, 1994) and Alexander (1990), a summary of interesting characteristics of the long jump take-off is reported below.

Variable	*Definition and Comment*
$VY_{TD\text{-}TO}$	The change in vertical velocity during the take-off phase - athletes generate around 3.5 $m.s^{-1}$ in vertical velocity.

<u>Kinematic variables relating to pivot mechanism</u> – (these can be mapped on to the theoretical model in figure 1.2).

$Speed_{TD}$	Speed of the centre of mass at touch-down - athletes generate high speed prior to touch-down on the board.
Ax_{TD}	The angle of leg placement at touch-down - the support leg is planted in front of the centre of mass at touch-down, which is thought to act as a 'lever'.
$Height_{TD}$	The height of the centre of mass at touch-down - the centre of mass is in its lowest vertical position at the instant of touch-down
$Height_{TD\text{-}TO}$	The change in height during the take-off phase - the low centre of mass at touch-down enables a greater vertical range to move through during the take-off. The centre of mass is raised by 29 cm from touch-down to take-off.
Knee angle $_{TD}$	The knee joint is extended to 167° at the instant of touch-down.
Hip flexion angle $_{TD}$	The hip joint is extended to 146° at touch-down, which is facilitated by backward inclination of the trunk by 7.5°.
Hip extension $_{TD\text{-}TO}$	The hip joint extends throughout the entire take-off phase, with a mean range of 54°. The trunk rotates into a vertical position by the end of the compression phase, and thereby raising the centre of mass. This is likely to have a positive effect on the pivot action.
Knee angle $_{TD\text{-}MKF}$	The knee joint experiences a marked degree of flexion in the compression phase, with a mean of 26°. This is likely to have a negative effect on the pivot action.
Hip adduction $_{TD\text{-}MHA}$	The hip joint adducts through 4° following touch-down to its minimum hip adduction angle (MHA). This occurs prior to

maximum knee flexion, and is also likely to have a negative effect on the pivot mechanism.

<u>Kinematic variables relating to the free limbs</u>

Free Limbs Total	The increase in positive relative momentum of the free limbs during the take-off phase - the free limbs contribute 10.7% to the peak vertical momentum of the centre of mass, of which 91% is generated during the compression phase.

The kinematic observations stated above that are thought to relate to the theoretical model were tested for their association with the gain in vertical velocity, $VY_{TD\text{-}TO}$. Their individual levels of association are presented in Appendix IV.

The 10 variables above were entered into a 'best subsets' multiple regression analysis (Minitab, version 11, 1996). The analysis revealed that a combination of the height of the centre of mass at touch-down, the knee angle at touch-down, and the change in knee angle from touch-down-maximum knee flexion produced the best possible estimation of the gain in vertical velocity from touch-down to take-off, $VY_{TD\text{-}TO}$. All variables made a significant contribution to the relationship, P<0.005. The regression equation and summary statistics are presented below:

$VY_{TD\text{-}TO} = -5.046 - 6.732\ \text{Height}_{TD} + 0.099\ \text{Knee angle}_{TD} + 0.052\ \text{Knee angle}_{TD\text{-}MKF}$

(Note, the change in knee angle from touch-down to maximum knee flexion is expressed as a negative value).

Predictor	**Coef.**	**SD**	**t**	**P**
Constant	-5.046	2.351	-2.15	0.057
Height $_{TD}$	-6.732	1.720	-3.91	0.003
Knee angle $_{TD}$	0.099	0.017	5.96	0.000
Knee angle $_{TD\text{-}MKF}$	0.052	0.014	3.62	0.005

$SE_e = 0.202$ $R^2(adj) = 72.7\%$

$F = 12.52$ $P = 0.001$

The theory that a pivot mechanism operates during the long jump take-off, and that its effectiveness is influenced by the athletes ability to resist joint compression appears to be supported by the results of the multiple regression analysis. The predictive equation indicates that a low centre of mass and extended knee joint at touch-down, combined with the ability to resist knee flexion explains 72.7% of the variance in the gain in vertical velocity from touch-down to take-off. However, although this provides very good predictive values of the gain in vertical velocity, 27.3% of the variance remains unexplained.

It is often reported that vertical velocity is generated at the expense of losing horizontal velocity, (Nixdorf and Bruggemann, 1990; Lees et al., 1994). The relationship between the gain in vertical velocity and loss in horizontal velocity from touch-down to take-off was tested and revealed a coefficient of determination of 24.7%. This indicates that 75% of the variance in the gain in vertical velocity is not explained by the loss in horizontal velocity. During the compression phase, from touch-down to maximum knee flexion, the relationship was stronger, the loss in horizontal velocity explained 48.2% of the variance in vertical velocity. This implies that some aspects of technique may be more related to the loss or maintenance of horizontal velocity than their role in generating vertical velocity. A theory that the loss in horizontal velocity is also related to some of the factors believed to be associated with the gain in vertical velocity is therefore proposed. To assess this theory the same 10 variables were entered into a 'best subsets' multiple regression analysis to examine their association with the loss in horizontal velocity. Individual coefficients of determination are presented in Appendix IV.

For the athletes in this study, the results supported the theory. It was found that the loss in horizontal velocity is also associated with several of the variables outlined as possible factors relating to the generation of vertical velocity. A combination of the change in height of the centre of mass and the amounts of hip adduction and hip extension gave the best possible estimation of the loss in horizontal velocity from touch-down to take-off. The regression equation and summary statistics are presented below:

$$\begin{aligned} VX_{\text{TD-TO}} = &-0.370 - 4.40\ \text{Height}_{\text{TD-TO}} + 0.041\ \text{Hip adduction}_{\text{TD-MHA}} \\ &+ 0.008\ \text{Hip extension}_{\text{TD-TO}} \end{aligned}$$

(Note, the change in hip adduction angle is expressed as a negative value)

Predictor	Coef.	SD	t	P
Constant	-0.370	0.383	-0.97	0.356
Height $_{TD-TO}$	-4.40	1.107	-3.97	0.003
Hip adduction $_{TD-MHA}$	0.041	0.009	4.67	0.000
Hip extension $_{TD-TO}$	0.008	0.004	2.04	0.069

$SE_e = 0.101$ $R^2(adj) = 84.5\%$

$F = 24.66$ $P = 0.000$

The results indicate that the 3 predictor variables explain 84.5% of the variance in the loss in horizontal velocity from touch-down to take-off. The remaining 15.5%, however, remains unexplained.

Relationship between approach speed and effective distance

A further objective of this study was to examine whether the strength of the relationship between approach speed and long jump distance could be improved upon by taking into account aspects of technique during the take-off phase.

This study determined approach speed in two ways: i) taking the average speed over 11 to 1 m from photo-electronic timing light data, and ii) taking the speed of the centre of mass at touch-down on the board from digitised co-ordinate data. A comparison between the two methods found an R^2 value only 9.2% between the two methods. As the latter is an instantaneous value, and the former is an average over a 10 m interval, then the low association may be due to athletes accelerating or decelerating in the final few strides of the approach. However, both methods were found to exhibit similar coefficients of determination with the effective distance, with R^2 values of 25.4% and 24.6% respectively. The fact that 75% of the variance in the effective distance remains unexplained lends support to the theory that take-off technique and the ability to utilise approach speed effectively become relatively more important than approach speed at an elite level. This is supported by an even smaller coefficient of determination between the speed at take-off and the effective distance, ($R^2 = 16.5\%$).

As the speed of approach is regarded as the most important factor in long jump performance, it was decided to test the theory above. The speed of the centre of mass at touch-down was combined with several 'take-off' variables in an attempt to increase its association with the effective distance. In this respect, there would be an 'input' variable (Speed $_{TD}$), several take-off 'action' variables representing the movements on the board, and an outcome variable, the effective jump distance. The take-off 'action' variables were chosen on the basis of the deterministic model, which highlights the projectile parameters, (figure 1.1, page 3). The height and the speed of the centre of mass at take-off can be broken down into their touch-down values plus their respective changes during the take-off. The variables chosen to represent the take-off phase were therefore the changes in height and speed of the centre of mass between touch-down and take-off, (Height $_{TD\text{-}TO}$, Speed $_{TD\text{-}TO}$), and the projection angle of the centre of mass at take-off. It was felt that these variables best described the take-off phase, i.e. raising the height of the centre of mass from its low position at touch-down and accounting for the interaction between vertical and horizontal velocity.

A 'best subsets' multiple regression analysis was performed which indicated that all four predictor variables generated the largest R^2(adj). However, the fourth variable (projection angle) was not significant (P=0.115), and considering the ratio of subjects to predictor variables, then only 3 predictors were used. The regression equation and statistical summary is presented below:

Effective distance = 1.396 + 0.485 Speed $_{TD}$ + 5.836 Height $_{TD\text{-}TO}$ + 0.655 Speed $_{TD\text{-}TO}$

(Note, Speed $_{TD\text{-}TO}$ is expressed as a negative value)

Predictor	**Coef.**	**SD**	**t**	**P**
Constant	1.396	1.348	1.04	0.325
Speed $_{TD}$	0.485	0.130	3.74	0.004
Height $_{TD\text{-}TO}$	5.836	1.364	4.28	0.002
Speed $_{TD\text{-}TO}$	0.655	0.235	2.78	0.019

$SE_e = 0.107$ R^2(adj) = 65.5%

F = 9.24 P = 0.003

The theory that elite long jumpers require good take-off technique in addition to a fast approach run is supported by the results of the multiple regression analysis. Compared to the relationship between the speed of touch-down and the effective jump distance, which was found to have a coefficient of determination of $R^2 = 24.6\%$, by taking into account the increase in height and the loss in speed of the centre of mass during the take-off, the coefficient of determination increased to an $R^2(adj)$ value of 65.5%. This means that the combination of the speed of the centre of mass at touch-down, and the changes in height and speed of the centre of mass during the take-off explain 65.5% of the variance in the effective distance. However, while this gives good predictive values of the effective distance, 34.5% of the variance in effective distance remains unexplained.

The theory, which is supported by the predictive equation, indicates that longer effective distances are associated with a fast approach speed and a technique that encourages the greatest possible gain in height and a minimal loss in speed of the centre of mass. In order to have a large increase in height the centre of mass must adopt a low position at touch-down and a high upright position at take-off. The maintenance of speed is related to the interaction between vertical velocity gained and horizontal velocity lost during the take-off.

Validity of the multiple regression equations

The three multiple regression equations were checked for validity on the 2nd best performance of 7 of the athletes. Validity was checked between actual and predicted values using three methods, table 4.1.11. The coefficients of determination were smaller than for the original data, but were all sufficiently large to explain between 52% and 65% of the variance in the independent variables. The limits of agreement found only small differences between the predicted and actual measurements, none of which were significant. The gain in vertical velocity was underestimated by 0.11 $m.s^{-1}$, the loss in horizontal velocity overestimated by 0.12 $m.s^{-1}$, and the effective distance was overestimated by 7 cm. These differences and the 95% error limits are reasonable for the variables being analysed. The three regression equations can therefore be regarded as valid.

Table 4.1.11. Validity of the multiple regression equations (n=7).

	Actual Mean ± SD	Predicted Mean ± SD	R^2 (%)	t	P	Limits of agreement
Vertical Velocity $_{TD-TO}$ ($m.s^{-1}$)	3.52 ± 0.26	3.41 ± 0.29	64.9	1.67	NS	-0.11 ± 0.35
Horizontal Velocity $_{TD-TO}$ ($m.s^{-1}$)	-1.30 ± 0.23	-1.42 ± 0.26	51.9	1.65	NS	-0.12 ± 0.37
Effective Distance (m)	7.41 ± 0.18	7.48 ± 0.17	60.1	-1.63	NS	0.07 ± 0.23

4.1.4 Discussion

It was shown in the results section that the effective long jump distance could be estimated from the speed at touch-down, and the change in height and speed of the centre of mass from touch-down to take-off. The theory that actions on the board become relatively more important to elite long jumpers than just relying on approach speed is therefore supported. The objective of the long jump take-off phase therefore appears to be to raise the centre of mass through the greatest possible range and to minimise the loss in speed of the centre of mass. The latter requires the athlete to generate vertical velocity without losing excessive amounts of horizontal velocity. This study has attempted to identify the key elements of technique that may serve to fulfil the objectives of generating vertical velocity and minimising the loss in horizontal velocity.

Relationship between the gain in vertical and the loss in horizontal velocity.
The generation of vertical velocity generally occurs at the expense of losing some of the horizontal velocity developed in the approach, and this was shown graphically in figure 4.1.4. The greatest gain in vertical velocity occurs during the compression phase, which accounts for 69.8% of the total gain between touch-down and take-off. The average gain in vertical velocity from touch-down to maximum knee flexion was 2.47 $m.s^{-1}$ and this corresponded to a loss of 1.30 $m.s^{-1}$ in horizontal velocity. The coefficient of determination between the gain and loss in vertical and horizontal velocity during the compression phase provides evidence to support this theory. An R^2 value of 48.2%

indicates that approximately half of the variance in vertical velocity can be explained the loss in horizontal velocity. These gains and losses are similar to those reported by Nixdorf and Bruggeman (1990), but are somewhat greater than the values of 2.02 and 1.02 $m.s^{-1}$ reported by Lees et al (1994). The athletes used in this study would therefore appear to base their technique more on generating vertical velocity than on maintaining horizontal velocity. In the extension phase some athletes demonstrated an ability to recover a small amount of horizontal velocity. This led to a weaker relationship between the gain in vertical velocity and loss in horizontal velocity from touch-down to take-off ($R^2 = 24.7\%$). The average gain in vertical velocity from touch-down to take-off was 3.54 $m.s^{-1} \pm 0.39$ with a corresponding loss in horizontal velocity of 1.38 $m.s^{-1} \pm 0.26$.

The study has used the theoretical model, outlined in section 1.1, to identify aspects of technique that relate to the generation of vertical velocity. The model indicates that athletes lower their centre of mass during the last few strides which allows them to strike the board with an extended support leg positioned well in front of the centre of mass at touch-down. Coupled with a fast approach, the support leg then acts as a pivot or lever whereby the body rides over the foot, raising the height of the centre of mass and generating vertical velocity. The theory acknowledges that vertical velocity is generated at the expense of a loss in horizontal velocity, and believes that the effectiveness of the 'pivot' mechanism is influenced by the ability of the athlete to resist compression of the knee and hip joints, (Lees et al., 1994). The kinematic variables relating to the pivot mechanism were identified and listed in section 4.1.3.3.

The 'pivot' mechanism

Several studies have reported the existence of a pivot mechanism acting in the long jump (and high jump) take-offs (Bosco et al., 1976; Dapena and Chung, 1988; Koh and Hay, 1990; Lees et al., 1994). However, various definitions as to when the pivot stops operating have been suggested and as such some confusion exists. Bosco et al. (1976) defined it to act from the point of touch-down to the instant in which an imaginary line from the centre of mass to the point of application of the ground reaction force reached a vertical position. This definition is acceptable if one can obtain the 'point of application' coordinates from a force platform as they did. This definition becomes less usable in kinematic analyses where such a point cannot easily be identified. Alternative measures have therefore been adopted in kinematic studies and these generally relate to the end of the compression phase, i.e. the minimum radial distance (Dapena and Chung, 1988) or the instant of maximum knee flexion (Lees et al., 1993, 1994).

Lees et al. (1993, 1994) made reference to the ankle joint as the point where the body pivots over the foot. Therefore, in order to draw a parallel with the definition of Bosco et al. (1976), the end of the pivot would be when the centre of mass is directly above the point of support, i.e. the ankle joint. This relates to the instant when the touch-down distance is zero, (variable Dx_{TD} in figure 4.1.5). In table 4.1.3 it can be seen that the centre of mass was 3 cm ± 5 behind the ankle joint at maximum knee flexion, but had a range of 15 cm behind to 4 cm in front of the ankle. Clearly, the instant of maximum knee flexion cannot be used as a consistent indicator of the end of the pivot action. It can also be argued that the body not only pivots about the ankle joint, but about the toes as well. From observation of cine-film during the digitising process, all athletes made contact with the heel and within 0.01 s (one frame) the forefoot was firmly planted on the board. The ankle joint then begins to dorsi-flex and this continues to dorsi-flex for a further 0.02 s after maximum knee flexion as the body and lower leg continues to rotate forwards, (figure 4.1.9 a). In figure 4.1.14, the horizontal distances between the centre of mass and the ankle (Dx) and the toe (Tx) have been plotted, where positive values indicate that the centre of mass is behind the ankle or toe. The instant at which the centre of mass is directly above the toe (Tx=0) occurs after the instant of 'minimum ankle angle'. Therefore as the ankle begins to plantar-flex and the heel is lifted off the track the body then pivots about the toe. The pivot action lasts for approximately 66% of the support phase.

Compared to using the instant of maximum knee flexion, a greater loss in horizontal velocity was found between touch-down and Tx=0 (-1.44 ± 0.24 m.s^{-1}), and a small gain in horizontal velocity was found between Tx=0 and take-off, (0.05 ± 0.14 m.s^{-1}). The latter was not apparent when using the instant of maximum knee flexion. This is supported by Tiupa et al. (1982), cited by Koh and Hay (1990), who stated that the horizontal ground reaction force is thought to oppose the forward motion of the athlete when the hip of the support leg is behind the foot, and facilitate that motion when the hip is in front of the foot. Therefore, the instant at which the centre of mass is directly above the toe provides a better reflection of the pivoting action on two counts:

i) it is more consistent with the definition of Bosco et al. (1976), and

ii) this point best describes the braking and drive-off characteristics of the athlete which are noticeable characteristics on the horizontal force trace in long jumping (Ramey, 1970).

The pivot action is therefore representative of the braking effect on the centre of mass, while the drive-off represents a 'push' off the board and a small recovery of horizontal velocity.

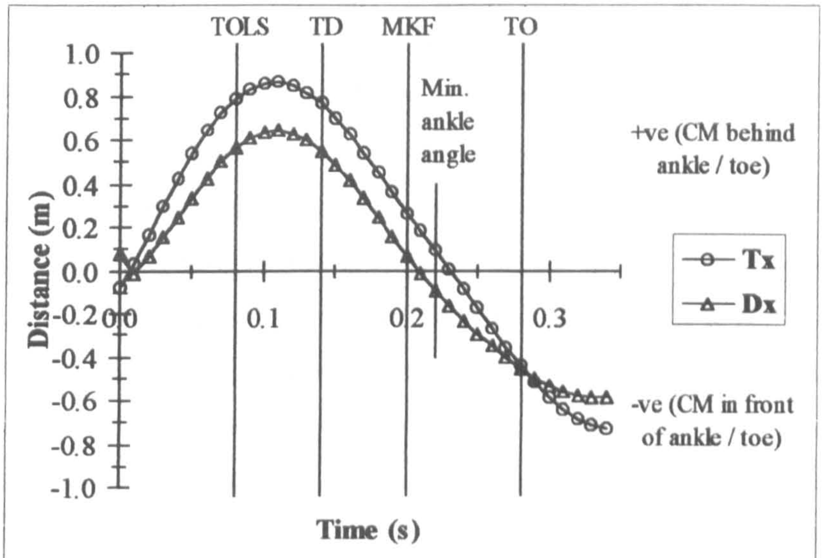


Figure 4.1.14. Graph depicting the two stage pivot mechanism (mean n=14).

The instant of maximum knee flexion is a very useful indicator of the end knee compression, but using this instant to mark the end of the pivot action under-estimates the contribution of the pivot mechanism. For example, from maximum knee flexion to the instant the centre of mass is directly above the toe, the height of the centre of mass was raised by a further 0.07 ± 0.02 m and an additional gain of 0.83 ± 0.26 $m.s^{-1}$ was found in vertical velocity. By the instant that the centre of mass was above the toe, (hereby known as the end of the pivot action), 93.3% of the total gain in vertical velocity (touch-down to take-off) had been attained. As the pivot mechanism extends into the extension phase, it must therefore be supplemented by activity of the free limbs and some knee extension. The assumption made by Lees et al. (1993, 1994), that the pivot mechanism acts in the compression phase, while the free limbs, concentric muscular contraction and stretch - shorten cycle enhancement act in the extension phase, therefore appears to be an over simplification of the long jump take-off phase. However, the benefit of using the instant of maximum knee flexion is that it separates the functions of knee joint compression and extension and gives an insight to the eccentric and concentric strength capabilities of the athlete.

Effect of the free limbs

The positive increase in the relative momentum of the combined free limbs was 32.1 N.s which was found to occur at, or shortly after the instant of maximum knee flexion. The peak vertical momentum of the centre of mass was 297.6 N.s (assuming body mass of 85 kg) which occurred just prior to take-off. The average contribution of the free limbs to vertical momentum of the athlete was therefore 10.8%. It was observed in figure 4.1.10 that the majority of positive relative momentum of the free limbs had been attained by the end of the compression phase, 29.4 N.s (9.9% of the peak vertical momentum of the centre of mass). This indicates that the pivot mechanism does not operate in isolation during the compression phase, as was originally proposed by Lees et al. (1993, 1994). The free limbs therefore have the potential to enhance the pivot action. However, it has been suggested that the vertical acceleration of the free limbs will impose a greater strain on the support leg muscles, Lees and Barton (1996). Therefore, if athletes do not have sufficient eccentric strength then their free limb movements may have a negative effect on the pivot mechanism, as this might cause greater joint flexion. This theory is supported by a large coefficient of determination of 35.5% between the positive increase in relative momentum of the free limbs and the amount of knee flexion from touch-down to maximum knee flexion. This indicates that 35.5% of the variance in the amount of knee flexion can be explained by the relative momentum generated by the free limbs during the compression phase, but 64.5% of the variance remains unexplained.

By the end of the pivot action, the contribution of the free limbs to the peak vertical momentum of the centre of mass had increased to 10.3%. Subtracting the contribution made by the free limbs from the percentage gain in vertical velocity from touch-down to the end of the pivot action, effectively quantifies the contribution of the pivot mechanism to be 83.0% (93.3% - 10.3%). As the centre of mass passes over the toes, the remaining

6.7% contribution to the gain in vertical velocity must be attributed directly to concentric muscular contractions and joint extension and the final movements of the free limbs.

Kinematic variables relating to the gain in vertical velocity and loss in horizontal velocity

Body position at touch-down

Several studies have analysed the technique of long jumpers in the last few strides of the approach. The lowering of the centre of mass and the placement of the touch-down leg in an extended position in front of the centre of mass at touch-down are considered to be two of the most important characteristics of long jump technique, (Hay and Nohara, 1990; Lees et al., 1994). Both these characteristics were observed in this study. It is apparent that the lowering of the centre of mass facilitates an outstretched leg in front of the body. Clearly, if the athlete adopted an erect, upright position at touch-down it would be impossible to plant the leg in front of the body, rather, the leg would be directly under the body. The variable used to describe the extended leg position in front of the body at touch-down was the touch-down angle (Ax_{TD} in figure 4.1.5).

Undoubtedly, a low centre of mass at touch-down is the major facilitator of a large touch-down angle. However, the advantage of using a 3D kinematic analysis is that factors outside the sagittal plane can also be quantified to examine their influence on this aspect of technique. Such a factor may be the angle of hips in the transverse plane which showed a noticeable angle of backward rotation at touch-down, (see Hip rotation angle in table 4.1.5). As the lead leg is attached to the rear hip joint, then this would effectively position the lead leg further behind the body. Consequently, this will shift the centre of mass of the whole body backwards, and as the centre of mass is a reference point for this measure, then a greater angle of leg placement will result. The position of the other reference point, the ankle joint, also affects the touch-down angle and this would be influenced by the amount of knee extension. Greater knee extension at touch-down would also increase the leg placement angle.

The average value for the touch-down angle in this study was 32.2° with a range of 27.0° to 34.4°. The data compared favourably with that of Nixdorf and Bruggeman

(1990) who found an average angle of 29.9° with a range of 26.6 to 31.5°. The touch-down angle in Nixdorf and Bruggeman's study was defined slightly differently, (the heel was used as a reference point rather the ankle joint) and so the values obtained in this study would be expected to be slightly greater than theirs. Lees et al. (1994) found the average touch-down angle to be 24.7° which is considerably smaller than the data obtained in this study. However, from the previous discussion the athletes examined in their study did not generate as much vertical velocity and lost less horizontal velocity compared to the athletes in the present study. This provides some evidence to support the theory that greater angles of leg placement at touch-down relate to greater gains and losses in vertical and horizontal velocity, Alexander (1990).

This theory was tested and the results provided some evidence to support it. For the athletes in the present study the significance of the leg placement angle at touch-down was found to be more associated with the loss in horizontal velocity than the gain in vertical velocity. The angle of leg placement at touch-down was found to account for 11.2% (R^2) of the variance in the gain in vertical velocity, and 31.9% of the variance in the loss in horizontal velocity. The latter supports the theory Alexander (1990) that greater angles of leg placement can lead to greater losses in horizontal velocity. A greater angle of leg placement at touch-down indicates that the centre of mass is further behind the ankle joint, and in a lower vertical position. The further the centre of mass is behind the point of support then the longer the braking effect will last, leading to a greater loss in horizontal velocity. However, the fact that 88.8% and 68.1% of the variances in the gain in vertical velocity and the loss in horizontal velocity remains unexplained, indicates that other factors also influence the changes in horizontal and vertical velocity. These factors are likely to relate to the body position at touch-down and actions during the take-off.

The knee extension angle at touch-down was proposed in the theoretical model to be one such characteristic. This aspect of technique was noted by Fukashiro et al. (1993) after analysing the contrasting jumping styles of Mike Powell and Carl Lewis at the 1991 World Championships. Powell's greater knee extension angle at touch-down (171°) was one of several factors attributed to his greater vertical velocity at take-off (3.70 $m.s^{-1}$).

Lewis based his technique on maintaining horizontal velocity, adopting a more flexed knee at touch-down (165°) and generating less vertical velocity ($VY_{TO} = 3.22$ m.s^{-1}). The coefficient of determination between the knee extension angle and the gain in vertical velocity found an association of 34.1%. In terms of the loss in horizontal velocity the level of association was lower, the touch-down angle accounting for 12.0%. These values support the theory that greater angles of knee extension at touch-down facilitate the generation of vertical velocity, and more flexed knee joints at touch-down are more associated with the maintenance of horizontal velocity. However, in terms of their predictive qualities 65.9% and 88.0% of the variances in the changes in vertical and horizontal velocity remain unexplained.

It was noted earlier that the hip began extension prior to touch-down and this continued throughout the entire take-off phase. At touch-down the average hip extension angle was 146° and this depends on the inclination of the trunk and the angle of the thigh in the sagittal plane. The need for an extended leg position in front of the centre of mass at touch-down requires the thigh to be at an angle of approximately 40.6° to the downward vertical (table 4.1.3). The trunk, however, was found to have an average backward inclination of 7.5° at touch-down (table 4.1.3). In terms of the relationship between the hip extension angle at touch-down and the changes in vertical and horizontal velocity the association was small accounting for only 8.1% and 3.3% of the variances respectively.

Joint angle changes

The lack of a significant relationship between the gain in vertical velocity and the change in knee joint angle $_{TD\text{-}MKF}$ led Lees et al. (1994) into the assumption that adduction actions of the hip joint may influence the effectiveness of the body to 'pivot' over the foot in the compression phase. This study attempted to clarify the three dimensional behaviour of the hip and knee joints and relate these changes to the changes in vertical and horizontal velocity. Larger amounts of compression denoted by greater changes of the hip and knee joint angles would be expected to limit the athlete's ability to generate vertical velocity.

The change in knee angle from touch-down to maximum knee flexion was not found to be directly associated with the gain in vertical velocity (r =-0.065, R2 = 0%). However, when entered into the multiple regression analysis its contribution was found to be significant. As the knee angle at touchdown was also a significant factor in predicting the gain in vertical velocity, the amount of knee flexion experienced modified the relationship and 'weighted' their contributions accordingly. The multiple regression analysis revealed that a greater gain in vertical velocity is associated with a technique that emphasises a low centre of mass at touch-down, a well extended knee joint at touch-down and the ability to resist flexion of the knee joint during the compression phase (R^2(adj) = 72.7%, P<0.001). The observations of Fukashiro et al. (1993) support such a theory. They noted that Mike Powell and Carl Lewis experienced similar amounts of knee flexion, 23° and 25° respectively, but attributed Powell's greater vertical velocity to a technique that was characterised by greater knee extension, lower centre of mass and greater trunk inclination at touch-down, and greater hip rotation throughout the take-off. Therefore, in its most flexed position, Powell's knee joint would be more extended than Lewis'. A more extended knee joint at maximum knee flexion will create a stronger and more rigid lever arm which will help to produce a more effective 'pivot' action and greater amounts of vertical velocity. It would appear that the possible detrimental effects of knee compression can be overcome by having a more extended knee joint at touch-down. The effectiveness of the pivot mechanism is therefore affected by the ability to resist knee flexion as originally postulated by Lees et al. (1994).

In the frontal plane, one athlete managed to resist hip adduction, but all other athletes adducted up to 10.6°. The amount of hip adduction experienced from touch-down to its minimum angle was found to be a strong predictor of the loss in horizontal velocity, R^2 = 64.2%, but less strong in predicting the gain in vertical velocity, R^2 = 11.4%. Based on the theoretical model, the results indicate that excessive adduction of the hip joint could have detrimental effects on both horizontal and vertical velocity changes. Ultimately this would cause greater losses in speed during the take-off. The strength of the relationship for the loss in horizontal velocity was improved using a multiple regression analysis. The results indicated that the loss in horizontal velocity is associated with the change in height of the centre of mass, and the amounts of hip adduction and extension. Greater hip extension facilitates the maintenance of horizontal velocity, which can be related to the activeness of the support leg, i.e. the horizontal movement of the ankle relative to the centre of mass. For the athletes in this study, this combination was found to account for 82.6% of the variance in the loss in horizontal velocity. However, 17.4% of the variance remains unexplained. The inability to resist hip adduction is likely to cause more medio-lateral movement of the centre of mass. However, it was observed in table 4.1.4 that the centre of mass stayed almost directly above the ankle joint (point of support) throughout the entire take-off phase. This implies that the free limbs, and in particular the contra-lateral arm, abduct more in order to preserve this 'balance', (see figure 4.1.12).

It might have been expected that weaker athletes would flex at the hip following impact with the board, but this was not the case. All athletes were found to commence hip extension prior to touch-down and this continued throughout the entire take-off phase. The role of hip extension would therefore appear to facilitate an 'active' leg placement, where the leg is swept backwards relative to the centre of mass, and help to minimise the loss in horizontal velocity. In terms of developing vertical velocity, hip extension would appear to work against to negative effects of knee flexion and hip adduction, and assist in raising the height of the centre of mass. However, a significant negative relationship between hip extension from touch-down to take-off and the gain in vertical velocity challenges such a theory ($r = -0.608$, $R^2 = 37.0\%$). This unexpected relationship suggests that less hip joint extension is associated with greater gains in vertical velocity. However, taking into account the positions of the trunk and the thigh at touch-down in the sagittal plane can explain this. The thigh is required to be extended in front of the body to provide the pivot, but the trunk was observed to be inclined to the rear, typically between 2° and 13°. Athletes who have less backward inclination of the trunk and a smaller angle of leg plant at touch-down are able to extend the hip through a greater range during the take-off because the hip is more flexed at touch-down. This implies that the inclination of the trunk in the sagittal plane is a key element of technique, which is supported by the observations of Keller (1974), cited by Hay (1986), and Fukashiro et al. (1993). Keller (1974) noted that, for each athlete analysed, the trial in which the trunk was most inclined at touch-down produced the longest effective distance. In that study the trunk angle ranged from a backward inclination of 17° to a forward inclination of 2°. Fukashiro et al. (1993) noted that greater backward inclination of the trunk was another aspect of Mike Powell's technique compared to Carl Lewis, and this facilitated a greater vertical velocity at take-off. However, neither study offered an explanation as to why this aspect of technique was significant. The benefits of an inclined trunk at touch-down are that:

i) it effectively positions the centre of mass of the trunk, head and arms further away from the point of support, and will ultimately lead to a greater leg placement angle at touch-down;

ii) it helps put the centre of mass in a lower position at touch-down, giving the body a greater range in which to raise the centre of mass and to generate vertical velocity; and

iii) the hip is in a more extended position at touch-down and is therefore in a stronger position to resist flexion.

The kinematic analysis noted that during the compression phase the trunk rotated into a vertical position and remained upright during the extension phase. Such a position would seem to be optimal as the centre of mass of the trunk would be in its highest vertical position. Rotation of the trunk beyond the vertical axis would negate the effect, as this would cause the height of the centre of mass to be lowered. To encourage forward rotation of the trunk could be seen to encourage hip flexion and this is clearly not the case. Although trunk rotation was observed, this is more likely to be a factor of the whole body pivoting about the point of support and through extension of the hip joint.

4.1.5. Conclusion

The three-dimensional analysis conducted in this study has provided a greater insight into the movement patterns of male long jumpers not only in the sagittal plane, but in the frontal and transverse planes also. Where previous studies have only described several characteristics of frontal and transverse plane movements, this study has investigated their significance in relation to performance. The experimental data taken from 14 jumps ranging from 7.14 to 7.84 m has provided evidence to support theoretical models proposed in the literature (Alexander, 1990; Lees et al., 1993 and 1994) and outlined in section 1.1. Regression analyses have produced formulas to estimate the effective distance, and the gain and loss in vertical and horizontal velocity of the centre of mass throughout the support phase.

The experimental model has shown that long jumpers attain the greatest effective distances when they combine a fast approach run with a technique that emphasises raising the centre of mass through the greatest possible range and minimising the loss of speed during the take-off. A fast approach represents the objective of the approach phase while the change in height of the centre of mass and the loss of speed represent aspects of technique during the take-off. The loss in speed of the centre of mass during the take-off is dependent on the interaction between a loss in horizontal velocity and a gain in vertical velocity of the centre of mass.

The three-dimensional kinematic analysis of the support leg, trunk and the free limbs highlighted a range of characteristics that were possible factors in generating vertical velocity and minimising the loss in horizontal velocity. The results provided evidence to confirm previous research findings that gains in vertical velocity are accompanied by losses in horizontal velocity. However, for the athletes in this study, some variables were more related to enhancing vertical velocity, while others were more related to the maintenance of horizontal velocity. In terms of generating vertical velocity the most important factors were found to be a low centre of mass a touch-down, a well extended knee joint and the ability to resist flexion of the knee during the compression phase. A strong lever is thus produced which facilitates greater vertical displacement and vertical velocity. As for the loss in horizontal velocity, the results found that the greater the angle of leg placement at touch-down was a major predictor. In addition to this, the magnitude of hip adduction and extension and the increase in height from touch-down to take-off were also strong predictors of the loss in horizontal velocity. Hip adduction is likely to create more lateral movement which would effectively slow the athlete down in the forward direction, while hip extension can reduce the braking effect and limit the loss in horizontal velocity.

One could speculate that athletes who base their technique on generating vertical velocity may benefit from prolonging the braking / pivot phase. A longer braking phase would result from placing the centre of mass as far behind the ankle / toe at touch-down, giving a greater range in which to pivot. This is achieved through a lower centre of mass, greater leg extension, greater knee joint extension, greater hip rotation and greater trunk inclination at touch-down. The pivot will work effectively if the athlete has sufficient eccentric strength to resist knee flexion and hip adduction. Athletes who wish to maintain their horizontal velocity may benefit from smaller leg placement angles, allowing them to end the braking phase sooner and increase the potential to recover relatively more horizontal velocity during the drive-off phase.

The results provided evidence to dispute the theory of Lees et al. (1994) that the pivot mechanism operates in isolation during the compression phase. Results also indicated that the pivot effect did not finish until mid-way through the extension phase, when the centre of mass was directly above the toes of the support leg. The long jump take-off phase is therefore more complex than originally proposed by Lees et al. (1993, 1994) and the separation of the four mechanisms becomes more complicated. The pivot mechanism was found to contribute 83.0% to the total gain in vertical velocity, but this is supplemented by stretch-shorten cycle enhancement and some joint extension. The contribution made by the free limbs was quantified to be 10.7%.

4.2 A three-dimensional analysis of the triple jump take-offs.

4.2.1 Introduction

The majority of work investigating jumping for distance has examined the long jump. The theories regarding the generation of vertical velocity in the long jump take-off have been applied to each phase of the triple jump. The mechanisms for the generation of vertical velocity are outlined in section 1.1. Whilst it is likely that the same mechanisms operate in all jumps, the literature indicates that each take-off in the triple jump has characteristic differences, (Verhoshanski, 1961, cited by Hay, 1992; Koh and Hay, 1990b). It is possible that characteristic differences in technique will influence the contribution that each mechanism makes to the generation of vertical velocity.

Whilst a limited number of two-dimensional analyses have been conducted on the triple jump, and one in the frontal plane (Bober, 1974), there have been no reports in the literature of full three-dimensional investigations. As discovered in section 4.1, three-dimensional analyses need to be conducted if the exact nature of the event is to be revealed.

The aims of this study were: i) to quantify the three-dimensional kinematics of the support leg, trunk and free limbs in the hop, step and jump take-offs, and ii) to quantify the contributions made by the pivot mechanism and the free limbs in each take-off. These aims collectively fulfil the requirements of objectives 2 and 3 in section 1.2. In addition, the functions of each take-off are assessed by comparing kinematic characteristics of the hop, step and jump take-offs with those of the long jump in section 4.1.

4.2.2 Method

The finalists of the 1995 UK National Championships men's triple jump were filmed using two high speed 16mm cine-cameras (Locam and Photosonics). One camera (Photosonics) was placed in the stand, approximately 20 m from the runway and in line with the 6 m mark. The stand produced an elevation of about 10 m. This camera was panned to capture each take-off. The second camera (Locam) was placed about 40 m in front and approximately 5 m to the side of the landing pit. This camera was kept stationary as each take-off could be seen from the one camera view. The angle between the optical axes therefore changed as the Photosonics camera was panned. For the hop take-off the angle between the optical axes was approximately 55°, for the step 75° and for the jump take-off 95°, see figure 4.2.1. Both cameras were set to record at a frequency of 100 Hz. Control markers were positioned alongside the track to compensate for movement of the camera. The calibration frame was recorded on both cameras in ten locations spanning the 13 m between the board and the landing pit. This meant that a 3D volume could be reconstructed at any position down the track to correspond to where the athlete landed. Digitising equipment included a NAC cine projector and a TDS digitising tablet operating through an Acorn A3000 computer. The film was digitised using the software developed by Bartlett and Bowen (1993). The 3D volume was reconstructed using the DLT technique and the centre of mass location was calculated using a 14 segment model defined by 18 points and segmental data proposed by Dempster (1955), Appendix II. The hop, step and jump take-off phases of 7 complete performances (the best jump collected per athlete) were digitised 3 times each and the mean processed data was taken to reduce errors. Velocity characteristics were calculated by direct differentiation, Lees (1980). An alternative method used to calculate touch-down and take-off velocities was presented by Miller and Hay (1986) which was based on projectile theory. These methods were compared, the results of which showed good agreement with the average difference generally being less than 0.2 $m.s^{-1}$, (Appendix IV).

The software did not compensate for the effects of panning a camera. To assess the possible effects of panning one camera the coordinates of a known stationary point (front left of the take-off board) in the jump take-off (panned, n=7) were compared to the same point in the long jump take-off (stationary, n=6). The jump phase was chosen because the optical axes of the cameras were similar to the long jump set-up. When both cameras were kept stationary the coordinates of the stationary point were found to have ranges of 7.3 mm, 4.6 mm and 8.1 mm in the X, Y and Z directions, i.e. digitising error. In comparison when one camera was panned the coordinates of the stationary point were found to have ranges of 11.1 mm, 9.1 mm and 5.6 mm in the X, Y and Z directions. The effects of panning the camera therefore creates approximately 4 mm more error in the X and Y directions, but 2.5 mm less error in the Z direction. In addition the percentage error of these deviations compared to the dimensions of the reconstructed area are still minimal, (0.44%, 0.36% and 0.23% in the X, Y and Z directions respectively). In the light of these findings the effect of panning one camera has been shown to have a minimal effect and as such this method appears to be viable.

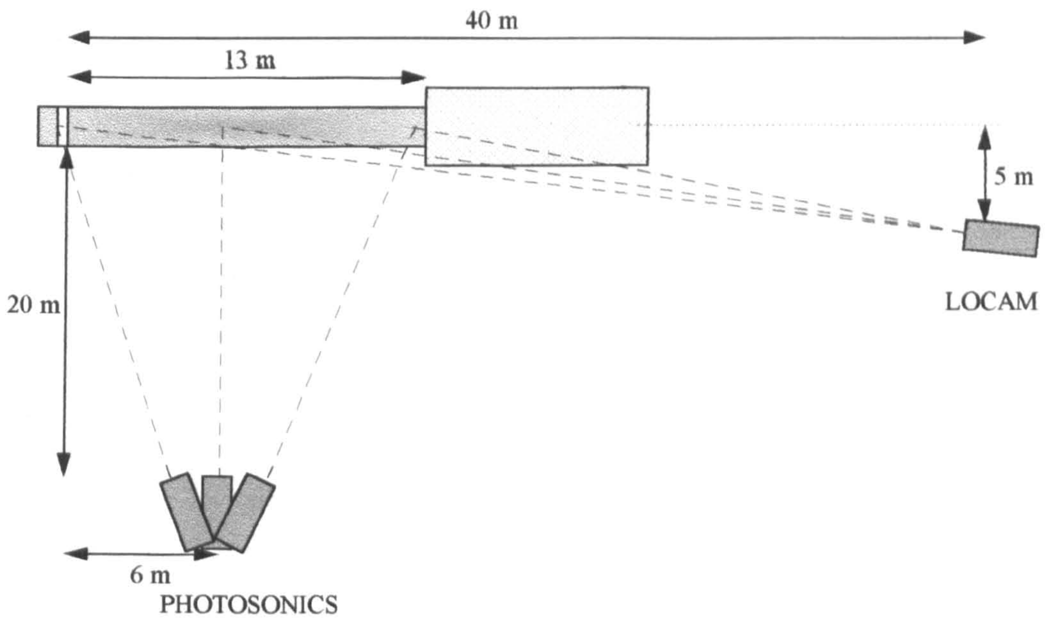


Figure 4.2.1. Camera set-up for the 3D analysis of the triple jump.

Prior to statistical analysis all data was checked for normality using the skewness and kurtosis measures outlined by Vincent (1995). Statistical comparisons of the hop, step and jump take-offs were then made using a one-way ANOVA with repeated measures (stacked design, Minitab version 11, 1996). Tukey's HSD post-hoc test was performed to identify where significant differences lay. Comparisons between kinematic characteristics of the long jump (section 4.1) with each of the triple jump take-offs were analysed using t-tests for independent samples. The variables chosen for comparison were selected on the basis of the theoretical model described in section 1.1 and the results of the long jump analysis in section 4.1.

As multiple comparisons were to be performed on the data, it was necessary to consider the risk of making Type I errors by calculating the familywise error rate. For comparisons between the triple jump take-offs the alpha level was set to $P<0.01$ and the number of comparisons restricted to 14. This meant that the probability of making a

Type I error was 13%. As the long and triple jump data were collected on different athletes, differences between the same variables in long and triple jump take-offs had to be investigated using 42 (3 x 14) independent t-tests (assuming unequal variances). The alpha level was reduced to $P<0.005$, leading to a familywise Type I error rate of 18% when comparing between long and triple jump take-offs. Due to the exploratory nature of this study the relatively higher probabilities of making Type I errors, compared to the standard 5%, are considered acceptable.

To guard against making Type II errors the effect size statistic and power was calculated for all significant findings using the statistical package nQuery Advisor Release 3.0 (Elashoff, 1999). The effect size statistic for the one-way repeated measures ANOVA is calculated as the variance of the means divided by the variance at each level (square of the standard deviation) and one minus the correlation between levels. For the independent t-test the effect size statistic is the difference in means divided by the within-group standard deviation. The effect size statistic provides an index of the separation expected between the observed means, and values greater than one would be indicative of meaningful differences.

To compare the heights of the centre of mass at touch-down and take-off with those found in the long jump, the standing height of both groups was required. As standing height could not be determined in competition an assessment was made based on the summation of segment lengths from the ankle joint to the vertex of the head at the instant of maximum knee flexion. The measured 'standing heights' of the 2 groups were not significantly different with the 14 long jumpers recording a mean of 1.74 ± 0.06 m compared to 1.70 ± 0.06 m in the 7 triple jumpers.

4.2.3 Results

The data presented in this section relate to the mean and standard deviation of the 7 triple jump performances analysed. A breakdown of official, effective and phase distances is presented prior to a closer examination of the kinematic characteristics of each take-off is made.

4.2.3.1 *Official, effective and phase distances*

The mean official distance of the 7 performances analysed was 15.20 ± 0.90 m, with a range of 13.83 m to 16.52 m. Phase distances and effective distances were calculated from the digitised coordinate data of the toe using the definitions of Hay (1992). The effective distance describes how far the athlete actually jumped and is calculated by summing the toe-to-board and official distances, figure 4.2.2. The sum of the hop, step and jump distances also equals the effective distance. The mean, standard deviation and the range of these distances are presented in table 4.2.1.

Figure 4.2.2. Relationship between the official, effective and phase distances, (Hay, 1992).

Table 4.2.1. Summary of official, effective and phase distances.

	Mean	SD	Range
Official Distance (m)	15.20	0.90	13.83 - 16.52
Toe-Board Distance (m)	0.12	0.09	0.03 - 0.29
Effective Distance (m)	15.32	0.09	13.99 - 16.58
Hop Distance (m)	5.65	0.53	4.88 - 6.28
Step Distance (m)	4.59	0.43	4.12 - 5.07
Jump Distance (m)	5.09	0.23	4.88 - 5.45

The average phase percentages (phase distance expressed as a percentage of the effective distance) were 36.8 ±2.4%, 29.9 ±2.0% and 33.2 ±1.2% for the hop, step and jump respectively. This classifies the average performance as 'hop dominated', i.e. a technique where the hop percentage is more than 2% greater than the next largest phase, Hay (1992). The hop percentage ranged from 34.3% to 40.0%, the step from 27.4% to 33.0% and the jump from 33.2% to 35.6%. On an individual basis 5 of the jumps were classified as 'hop dominated' and the other 2 jumps were regarded as 'balanced', i.e. where the difference between the two longest phases is less than 2%.

Strong positive relationships were found between the effective distance and all the phase distances, (r=0.738, 0.694, 0.778 for the hop, step and jump distances respectively). The large coefficients of determination between each phase distance and the effective distance (54.5%, 48.2% and 60.5% respectively) indicates in this group of athletes, the better performances were the result of longer distances in all the phases.

4.2.3.2. *Kinematic characteristics*

This section examines the 3 dimensional kinematics of each take-off, paying particular attention to the height and velocity characteristics of the centre of mass, movements of the trunk and support leg in the sagittal, frontal and transverse planes, and the action of the free limbs in generating relative momentum. Mean and standard deviation data for the 7 athletes are presented at the instants of touch-down, maximum knee flexion, the end of the pivot (Tx=0) and take-off (as defined in section 1.4). The compression phase is defined as the period between touch-down and maximum knee flexion and the extension phase between maximum knee flexion and take-off. The instant when the centre of mass is directly above the toe of the support foot, Tx=0, is taken to represent the end of the pivot action or braking phase.

Height and velocity characteristics of the centre of mass

Data relating to the height and velocity of the athletes' centre of mass at key moments in each take-off phase are summarised in table 4.2.2 and presented graphically in figure 4.2.3.

From the instant of take-off into the last-stride (TOLS) the centre of mass was observed to drop by an average of 3 cm, landing on the board at a height of 0.99 m. Throughout the compression phase of the hop take-off there was no noticeable increase or drop in height, remaining at 0.99 m. In contrast the centre of mass showed significant reductions in height during the step and jump (compared to the hop) of 6 cm and 5 cm from touch-down to maximum knee flexion. Despite these reductions in height prior to maximum knee flexion there is a net increase in height from touch-down to take-off in all take-offs. In the hop take-off the centre of mass was raised by 16 cm, compared to 7 cm and 15 cm in the step and jump take-offs.

The greatest increases in height were found to occur in the extension phase where the centre of mass was raised through 16 cm, 14 cm and 20 cm in the hop, step and jump respectively. The heights of the centre of mass at the instant of take-off were similar between the 3 take-offs, recording heights of 1.15 m, 1.13 m and 1.16 m respectively. This indicates that athletes aim to produce similar amounts of extension and forward inclination in each of the take-offs.

Figure 4.2.3 shows the instantaneous horizontal and vertical velocities of the centre of mass in each of the triple jump take-offs. It can be seen that the horizontal velocity of the centre of mass decreased progressively from one take-off to the next. Table 4.2.2 shows that horizontal velocity decreased from 9.94 $m.s^{-1}$ as athletes touch-down into the hop to 6.76 $m.s^{-1}$ as they take-off into the jump. Horizontal velocity was lost during the support phase of each take-off and this was accompanied by an increase in vertical velocity, as in the long jump. The average losses in horizontal velocity during the hop, step and jump take-offs were similar, -0.92 $m.s^{-1}$, -0.97 $m.s^{-1}$ and -1.09 $m.s^{-1}$ respectively. The gains in vertical velocity during the step and jump take-offs (4.10 $m.s^{-1}$ and 4.16 $m.s^{-1}$) were found to be significantly greater than the gains generated in the hop take-off, 2.71 $m.s^{-1}$. These differences are due to the high negative vertical velocities experienced at touch-down into the step and jump (-2.43 $m.s^{-1}$ and -2.05 $m.s^{-1}$) compared to the hop, -0.68 $m.s^{-1}$, and the need to reverse this deficit prior to generating positive vertical velocity. The vertical velocities of the centre of mass at take-off were 2.02 $m.s^{-1}$, 1.67 $m.s^{-1}$ and 2.12 $m.s^{-1}$ in the hop, step and jump take-offs respectively. At the end of the pivot action, when the centre of mass was directly above the toe, the average gains in vertical velocity were 2.06 $m.s^{-1}$, 3.07 $m.s^{-1}$ and 3.35 $m.s^{-1}$ in the hop, step and jump take-offs respectively. Expressed as a percentage of the total gain in vertical velocity, 75.5%, 74.8% and 80.2% had been attained by the end of the pivot action.

The results showed that the medio-lateral component of velocity was minimal with average values of less than 0.20 m.s^{-1}. In this respect the medio-lateral component of velocity is not regarded as a main characteristic of performance, although it is incorporated into the calculation of the resultant speed. The results indicated that less speed was lost in the hop take-off, -0.71 m.s^{-1}, compared to the step and jump take-offs, -1.11 m.s^{-1} and -1.02 m.s^{-1}.

The projection angle of the centre of mass at touch-down was significantly smaller in the hop touch-down (-3.8°) than in the step and jump touch-down (-15.0° and -14.6°). At take-off the projection angles were similar in the hop and step (12.6° and 11.6°), but greater in the jump, 17.4°.

Table 4.2.2. Height and velocity data at key moments in the hop (H), step (S) and jump (J) take-off phases.

		Touch-down		Maximum Knee Flexion		End of Pivot		Take-off	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Height (m)	H	0.99	0.05	0.99	0.04	1.01	0.04	1.15	0.04
	S	1.05	0.03	0.99	0.03	0.99	0.03	1.13	0.04
	J	1.01	0.06	0.96	0.05	0.98	0.04	1.16	0.04
VX (m.s^{-1})	H	9.94	0.19	9.22	0.16	9.11	0.20	9.02	0.12
	S	9.07	0.27	8.03	0.28	8.03	0.29	8.11	0.35
	J	7.85	0.35	6.85	0.27	6.71	0.27	6.76	0.25
VY (m.s^{-1})	H	-0.68	0.11	1.06	0.38	1.37	0.48	2.02	0.42
	S	-2.43	0.30	0.55	0.16	0.64	0.25	1.67	0.29
	J	-2.05	0.19	0.85	0.42	1.30	0.42	2.12	0.35
VZ (m.s^{-1})	H	0.18	0.13	0.18	0.07	0.17	0.08	0.09	0.06
	S	0.12	0.23	0.12	0.21	0.08	0.21	0.12	0.25
	J	0.21	0.21	0.11	0.25	0.15	0.33	0.13	0.31
Speed (m.s^{-1})	H	9.96	0.18	9.29	0.14	9.23	0.15	9.25	0.06
	S	9.40	0.21	8.05	0.28	8.06	0.30	8.29	0.33
	J	8.12	0.34	6.92	0.25	6.86	0.23	7.10	0.26

(VX = Horizontal (sagittal) velocity, VY = Vertical velocity, VZ = Medio-lateral velocity)

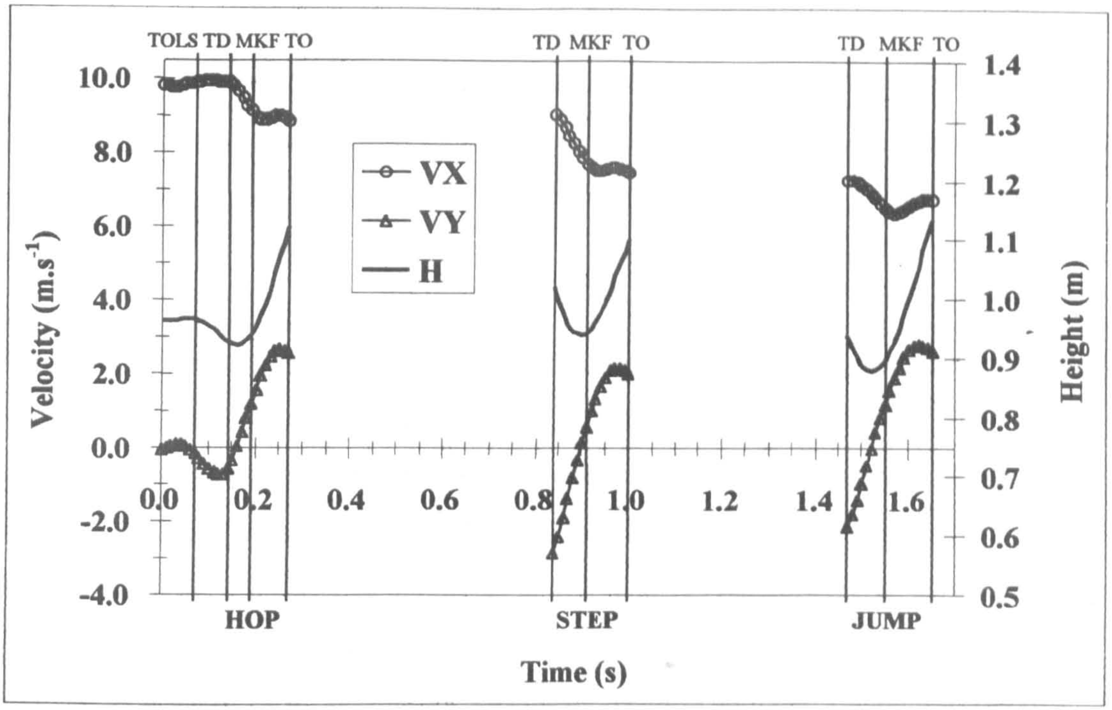


Figure 4.2.3. Typical horizontal (VX) and vertical (VY) velocity and height (H) profiles of the centre of mass in the hop, step and jump take-offs (subject A4, official distance 16.52 m). (TOLS = take-off last stride, TD = touch-down, MKF = maximum knee flexion, TO = Take-off).

Kinematics of the trunk and support leg

Sagittal plane kinematics

Table 4.2.3 shows the mean and standard deviation of selected kinematic variables in the sagittal plane. A diagrammatic representation of these variables and their conventions can be found in section 4.1 figure 4.1.5.

The variables Ax and Dx relate to the angle (to the downward vertical) and horizontal displacement of the ankle relative to the athletes centre of mass. At touch-down it can be seen that the support leg is planted well in front of the centre of mass in all take-offs at angles of 24.1°, 21.5° and 23.7° respectively, (Ax_{TD} table 4.2.3). These angles correspond to horizontal distances of 0.39 m, 0.36 m and 0.39 m respectively, (Dx_{TD} in table 4.2.3). By the end of the compression phase, the centre of mass had already passed over the ankle (Dx_{MKF} = -0.10 m, -0.18 m and -0.12 m) but was still behind the toe, (Tx_{MKF} = 0.09 m, 0.02 m and 0.09 m) in the hop, step and jump take-offs respectively. The negative sign indicates that the centre of mass is in front of the ankle or toe. At the instant of take-off the ankle and toe are positioned well behind the centre of mass (-0.64 m, -0.70 m and -0.62 m) with relatively larger angles of inclination (-36.4°, -39.4° and -34.4° to the downward vertical) than those observed at touch-down. The more negative this angle, the less upright is the line connecting the centre of mass to the ankle joint.

The angle of the trunk in the sagittal plane was found to be inclined forward at the instants of touch-down and remained forward throughout each of the take-offs. The trunk angle at touch-down into the jump was inclined further forward, 10.0°, than in the hop and step, both 5.8°. In the hop and jump take-offs very little trunk rotation was observed with the trunk staying in the region of 7° and 11° respectively. In the step take-off, however, the trunk was noted to rotate forwards through 5.8° in the compression phase to an angle of 11.8°, which was then preserved until take-off. The hip extension angle at touch-down was greater in the step take-off, 141°, than in the hop and jump take-offs, both 134°. All triple jumpers exhibited hip extension from before touch-down through to take-off. The range of hip extension from touch-down to take-off was slightly greater in the hop take-off than in the step and jump take-offs, 70.6°, 63.2° and 64.7° respectively. At take-off, the hip joint was hyper-extended in all take-offs at angles of 205°, 203° and 198°. As the trunk angle remains relatively stable, almost all hip extension is the result of the backward sweeping movement of the thigh. Typically, the thigh rotates through a range of 71.5°, 67.9° and 65.8° from touch-down to take-off in the hop, step and jump take-offs respectively.

In terms of landing leg activeness, the negative relative ankle velocities at touch-down indicated that all the touch-downs were classified as 'active'. The relative ankle velocity at touch-down into the jump take-off was the lowest of the 3 take-offs.

Table 4.2.3. Sagittal plane kinematics of the hop, step and jump take-offs.

		Touch-down		Maximum Knee Flexion		End of Pivot Tx=0		Take-off	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Leg placement angle (sagittal) Ax (°)	H	24.1	3.2	-6.4	3.3	-11.9	0.7	-36.4	2.4
	S	21.5	1.5	-11.5	2.5	-12.7	1.0	-39.4	1.0
	J	23.7	1.9	-7.8	2.9	-13.1	1.0	-34.4	1.4
Centre of mass to ankle distance Dx (m)	H	0.39	0.05	-0.10	0.05	-0.19	0.01	-0.64	0.05
	S	0.36	0.03	-0.18	0.04	-0.20	0.02	-0.70	0.04
	J	0.39	0.03	-0.12	0.05	-0.20	0.02	-0.62	0.04
Centre of mass to toe distance Tx (m)	H	0.61	0.06	0.09	0.05	0.00	0.00	-0.65	0.07
	S	0.57	0.04	0.02	0.05	0.00	0.00	-0.70	0.06
	J	0.61	0.04	0.09	0.06	0.00	0.00	-0.62	0.06
Relative ankle velocity ($m.s^{-1}$)	H	-6.1	0.8	-9.1	0.3	-8.7	0.3	-3.3	1.1
	S	-6.5	0.8	-7.8	0.3	-7.7	0.2	-3.6	0.4
	J	-5.3	0.5	-6.7	0.4	-6.4	0.5	-2.9	0.8
Trunk angle (sagittal) (°)	H	5.8	2.9	7.1	3.3	7.6	3.2	6.1	2.1
	S	5.8	4.4	11.6	3.3	11.6	3.5	11.0	3.6
	J	10.0	2.3	11.2	3.5	11.8	4.1	11.5	7.5
Thigh angle (sagittal) (°)	H	39.3	2.4	20.0	3.8	13.9	2.7	-32.2	2.3
	S	32.5	2.6	18.7	1.1	17.4	3.5	-35.4	0.9
	J	35.4	2.7	22.2	3.1	16.4	4.9	-30.4	1.9
Hip extension angle (°)	H	134	3.9	154	6.5	159	5.6	205	3.6
	S	141	6.2	151	4.1	152	4.3	203	3.4
	J	134	4.0	147	6.0	152	6.8	198	9.1

Frontal plane kinematics

Table 4.2.4 shows data relating to the frontal plane. The variables analysed here are the same as those analysed in section 4.1 for the long jump. Please refer to figure 4.1.6 for definitions and conventions.

It can be seen that the angle of leg placement at touch-down in the medio-lateral direction, Az, is similar for all take-offs with angles of zero degrees. Throughout each take-off the centre of mass remains within a few degrees to either side of the ankle joint which enables balance to be preserved.

The trunk was observed to be inclined towards the side of support throughout each take-off. At touch-down it was more inclined to the side of support into the step, -14.1°, than the hop, -8.3°. There was little movement in the hop take-off with the angle remaining at approximately -8.4°, but in the step and jump take-offs the trunk rotated into more upright positions. At the instant of take-off there was some inclination towards the side of support leaving the ground at angles of -8.4°, -8.7° and -4.9° respectively.

The angle of the thigh in the frontal plane was close to vertical in the hop take-off, 1.8°, but slightly more inclined to the side of support in the step and jump take-offs, 4.5° and 5.6°. Throughout each take-off the thigh gradually became more inclined, adopting angles of 4.5°, 7.8° and 6.5° at take-off.

Examination of the hip adduction angle revealed some interesting results. In the hop take-off, 5 of the 7 athletes experienced no adduction following touch-down, while all athletes experienced some adduction in the step and jump take-offs. Athletes experience more hip adduction (from touch-down to minimum) in the jump take-off, 7.8°, than in both the hop and step take-offs, 2.0° and 4.9°. The minimum hip adduction angles were 83.0°, 82.9° and 73.7° for the hop, step and jump take-offs respectively. From the minimum angle to take-off athletes abducted through 17.6°, 14.6° and 25.0° in the hop, step and jump take-offs.

Table 4.2.4. Frontal plane kinematics of the hop, step and jump take-offs.

		Touch-down		Maximum Knee Flexion		End of Pivot Tx=0		Take-off	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Leg placement angle (frontal) Az (°)	H	0.6	1.2	-0.7	1.0	-0.7	1.1	0.2	2.0
	S	-0.4	2.3	-1.7	2.9	-1.7	2.9	-3.4	3.3
	J	-0.4	3.5	-0.3	4.7	-0.1	5.0	0.5	5.2
Leg Placement distance (frontal) Dz (m)	H	0.01	0.02	-0.01	0.02	-0.01	0.02	0.00	0.03
	S	-0.01	0.04	-0.03	0.04	-0.03	0.04	-0.05	0.05
	J	-0.01	0.05	0.00	0.07	0.00	0.08	0.01	0.08
Trunk angle (frontal) (°)	H	-8.3	2.7	-8.6	3.1	-8.7	3.2	-8.4	3.6
	S	-14.1	3.4	-10.9	3.8	-10.7	3.9	-8.7	4.5
	J	-10.4	5.0	-5.5	6.3	-4.9	6.8	-4.9	8.3
Thigh angle (frontal) (°)	H	1.8	3.3	0.5	4.0	0.6	3.8	4.5	1.8
	S	4.5	5.1	3.0	6.8	3.0	6.7	7.8	3.0
	J	5.6	3.9	5.9	7.6	5.3	7.6	6.5	5.0
Hip adduction angle (°)	H	85.0	5.4	88.3	7.8	90.4	7.2	100.6	6.0
	S	87.8	6.3	88.2	7.6	88.4	6.5	97.5	5.0
	J	81.4	9.2	78.8	11.7	82.4	10.3	98.7	6.6

Transverse plane kinematics

Table 4.2.5 shows the hip rotation, shoulder rotation and hip-shoulder separation angles in the transverse plane. For definitions of these angles and the conventions used refer to figure 4.1.7 in section 4.1.

The range of the hip-shoulder separation angle between touch-down and take-off measures the degree of trunk rotation during the take-off phase. The results indicate that the trunk rotates through large ranges of 95.7° in the hop, 106° in the step and 99.7° in the jump. In the hop take-off the amount of trunk rotation is evenly split between the rotation of the hips, 46.5°, and the shoulders, 49.2°. In the step take-off there is slightly more hip rotation, 56.4°, than shoulder rotation, 49.7°. In the jump take-off there is greater hip rotation than shoulder rotation, 57.2° and 42.4° respectively.

Table 4.2.5. Transverse plane kinematics of the hop, step and jump take-offs.

		Touch-down		Maximum Knee Flexion		End of Pivot Tx=0		Take-off	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Hip rotation angle (°)	H	-20.4	8.2	7.1	11.4	13.3	9.8	26.1	7.8
	S	-25.6	4.6	11.4	9.2	12.6	10.3	30.8	6.8
	J	-33.2	6.1	-1.1	7.9	6.0	7.2	24.0	5.5
Shoulder rotation angle (°)	H	30.6	7.9	18.1	6.7	14.5	6.7	-18.6	9.2
	S	28.6	7.1	9.4	9.8	8.9	10.6	-21.1	10.7
	J	21.2	12.1	1.8	10.1	-1.7	9.0	-21.2	6.3
Hip-Shoulder separation angle (°)	H	-51.0	10.5	-11.0	12.3	-1.2	10.2	44.7	6.3
	S	-54.2	8.7	2.0	10.4	3.7	13.0	51.9	9.1
	J	-54.4	13.3	-2.9	12.2	7.7	10.8	45.3	9.9

Three-dimensional movement

Table 4.2.6 shows the changes in the 3D knee and ankle joints of the support leg. The knee joint was slightly more flexed at touch-down into the hop, 156°, than at touch-down in the step and jump take-offs, both 160°. Following touch-down the knee flexed through a greater range in the compression phase of the step and jump take-offs, both 29.2°, than in the hop, 21.9°, although the minimum angles of the knee were similar, 134°, 131° and 131°. The knee angle therefore compresses approximately 7° less in the hop take-off than in the step and jump take-offs. In the extension phase of the hop take-off athletes demonstrated 30.1° of knee extension compared to 37.5° and 37.9° in the step and jump take-offs. The difference of 7° in the amount of compression between the hop take-off and the step and jump take-offs is reversed in the amount of knee extension.

It is apparent that due to the more flexed knee at touch-down athletes are able to extend their knee joint through a greater range than they compress, typically 8° from touch-down to take-off. The knee extension angle at take-off in the hop take-off, (164°) was 4° less extended than at take-off into the step and jump take-offs, (both 168°), indicating that full extension is not achieved in the hop.

The ankle joint showed similar angles and movement patterns in all 3 take-offs. From an angle of approximately 110° at touch-down the ankle dorsi-flexes to a minimum angle of 84° which occurs at the end of the pivot action, Tx=0. As the centre of mass moves in front of the toe, the ankle begins to plantar-flex (from Tx=0 to take-off). At take-off the ankle had plantar-flexed through ranges of 50°, 47°, and 56° to leave the ground with angles between 131° and 139°.

Table 4.2.6. 3D knee and ankle joint angles.

		Touch-down		Maximum Knee Flexion		End of Pivot Tx=0		Take-off	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
3D Knee angle (°)	H	156	3.9	134	3.9	135	4.4	164	2.6
	S	160	4.1	130	5.9	131	6.4	168	3.2
	J	160	4.1	130	7.4	133	9.4	168	2.2
3D Ankle angle (°)	H	110	4.3	87	5.1	84	4.4	134	7.8
	S	112	3.3	85	3.9	84	3.9	131	6.0
	J	109	3.2	86	5.1	83	4.5	139	7.0

Kinematics of the Free Limbs

The relative momentum characteristics of the free limbs are presented prior to taking a closer look at the movement patterns of each individual limb.

i) *Relative momentum*

Table 4.2.7 shows the mean and standard deviation of the peak positive increase in relative momentum of the free limbs in the hop, step and jump take-offs. The results show that triple jumpers progressively generate more relative momentum of the combined free limbs (total) throughout each take-off. In the hop take-off the combined action of the free limbs generated 22.4 N.s which increased to 29.2 N.s in the step and increased further again to 37.6 N.s in the jump take-off. As a percentage of the peak vertical momentum of the centre of mass, the free limbs were found to contribute most in the step and jump take-offs (both 19.0%) and the least in the hop take-off (12.2%). The positive increase in relative momentum generated by the lead leg was greater in the step, 17.8 N.s, and jump, 16.8 N.s, take-offs compared to that generated in the hop, 7.9 N.s. The co-lateral arm showed a progressive increase in relative momentum from the hop take-off through to the jump take-off (8.2 N.s, 11.1 N.s and 13.5 N.s respectively). The contra-lateral arm generated similar levels of relative momentum in each take-off with contributions of 6.6 N.s, 4.8 N.s and 8.7 N.s respectively.

In the hop take-off the lead leg and both arms were found to generate similar levels of relative momentum. In the step and jump take-offs the lead leg generated the greatest amount of relative momentum whilst the contra-lateral arm was found to generate the least. Significant differences were found between the contributions of the lead leg and the contra-lateral arm in both the step and jump take-offs ($F=9.47$, $P<0.01$ in the step, $F=4.53$, $P<0.05$ in the jump).

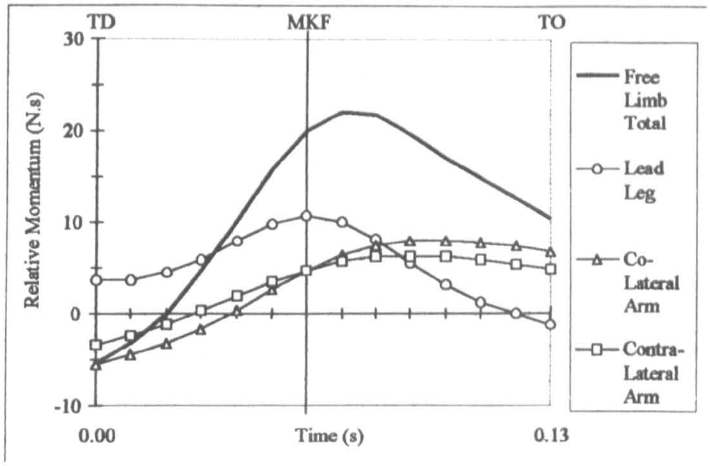
Table 4.2.7. Gain in positive relative momentum of the free limbs in the triple jump take-offs.

Relative Momentum (N.s)	HOP		STEP		JUMP	
	Mean	SD	Mean	SD	Mean	SD
Co-Lateral Arm	8.2	2.4	11.1	3.1	13.5	2.4
Contra-Lateral Arm	6.6	4.6	4.8	4.2	8.7	5.8
Lead Leg	7.9	5.4	17.8	8.2	16.8	6.2
Free Limbs Total	22.4	7.2	29.2	9.2	37.6	10.0
Peak Centre of Mass Momentum	184	34.0	159	21.6	199	25.9
Free Limb Contribution (%)	12.2	3.4	19.0	7.9	19.0	4.7

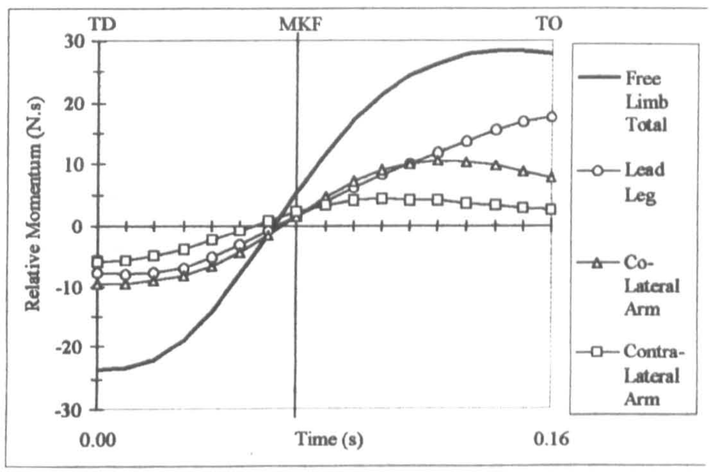
Figure 4.2.4 shows the mean (n=7) relative momentum profiles of the co-lateral and contra-lateral arms, the lead leg and of the combined action of the free limbs in each of the three take-offs. It can be seen in figure 4.2.4 that temporal differences exist between the timing of the peak relative momentum of the free limbs. The peak relative momentum of the combined free limbs (total) was found to occur significantly earlier in the hop take-off, 52.1% of support, compared to 90.4% and 88.5% of support in the step and jump take-offs. In the hop take-off the combined action of the free limbs begin to develop positive relative momentum shortly after touch-down and reach peak values around maximum knee flexion. In the step and jump take-offs the free limbs total is negative for most of the compression phase, becoming positive close to maximum knee flexion and reaching a peak close to take-off.

The timing of the peak relative momentum of the combined free limbs appears to be more dominated by the relative momentum of the lead leg than of either of the arms. The lead leg can be seen to have positive relative momentum at touch-down in the hop take-off and reaches a peak around maximum knee flexion (45.2% of support). In the step and jump take-offs the relative momentum of the lead leg is negative for the entire compression phase, becomes positive around maximum knee flexion and reaches a peak close to take-off (99.2% and 90.0% of support respectively). In each of the take-offs, both the co-lateral and contra-lateral arms exhibited negative relative momentum at touch-down and all reached their peak in the extension phase. The relative momentum of the co-lateral arm was found to peak at 72.9%, 77.0% and 74.4% of the support phase in the hop, step and jump take-off. The relative momentum of the contra-lateral arm was also found to peak in the mid-part of the extension phase, occurring at 73.1%, 68.7% and 84.4% of support in the hop, step and jump take-offs respectively.

a) Hop take-off (mean, n=7)



b) Step take-off (mean, n=7)



c) Jump take-off (mean, n=7)

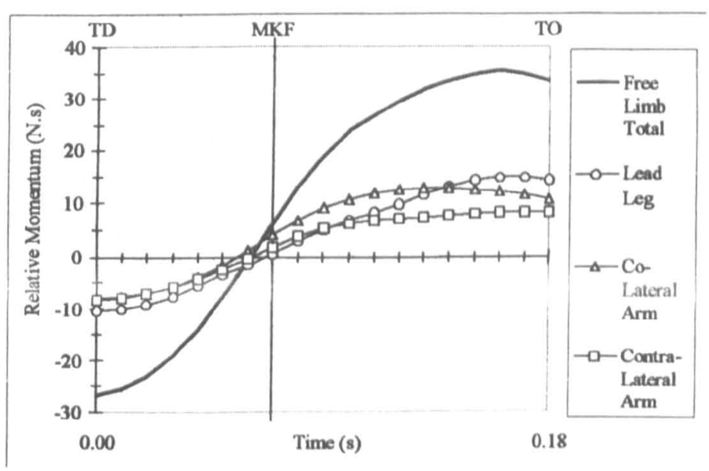


Figure 4.2.4. Relative momentum profiles of individual and combined free limbs in the a) hop, b) step, and c) jump take-offs. (TD = touch-down, MKF = maximum knee flexion, TO = take-off).

ii) *Kinematics of the Free Limbs*

The kinetograms in figures 4.2.5, 6 and 7 show the average positions of the elbow and wrist (or knee and ankle) joint centres relative to the shoulder (or hip) joint in the sagittal and frontal planes. To aid understanding, the co-lateral arm is plotted to represent the left arm and the contra-lateral arm and the lead leg have all been plotted to represent the right hand limbs. Positive positions of the limb in the sagittal plane indicate that the segment is in front of the shoulder / hip joint. In the frontal plane positive positions indicate that the segment has moved across the body (adduction) and negative values indicate movement away from the body (abduction). Positions have been plotted at the instants of touch-down, maximum knee flexion, PEAK relative momentum and take-off. The mean and standard deviation of the upper arm / leg and elbow / knee angles are presented in tables 4.2.8, 9 and 10.

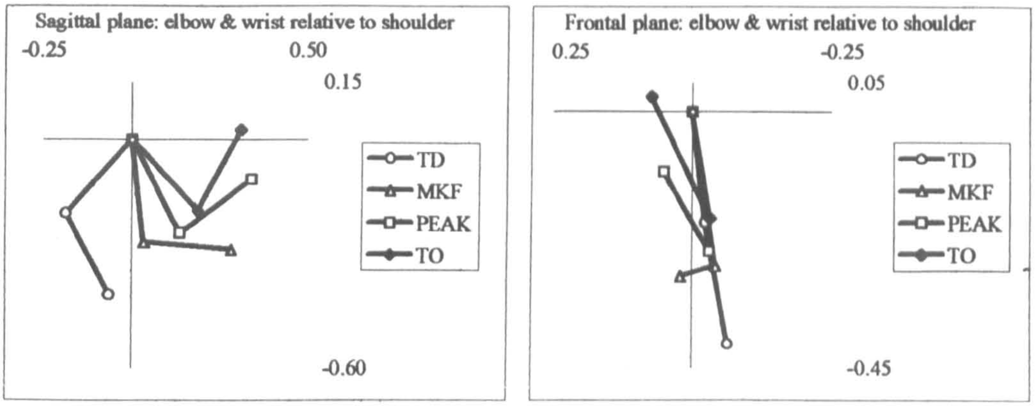
Co-lateral Arm

The action of the co-lateral arm in all 3 take-offs can be described as a 'back-to-front' movement with minimal medio-lateral deviation. However, whilst the basic movement pattern is similar there are some noticeable differences.

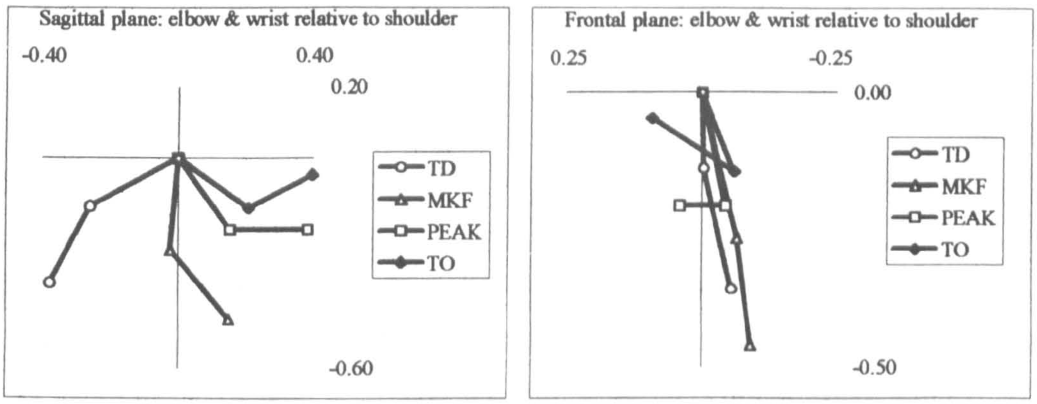
It is quite clear from figure 4.2.5 that the elbow is more extended at touch-down in the step and jump take-offs than at touch-down in the hop take-off. During the take-off the arm flexes through similar amounts from touch-down to take-off, typically between 33° and 43°. At take-off the arm is still significantly more flexed in the hop take-off than in the step and jump. The upper arm starts from a more rearward position in the step take-off (-62.4°), than in the hop (-44.2°) before rotating forwards through to take-off. The range of upper arm rotation from touch-down to take-off was found to progressively increase from the hop through to the jump take-off. In the hop take-off the upper arm rotated through 89.1°, in the step it increased to 118° and in the jump it rotated further through 148°. The position of the upper arm at peak relative momentum was further forward in the jump, 60.1°, than in the hop, 29.4° and step, 37.3°. The angles of the elbow at peak relative momentum were 82.0°, 112° and 108° in the hop, step and jump take-offs respectively. This indicates that the elbow remains more flexed throughout the hop take-off than throughout the step and jump take-offs. From peak relative momentum through to take-off the upper arm continues to rotate forwards and the elbow continues to flex. At the instant of take-off there is a noticeable difference in the position of the upper arm and forearm in the jump take-off compared to the hop and step. In the hop and step take-offs the upper arm reaches an angle of 44.9° and 55.2° to the vertical compared to the horizontal alignment, 90.8°, in the jump take-off. The wrist reaches a position well above the shoulder joint in the jump take-off whereas in the hop and step take-offs it is located around shoulder level.

Although the movement pattern in the sagittal plane was consistent in so far as the limb moved from the back to the front, there was no consistent pattern of upper arm movement in the frontal plane. In the hop take-off 2 of the 7 athletes demonstrated a net movement across the body (adduction), whilst the other 5 showed a net movement away from the body (abduction). The average range of movement from touch-down to take-off was -3.8 ± 19.6° with a range of -38.9° (abduction) to +11.0° (adduction). In the step take-off 6 athletes showed a net abduction of the upper arm whilst the other athlete showed a net adduction. The average range of upper arm movement from touch-down to take-off was -25.5 ± 37.0° with a range of -75.8° (abduction) to +36.3° (adduction). In the jump take-off 5 athletes abducted and 2 adducted the upper arm from touch-down to take-off. The average range of movement was -33.9 ± 87.5° with a range of -125.6° to +80.5°. The average movement from touch-down to take-off indicates that the preferred action of the co-lateral arm is abduction. However, with such wide ranges of abduction and adduction in each take-off it also indicates that athletes have individual techniques.

a) Hop: Co-lateral arm sagittal and frontal planes



b) Step: Co-lateral arm sagittal and frontal planes



c) Jump: Co-lateral arm sagittal and frontal planes

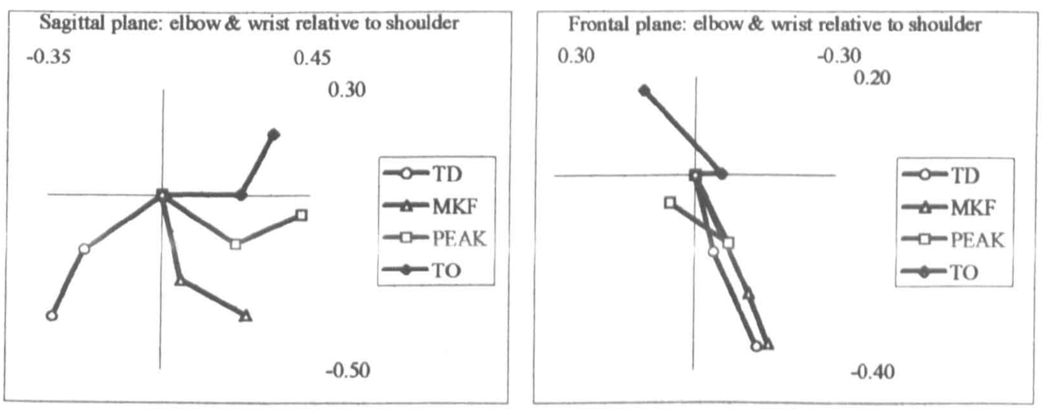


Figure 4.2.5. Mean movement patterns of the co-lateral arm in the hop, step and jump take-offs. (n=7). (TD = touch-down, MKF = maximum knee flexion, PEAK relative momentum, TO = take-off).

Table 4.2.8. Upper arm and elbow angles of the co-lateral arm at the instants of touch-down, PEAK relative momentum and take-off in the hop (H), step (S) and jump (J) take-offs.

		Touch-down		PEAK relative momentum		Take-off	
		Mean	SD	Mean	SD	Mean	SD
Upper Arm angle sagittal (°)	H	-44.2	8.9	29.4	5.3	44.9	10.0
	S	-62.4	11.7	37.3	20.7	55.2	17.4
	J	-57.4	9.3	60.1	16.8	90.8	15.1
Upper Arm angle frontal (°)	H	-5.9	8.1	-6.8	9.0	-9.7	13.8
	S	-3.3	22.8	-16.6	22.8	-28.8	24.8
	J	-17.4	27.9	-32.2	33.4	-51.3	81.4
Elbow angle (°)	H	106	9.9	81.9	14.0	72.5	13.2
	S	143	20.1	112	20.1	99.3	19.7
	J	139	22.7	108	22.7	101	19.6

Contra-lateral Arm

The action of the contra-lateral arm dictates whether the observed arm technique is classified as 'single' arm or 'double' arm (Hay, 1992), although it is acknowledged that other, more specific actions have been described in the literature (Masters, 1986; Susanka et al., 1987). In the single arm action the co-lateral and contra-lateral arms move in opposite directions (in the sagittal plane). This means that the contra-lateral arm would move in a front-to-back direction as the co-lateral arm moves from back-to-front (as previously mentioned). In the double arm technique both arms move in the same direction, i.e. back-to-front.

For the purpose of this study the contra-lateral arm movements have been separated into either single or double arm actions. When the net movement of the upper arm (from touch-down to take-off) in the sagittal plane is negative (backwards) then the technique is classed as 'single arm'. When the net movement of the upper arm is positive (forwards) then it is classed as 'double arm'. The movement patterns of single and double arm techniques in the hop, step and jump take-offs are presented in Figures 4.2.6a, b and c, and a summary of elbow and upper arm angles are presented in Table 4.2.9.

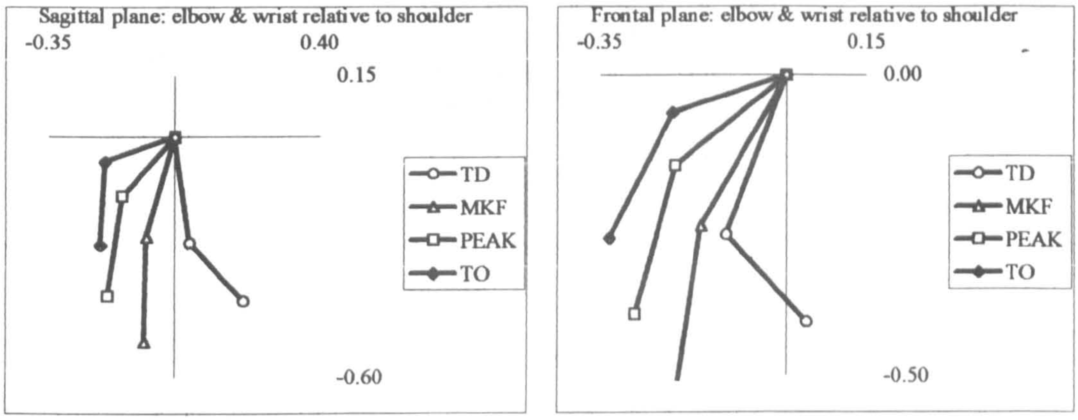
In the hop take-off the preferred arm action amongst this group of athletes was the single arm technique which was performed by 5 of the 7 athletes. By definition there is a difference in the movement pattern of the upper arm in the sagittal plane. In the single arm technique the upper arm was observed to rotate backwards through 81.2° while in the double arm technique it was observed to rotate forwards through 27.0°. However, this appears to be the only difference. The position of the arm at touch-down, the angle of the elbow and the movement of the upper arm in the frontal plane were found to be similar during both single and double arm techniques. At touch-down the upper arm is close to the vertical in the sagittal plane (9° and 3° for single and double arm respectively), in an abducted position of around 20° and the elbow extended to angles of 111° and 94° respectively. In both techniques the elbow extends in the compression phase and flexes in the extension phase. However, it is apparent that the elbow is more extended throughout the single arm action compared to the double arm. At maximum knee flexion, the elbow angle in the single arm action was 152° compared to 116° in the double arm action. At take-off, the single arm remains more extended than the double arm with angles of 123° and 95°. During the take-off all athletes were observed to abduct the upper arm. The average range of abduction for the single arm technique was 51.9° compared to 37.9° in the double arm technique. The average positive increases in relative momentum of the contra-lateral arm in single and double arm actions were 8.2 N.s and 2.4 N.s respectively. It would appear therefore that the single arm technique is more beneficial to the generation of vertical velocity than the double arm technique in the hop take-off. The observations made above indicate that more vertical relative momentum can be generated when the arm is straighter and moves through a greater range of motion in the sagittal plane.

In the step take-off 4 athletes used a double arm technique and 3 used a single arm technique. In this take-off the movement patterns of single and double arm actions are almost the direct opposite, but the magnitudes are similar. From touch-down to take-off the single arm action shows a backward rotation of 91.5°, abduction of 33.5° and a net extension of the elbow of 29.0°. In contrast, the double arm action shows a net rotation forwards of 88.3°, adduction of 22.9° and flexion of the elbow of 26.2°. Although the average values indicate a net adduction of the upper arm in the double arm action, one athlete actually abducted through a range of 22.6°. The relative momentum generated by single and double arm techniques in the step take-off were almost identical to those generated in the hop. The single arm technique was found to generate the greatest amount with 8.8 N.s, compared to 2.2 N.s by the double arm technique. As the range of movement in the sagittal plane and the elbow angle at peak relative momentum were similar (121 and 118°) the explanation for this finding is likely to be the actual position of the upper arm at peak relative momentum. As the upper arm starts from a more inclined position in the double arm action (-50.8° compared to 23.8°) it has more of a downward descent than the single arm action. Consequently the single arm action commences its upward stroke earlier in the take-off than the double arm, enabling it to generate more positive relative momentum. At the instants of peak relative momentum and take-off the upper arm is more inclined, i.e. more horizontal, in the single arm action than the double, table 4.2.9. The arm therefore reaches a higher vertical position, which will also lead to an increase in the height of the centre of mass.

In the jump take-off the preferred technique was the double arm action which was observed in 6 of the 7 athletes. Starting from a rear (-52.4°), abducted (-44.9°) position with an extended elbow (138°) the upper arm rotates through 110° forwards, abducts 13.6° and the elbow flexes 62.8° prior to take-off. The final position at take-off is in front of the body (57.7°), abducted (-58.5°) and the elbow is flexed to 75.6°. The upper arm movement pattern of the athlete who demonstrated a single arm action was similar to the single arm action in the step take-off. A noticeable difference was that he had a more extended elbow throughout the take-off and reached almost full extension during the compression phase, 174°. At take-off his elbow had flexed to 124°, which was similar to that found in the step take-off. However, it can be seen in figure 4.2.4c that in the extension phase not only did the elbow flex, but the upper arm externally rotated to place the wrist in a higher position than the elbow. Interestingly this particular athlete adopted a single arm technique in all 3 take-offs. In both the hop and step his contra-lateral arm generated 12.8 N.s of relative momentum, while in the jump take-off it only recorded 2.5 N.s. The average relative momentum generated using a double arm technique in the jump take-off was 9.7 N.s, with a range of 2.2 N.s to 16.4 N.s. It would appear from this data that a double arm technique in the jump take-off is more conducive to the generation of vertical velocity.

Figure 4.2.6a) Hop: Contra-lateral arm sagittal and frontal planes

Single arm technique (n=5)



Double arm technique (n=2)

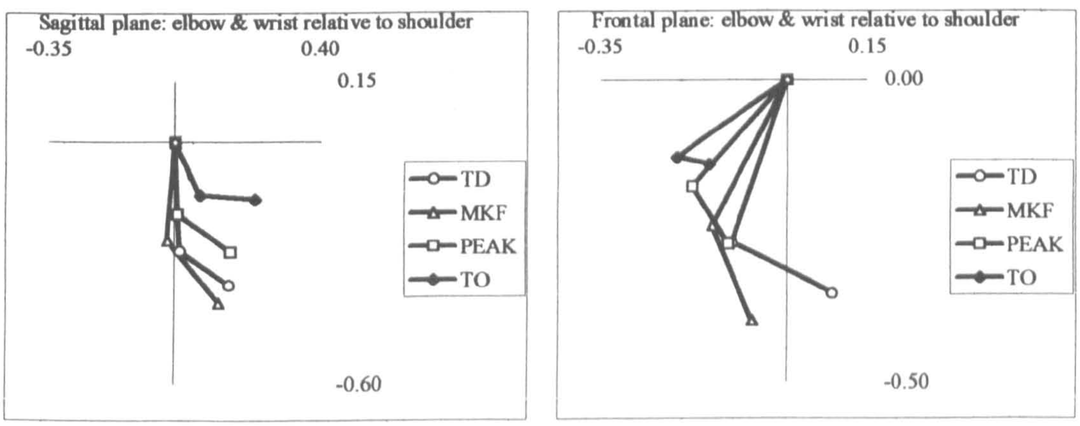
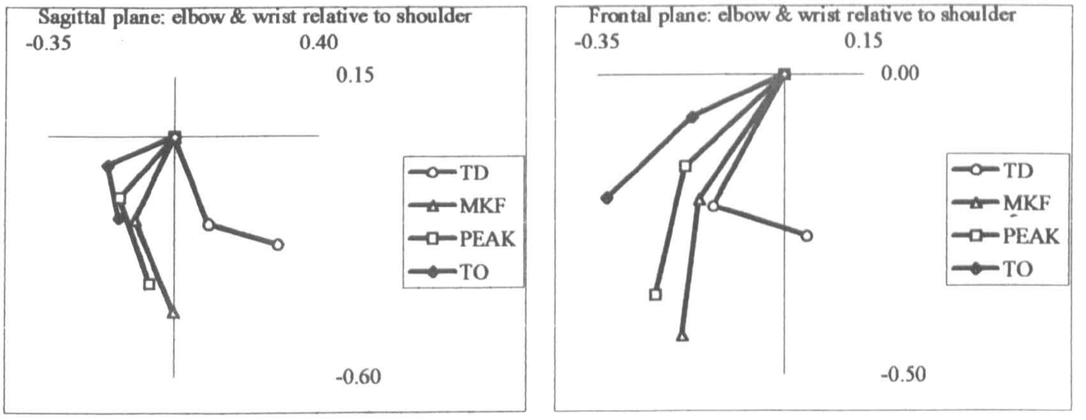


Figure 4.2.6b) Step: Contra-lateral arm sagittal and frontal planes

Single arm technique (n=3)



Double arm technique (n=4)

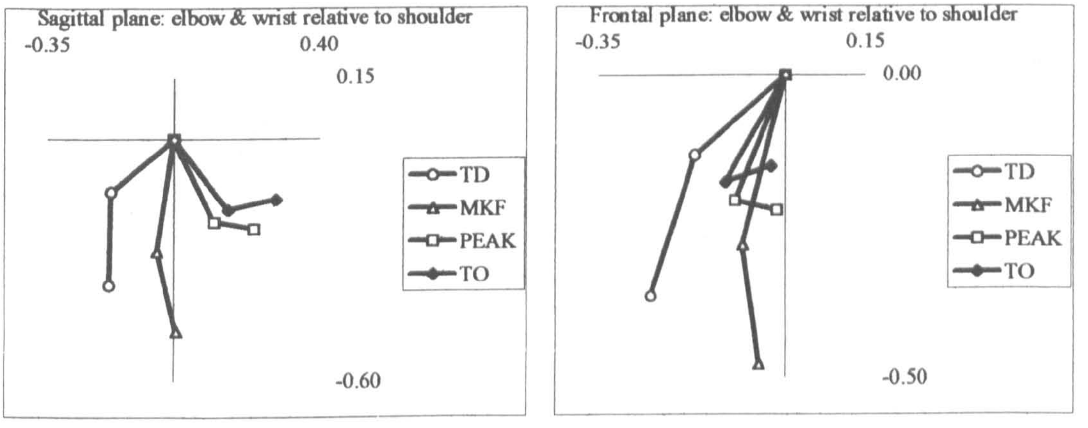
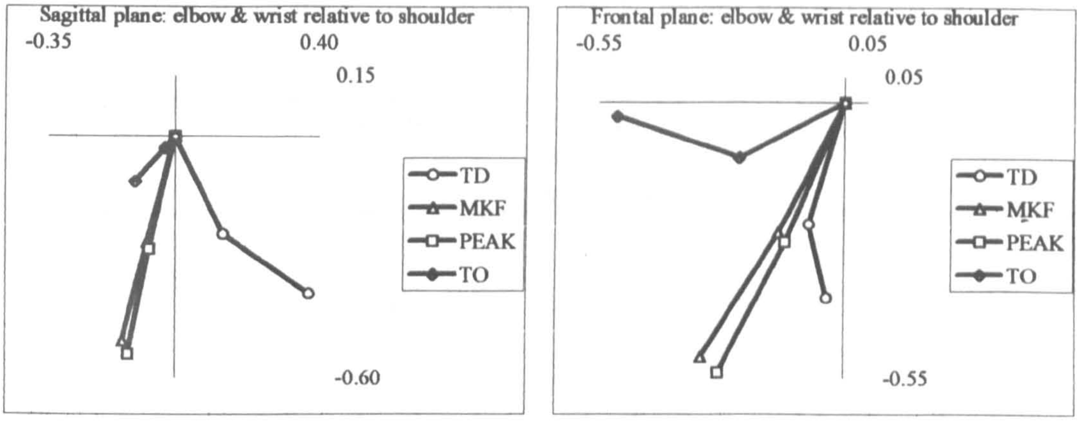


Figure 4.2.6c) Jump: Contra-lateral arm sagittal and frontal planes

Single arm technique (n=1)



Double arm technique (n=6)

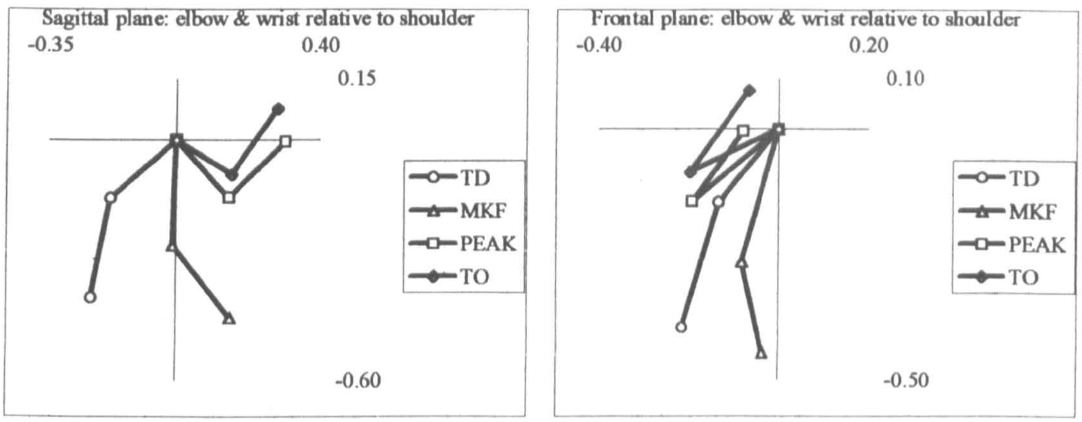


Figure 4.2.6. Mean movement patterns of single and double arm actions of the contra-lateral arm in a) the hop, b) the step and c) the jump take-offs. (n=7). (TD = touch-down, MKF = maximum knee flexion, PEAK relative momentum, TO = take-off).

Table 4.2.9. Upper arm (UA) and elbow angles of the contra-lateral arm at the instants of touch-down, maximum knee flexion, PEAK relative momentum and take-off for single and double arm techniques in the hop, step and jump take-offs. (TD-TO = change from touch-down to take-off)

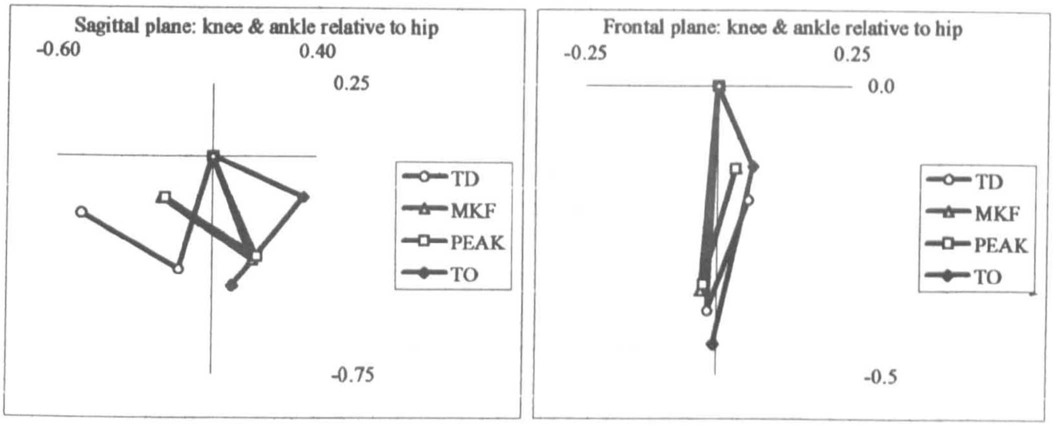
	Touch-down	Maximum Knee Flexion	PEAK relative momentum	Take-off	TD-TO
HOP **Single Arm (n=5)**					
UA Angle (Sagittal)	9.0	-17.8	-46.2	-72.2	-81.2
UA Angle (Frontal)	-23.1	-32.8	-55.4	-75.0	-51.9
Elbow Angle	111	152	137	123	12.0
Double Arm (n=2)					
UA Angle (Sagittal)	3.3	-4.2	9.4	30.2	27.0
UA Angle (Frontal)	-20.6	-30.5	-46.5	-58.5	-37.9
Elbow Angle	94.0	116	107	95.3	1.3
STEP **Single Arm (n=3)**					
UA Angle (Sagittal)	23.8	-27.3	-43.6	-67.7	-91.5
UA Angle (Frontal)	-31.2	-37.4	-50.2	-64.6	-33.4
Elbow Angle	92.1	128	121	121	28.9
Double Arm (n=4)					
UA Angle (Sagittal)	-50.8	-9.4	18.9	37.5	88.3
UA Angle (Frontal)	-51.2	-15.6	-24.4	-28.3	22.9
Elbow Angle	132	142	118	106	-26.0
JUMP **Single Arm (n=1)**					
UA Angle (Sagittal)	29.0	-16.6	-14.8	-44.6	-73.7
UA Angle (Frontal)	-17.8	-30.0	-25.9	-65.0	-47.1
Elbow Angle	142	174	174	124	-18
Double Arm (n=6)					
UA Angle (Sagittal)	-52.4	-1.8	43.1	57.7	110
UA Angle (Frontal)	-44.9	-16.8	-52.1	-58.5	-13.6
Elbow Angle	138	126	77.4	75.6	-62.4

Lead leg

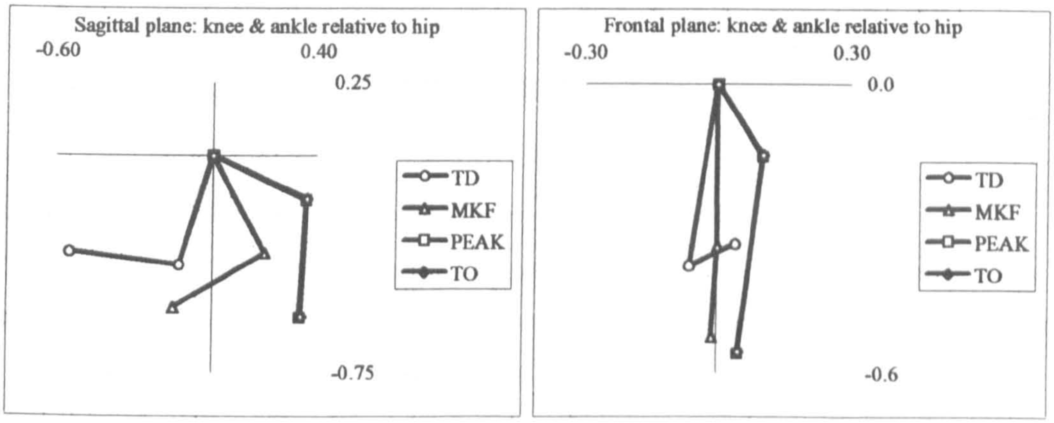
It can be seen in figure 4.2.7 and table 4.2.10 that at touch-down into the hop, step and jump take-offs the position of the upper leg (sagittal) is similar, but the knee is more flexed in the hop. One notable difference in the frontal plane is that the ankle starts in a more medial position in the jump take-off than in the hop and step. This is probably due to rotation effects caused by changing support leg for the jump take-off. The main difference throughout the take-off phases is the more flexed knee in the hop take-off.

The mean knee flexion angle at maximum knee flexion in the hop take-off was 35.3° compared to 86.3° and 91.4° in the step and jump take-offs. Although the knee extends in the latter part of the take-offs the knee joint is still significantly more flexed at take-off in the hop than in the step and jump take-offs (68.4°, 105.7° and 92.7°). As previously mentioned the lead leg reaches peak relative momentum around maximum knee flexion in the hop take-off compared to the instant of take-off in the step and jump take-offs. It is therefore not surprising that at PEAK relative momentum the angle of the upper leg is different. The upper leg can be seen to be less inclined to the downward vertical in the hop take-off, 26.5°, than in the step and jump take-offs, 67.3° and 62.8°. Despite these differences at PEAK relative momentum, the position of the upper leg at the instant of take-off in each take-off was similar, adopting angles of between 67 and 68° to the downward vertical (table 4.2.10). The range through which the upper leg rotates is also very similar between the 3 take-offs with values of 86.3°, 86.9° and 87.5°. Figure 4.2.7 also shows that the upper leg adducts from touch-down to take-off in all 3 take-offs. The upper leg was found to adduct through a greater range from touch-down to take-off in the step take-off, 45.6°, compared to 29.6 and 11.9° in the hop and jump take-offs.

a) Hop: Lead leg sagittal and frontal planes



b) Step: Lead leg sagittal and frontal planes



c) Jump: Lead leg sagittal and frontal planes

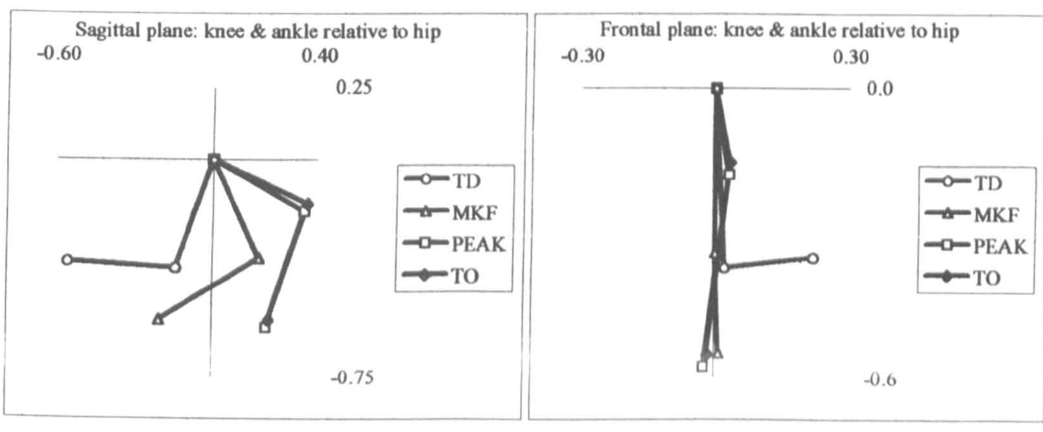


Figure 4.2.7. Mean movement patterns of the lead leg in the hop, step and jump take-offs. (n=7). (TD = touch-down, MKF = maximum knee flexion, PEAK relative momentum, TO = take-off).

Table 4.2.10. Upper leg and knee angles of the lead leg at the instants of touch-down, PEAK relative momentum and take-off in the hop (H), step (S) and jump (J) take-offs.

		Touch-down		PEAK relative momentum		Take-off	
		Mean	SD	Mean	SD	Mean	SD
Upper Leg angle sagittal (°)	H	-18.1	4.0	26.5	7.3	68.2	8.2
	S	-19.0	7.5	67.3	6.2	67.9	6.3
	J	-20.5	6.8	62.8	8.6	67.0	8.9
Upper Leg angle frontal (°)	H	-2.7	4.3	-4.8	3.9	26.8	23.0
	S	-9.3	5.8	35.4	15.1	36.2	14.6
	J	3.6	9.7	12.3	13.0	15.5	13.9
Knee angle (°)	H	80.7	12.9	34.0	7.0	68.4	12.3
	S	100	15.8	106	17.7	106	18.0
	J	107	13.6	97.0	6.9	92.7	9.0

Comparisons with long jump and summary of statistical analyses

The mechanisms that are believed to facilitate the generation of vertical velocity in the long jump, and are described in the theoretical model in section 1.1, are also believed to operate in the triple jump take-offs. A number of variables were identified in section 4.1.3.3 (page 102) for their association with the gain and loss in vertical and horizontal velocity in the long jump take-off. To identify differences in technique between the long and triple jump take-offs, and the apparent function of each take-off (i.e. to generate vertical velocity or to minimise the loss in horizontal velocity), the same kinematic variables were compared. Comparisons between the triple jump take-offs were tested using a one-way ANOVA and Tukeys HSD post-hoc test, and comparisons between the long and triple jump take-offs were tested using independent t-tests. The results, which are presented in Tables 4.2.11 and 4.2.12, form the basis of the discussion section.

Table 4.2.11. Results of ANOVA analyses between triple jump take-offs.

Variable	F	P	Tukey HSD Hop v Step	Hop v Jump	Step v Jump	Effect Size	Power (%)
Vertical Velocity $_{TD\text{-}TO}$ (m.s^{-1})	33.12	0.000	*	*		2.46	99
Horizontal Velocity $_{TD\text{-}TO}$ (m.s^{-1})	0.56	0.579				0.13	
Speed $_{TD}$ (m.s^{-1})	96.76	0.000	*	*	*	8.66	99
Leg placement angle, Ax $_{TD}$ (°)	2.66	0.097				0.70	-
Height $_{TD}$ (m)	3.39	0.056				1.35	
Height $_{TD\text{-}TO}$ (m)	12.05	0.000	*		*	1.22	88
Knee angle $_{TD}$ (°)	2.02	0.161				0.29	
Hip extension angle $_{TD}$ (°)	4.19	0.032				0.62	
Knee angle $_{TD\text{-}MKF}$ (°)	5.41	0.014	*	*		0.66	80
Hip adduction $_{TD\text{-}MIN}$ (°)	2.99	0.076				0.90	
Hip extension $_{TD\text{-}TO}$ (°)	3.85	0.040				0.30	
Free Limbs Relative Momentum (N.s)	5.22	0.016		*		0.88	73
Free Limbs Contribution (%)	3.41	0.055				0.45	
Pivot Contribution (%)	2.76	0.090				0.34	

*= $P<0.05$

When comparing the kinematics between the triple jump take-offs only 3 variables were found to produce significance levels below $P<0.01$. The results indicated that:

- significantly less vertical velocity is generated between touch-down and take-off in the hop take-off compared to both the step and jump take-offs;
- the speed of the centre of mass at the instant of touch-down progressively reduced through consecutive take-offs, and
- the gain in height of the centre of mass from touch-down to take-off was significantly lower in the step take-off compared to the hop and jump take-offs.

Results of Tukeys post hoc test provided some evidence to suggest that differences may also exist for the amount of knee flexion and the amount of free limbs relative momentum. Although these variables just fell short of the $P<0.01$ level of significance the high levels of power indicate a low risk of making a type II error. It could therefore be argued that less knee flexion is experienced in the hop take-off compared to the step and jump take-offs, and that greater free limbs relative momentum is generated in the jump take-off compared to the hop.

Table 4.2.12. Results of t-test analyses between long jump and a) hop, b) step and c) jump take-offs. (Height $_{TD}$ / SH is the centre of mass height relative to standing height)

a) Long jump *v*'s Hop take-off

Variable	t	P	Effect Size	Power (%)
Vertical Velocity $_{TD\text{-}TO}$ ($m.s^{-1}$)	4.89	0.000	2.23	96
Horizontal Velocity $_{TD\text{-}TO}$ ($m.s^{-1}$)	-3.83	0.003	1.80	83
Speed $_{TD}$ ($m.s^{-1}$)	-0.18	0.860	0.07	
Leg placement angle, Ax $_{TD}$ (°)	6.02	0.000	3.01	99
Height $_{TD}$ / SH (%)	-0.41	0.690	0.25	
Height $_{TD\text{-}TO}$ (m)	8.37	0.000	4.04	99
Knee angle $_{TD}$ (°)	5.57	0.000	2.51	99
Hip extension angle $_{TD}$ (°)	5.49	0.000	2.42	98
Knee angle $_{TD\text{-}MKF}$ (°)	-2.48	0.024	1.09	
Hip adduction $_{TD\text{-}Min}$ (°)	-6.18	0.000	2.71	99
Hip extension $_{TD\text{-}TO}$ (°)	-1.05	0.320	0.50	
Free Limbs Relative Momentum (N.s)	2.85	0.014	1.31	
Free Limbs Contribution (%)	-1.30	0.220	0.63	
Pivot Contribution (%)	7.27	0.000	3.66	99

b) Long jump *v*'s Step take-off

Variable	t	P	Effect Size	Power
Vertical Velocity $_{TD\text{-}TO}$ ($m.s^{-1}$)	-3.07	0.011	1.44	
Horizontal Velocity $_{TD\text{-}TO}$ ($m.s^{-1}$)	-2.51	0.036	1.28	
Speed $_{TD}$ ($m.s^{-1}$)	4.20	0.001	1.85	85
Leg placement angle, Ax $_{TD}$ (°)	13.22	0.000	5.84	99
Height $_{TD}$ / SH (%)	-4.84	0.000	2.06	92
Height $_{TD\text{-}TO}$ (m)	17.48	0.000	8.15	99
Knee angle $_{TD}$ (°)	3.51	0.004	1.59	70
Hip extension angle $_{TD}$ (°)	2.03	0.067	0.95	
Knee angle $_{TD\text{-}MKF}$ (°)	1.32	0.200	0.54	
Hip adduction $_{TD\text{-}Min}$ (°)	-2.94	0.010	1.31	
Hip extension $_{TD\text{-}TO}$ (°)	1.60	0.120	0.31	
Free Limbs Relative Momentum (N.s)	0.71	0.490	0.34	
Free Limbs Contribution (%)	-2.85	0.029	1.65	
Pivot Contribution (%)	5.27	0.001	2.61	99

c) Long jump *v*'s Jump take-off

Variable	t	P	Effect Size	Power
Vertical Velocity $_{TD\text{-}TO}$ ($m.s^{-1}$)	-3.50	0.004	1.62	72
Horizontal Velocity $_{TD\text{-}TO}$ ($m.s^{-1}$)	-2.36	0.037	1.10	
Speed $_{TD}$ ($m.s^{-1}$)	11.27	0.000	5.16	99
Leg placement angle, Ax $_{TD}$ (°)	9.26	0.000	4.18	99
Height $_{TD}$ / SH (%)	-1.18	0.270	0.60	
Height $_{TD\text{-}TO}$ (m)	7.57	0.000	3.89	99
Knee angle $_{TD}$ (°)	3.57	0.003	1.62	73
Hip extension angle $_{TD}$ (°)	5.70	0.000	2.51	99
Knee angle $_{TD\text{-}MKF}$ (°)	1.03	0.330	0.49	
Hip adduction $_{TD\text{-}Min}$ (°)	-2.83	0.016	1.32	
Hip extension $_{TD\text{-}TO}$ (°)	2.04	0.069	0.98	
Free Limbs Relative Momentum (N.s)	-1.31	0.220	0.64	
Free Limbs Contribution (%)	-4.55	0.002	2.36	98
Pivot Contribution (%)	4.61	0.002	2.32	97

The statistical analyses above revealed that the following technique variables were characteristically different across all the triple jump take-offs when compared to the long jump take-off:

- the leg angle at touch-down, Ax_{TD}
- the gain in height of the centre of mass between touch-down and take-off
- the knee angle at touch-down
- the percentage contribution made by the pivot mechanism to the generation of vertical velocity.

In addition to these common differences, each take-off had several other differences when compared to the long jump. The hop take-off was also significantly different to the long jump take-off for the magnitude of vertical velocity generated and horizontal velocity lost between touch-down and take-off, the hip extension angle at touch-down and the amount of hip adduction. The step take-off was also found to be different to the long jump take-off for the speed and height of the centre of mass at touch-down. Finally, the jump take-off was different to the long jump for the gain in vertical velocity, the speed of the centre of mass and the hip extension angle at touch-down and the percentage contribution of the free limbs to vertical momentum.

4.2.4 Discussion

This section begins by comparing the data found in this study with published data on the triple jump take-offs. The functional characteristics of the hop, step and jump take-offs are then assessed by paying particular attention to relationships between phase distances and the changes in height and horizontal and vertical velocities of the centre of mass. This is supplemented by comparisons made with the long jump take-off and variables relating to the pivot mechanism and free limb movements discussed in section 4.1.3.3.

4.2.4.1 *Comparisons with previous research*

Previous studies investigating the triple jump take-offs have concentrated on presenting information on horizontal and vertical velocities and the projection angle of the centre of mass at take-off. It can be seen in Table 4.2.13 that the horizontal and vertical velocity of the centre of mass and the projection angle at take-off compare favourably with other studies that have examined athletes of similar ability to this study, (Hillmann, (1981);

Milburn, (1982), and Fukashiro and Miyashita, (1983)). They found horizontal take-off velocities to be in the ranges of 8.55 $m.s^{-1}$ to 9.50 $m.s^{-1}$ for the hop take-off, 7.77 $m.s^{-1}$ to 8.56 $m.s^{-1}$ for the step take-off and 6.60 $m.s^{-1}$ to 6.91 $m.s^{-1}$ for the jump take-off. The study found mean values of 9.02 $m.s^{-1}$, 8.11 $m.s^{-1}$ and 6.76 $m.s^{-1}$, which fall comfortably into the ranges outlined above for the hop, step and jump take-offs respectively. The vertical velocity at take-off found in this study (2.02 $m.s^{-1}$, 1.67 $m.s^{-1}$ and 2.12 $m.s^{-1}$) were in close agreement with those reported by Hillmann (1981) and Milburn (1982), but slightly lower than those reported by Fukashiro and Miyashita (1983). Typical ranges for the vertical velocity at take-off were 1.90 $m.s^{-1}$ to 2.36 $m.s^{-1}$, 1.30 $m.s^{-1}$ to 1.92 $m.s^{-1}$, and 2.03 $m.s^{-1}$ to 2.50 $m.s^{-1}$ for the hop, step and jump take-offs respectively. With the exception of Bober's (1974) findings, projection angles of the centre of mass at take-off are typically within the ranges of 12.1° to 14.9° for the hop, 9.3° and 14.0° in the step and 16.9° to 21.6° in the jump take-off. The mean projection angles found in this study were 12.6°, 11.7°, and 17.4° and these compare favourably with the ranges outlined above. The trends in the data also support the findings of previous studies. The horizontal velocity decreased in a stepwise fashion from take-off to take-off, the lowest vertical velocity at take-off was found in the step and the largest projection angle was observed in the jump take-off.

Table 4.2.13. Summary of previous research findings highlighting distance, velocity, height, projection angle and touch-down distance.

Author(s)	Effective Distance (m)	Phase	Phase Distance (m)	VX_{TD} (ms^{-1})	VX_{TO} (ms^{-1})	VY_{TO} (ms^{-1})	VX_{TD-TO} (ms^{-1})	VY_{TD-TO} (ms^{-1})	PA (°)	H_{TD-TO} (m)	D_{TD} (m)
Bober (1974)	15.05 - 16.16 (O)	H	-	-	8.20	2.65			18.0		
		S	-	-	7.20	2.06			16.0		
		J	-	-	7.00	2.57			20.0		
Fukashiro et al. (1981)	14.45 (O)	H	5.33	-	8.48	2.20	-	-	14.5	-	-
		S	4.20	-	7.76	1.76	-	-	12.8	0.07	0.59*
		J	4.92	-	6.59	2.10	-	-	17.7	0.14	0.61*
Hillmann (1981)	15.86 (O)	H	5.61	10.40	9.50	2.00	-0.90		12.1		
		S	4.81		8.20	1.80	-1.30		12.7		
		J	5.46		6.60	2.50	-1.60		20.4		
Milburn (1982)	15.19 (O)	H	5.36	9.20	8.90	1.90	-0.30		12.4		
		S	4.63		8.00	1.30	-0.90		9.3		
		J	5.19		6.90	2.10	-1.10		16.9		
Fukashiro & Miyashita (1983)	14.06 (O)	H	-	8.82	8.40	2.12	-0.42	2.35	14.2	-	-
		S	-		7.75	1.64	-0.65	4.10	11.9	-	-
		J	-		6.57	2.03	-1.18	4.11	17.2	-	-
Fukashiro & Miyashita (1983)	14.8 (O)	H	-	9.04	8.55	2.28	-0.49	2.54	14.9	-	-
		S	-		7.77	1.87	-0.78	4.55	13.5	-	-
		J	-		6.61	2.18	-1.16	4.37	18.3	-	-
Fukashiro & Miyashita (1983)	15.96 (O)	H	-	9.77	9.00	2.36	-0.77	2.68	14.7	-	-
		S	-		8.56	1.92	-0.44	4.59	12.6	-	-
		J	-		6.91	2.26	-1.65	4.58	18.1	-	-
Hay & Miller (1985)	16.61 (E)	H	5.91	10.02	9.42	2.09	-0.60		12.5		
		S	4.88		8.06	1.82	-1.40		12.7		
		J	5.82		6.96	2.37	-1.10		18.8		
Bruggeman (1990)	17.28 (O)	H	6.19	10.06	9.29	2.39	-0.77	3.27	14.4	0.17	0.41#
		S	5.25		8.29	2.06	-0.99	4.98	14.0	0.10	0.41#
		J	5.88		6.84	2.68	-1.50	5.28	21.6	0.18	0.41#
Koh and Hay (1990)	16.72 (E)	H	5.93	10.20	9.51	-	-0.69	-	-	-	0.55"
		S	5.11		8.26	-	-1.25	-	-	-	0.53"
		J	5.68		6.76	-	-1.50	-	-	-	0.60"
Present study	15.32 (E)	H	5.65	9.96	9.02	2.02	-0.92	2.71	12.6	0.16	0.39+
		S	4.59	9.07	8.11	1.67	-0.97	4.10	11.7	0.07	0.36+
		J	5.09	7.85	6.76	2.12	-1.09	4.16	17.4	0.15	0.39+

O = Official distance; E = Effective distance
VX = Horizontal Velocity, VY = Vertical velocity, PA = Projection angle, H = Height of the centre of mass, D_{TD} = Touch-down distance
Definitions of D_{TD}: * = CM-toe, # = CM- Heel, " = Hip-CG foot, + = CM-Ankle

4.2.4.2 *Characteristics and functions of the triple jump take-offs*

The deterministic model of the long jump (Figure 1.1) highlighted that the effective distance was a function of the speed, projection angle and height of the centre of mass at take-off. Hay and Miller (1985) extended this model to cover each phase of the triple jump, Figure 4.2.8. Both these models identify the flight distance as being the major determinant of the effective distance and thus the emphasis on the parameters of projectile motion. Results from section 4.1 indicate that the longest jump distances are associated with an athletes ability to minimise the loss in speed and to raise the centre of mass through the greatest possible range from touch-down to take-off. The maintenance of speed is probably more critical in the triple jump as athletes have to apportion their effort through three take-offs. The loss in speed through each take-off is dependent on the gains in vertical velocity and losses in horizontal velocity. The following sections will therefore examine these characteristics and attempt to establish differences between the functions of each take-off by comparing the results with those of the long jump take-off previously analysed.

Figure 4.2.8. Deterministic model of the triple jump (Hay and Miller, 1985).

The Hop Take-off

The findings of this study indicate that triple jumpers approached the board at the same speed as did the long jumpers in section 4.1, recording horizontal touch-down velocities of 9.94 $m.s^{-1}$ and 9.93 $m.s^{-1}$ respectively. Past studies have generally found that triple jumpers approach the board at a lower velocity than their long jump counterparts, (Bruggeman, 1990; Hay, 1993). A comparison of approach speeds of 7 athletes who competed in both long and triple jumps found differences of up to 0.77 $m.s^{-1}$ slower in the triple jump, (Hay, 1993). The lower approach velocity in the triple jump was stated to be indicative of the different demands placed on the triple jumper, i.e. their need to maintain speed and balance throughout the 3 phases. Unfortunately this type of comparison could not be made in the present study as no athletes 'doubled-up' in both events. However, previous studies have reported horizontal velocities at touch-down of between 10.0 $m.s^{-1}$ and 10.4 $m.s^{-1}$ for athletes jumping between 15.86 m and 17.28 m, (Hillmann, 1981; Hay and Miller, 1985; Koh and Hay, 1990; Bruggeman, 1990, Table 4.2.13). A horizontal velocity of just below 10.0 $m.s^{-1}$ is therefore realistic for athletes attaining a mean effective distance of 15.32 m.

Triple jumpers were found to touch-down on the board with a more negative vertical velocity of -0.68 $m.s^{-1}$, compared to long jumpers. This is due to the centre of mass dropping through 0.03 m during the last stride compared to only 0.01 m in the long jump. The height of the centre of mass relative to standing height at touch-down into the hop was similar to the long jump, recording H_{TD} / SH values of 56.1 and 58.0% respectively (table 4.2.11). During the compression phase the centre of mass showed no noticeable change, remaining at a height of 0.99 m, while the long jumpers achieved an increase of 0.06 m by maximum knee flexion. In the extension phase the long jumpers raised their centre of mass through a further 0.23 m, which compared to only a 0.16 m increase in the extension phase of the hop take-off. The net change in height of the centre of mass during the hop take-off was 0.16 m, which agrees with the findings of Bruggeman (1990), but was significantly smaller than 0.29 m increase in the long jump, ($P<0.000$, effect size = 4.04). The height of the centre of mass (relative to standing height) at take-off was therefore lower in the hop take-off than in the long jump, recording values of 67.5% and 72.9% respectively.

In terms of the maintenance of speed results indicated that triple jumpers lost similar amounts in the hop take-off compared to long jumpers recording values of 0.71 $m.s^{-1}$ and 0.74 $m.s^{-1}$ respectively. This suggests that the maintenance of speed is a major function of both hop and long jump take-offs. However, it appears that the method of maintaining speed differs between the long and hop take-offs. The relatively smaller loss in horizontal velocity, -0.92 $m.s^{-1}$, and the significantly smaller gain in vertical velocity, 2.71 $m.s^{-1}$, ($P<0.000$, effect size = 2.23) indicates that one objective of the hop take-off is to maintain speed through the preservation of horizontal velocity. However, sufficient vertical velocity also needs to be generated in order to initiate a projection angle of between 12° and 15°.

The comparison with the long jump take-off has revealed that triple jumpers do not prioritise maximal gains in height and vertical velocity in the hop take-off, and appear to limit the loss in horizontal velocity. However, strong relationships were found between the hop distance and the changes in height and horizontal and vertical velocities of the centre of mass, Table 4.2.14. The large coefficients of determination indicate that longer hop distances are highly associated with larger gains in height of the centre of mass, greater gains in vertical velocity and greater losses in horizontal velocity. These variables were found to explain 88%, 74% and 91% of the variance in the hop distance respectively.

The function of the hop take-off would appear to be to maintain speed primarily through minimising the loss in horizontal velocity, but if longer hop distances are to be attained, greater increases in the height of the centre of mass and greater gains in vertical velocity are required.

Table 4.2.14. Relationships between the hop distance and changes in height, horizontal velocity and vertical velocity of the centre of mass during the hop take-off.

Hop Distance *vs*	r	P	R^2
Height $_{TD-TO}$	0.937	0.01	88%
Horizontal velocity $_{TD-TO}$	-0.956	0.01	91%
Vertical velocity $_{TD-TO}$	0.862	0.05	74%

The Step Take-off

After the flight phase of the hop, athletes touch-down into the step take-off with a large negative vertical velocity, -2.43 $m.s^{-1}$, which not surprisingly is more negative than that into the long jump take-offs. Due to the loss in speed during the hop take-off, the horizontal velocity at touch-down into the step was around 0.87 $m.s^{-1}$ lower than that of the long jump and hop. The change in horizontal velocity from touch-down to take-off was similar to that observed in the hop take-off, -0.97 m.s^{-1}, but less than that lost in the long jump, -1.38 m.s^{-1} (P=0.036, effect size = 1.28). A greater gain in vertical velocity was found during the step take-off, 4.10 m.s^{-1}, and this was significantly greater than hop take-offs, (P<0.01, effect size = 2.46). This is because athletes need to overcome the large negative vertical velocity at touch-down before generating the positive vertical velocity that is required to achieve a good projection angle. However, although the step take-off exhibits the largest gain in vertical velocity, its magnitude at take-off is the lowest of all take-offs, 1.67 m.s^{-1}. This undoubtedly leads to greater losses in speed, -1.11 m.s^{-1}, compared to the long and hop take-offs. The height of the centre of mass relative to standing height at touch-down, 62.0%, was greater than that observed in the long jump, 56.1%, (P<0.000, effect size = 2.06). Unlike the hop take-off, where the centre of mass showed no increase in height during the compression phase, the centre of mass actually dropped by 0.06 m in the step take-off. This is undoubtedly due to the large negative vertical velocity at touch-down which creates a large impact force at touch-down. Athletes then raise their centre of mass through 0.14 m in the extension phase, which is similar to that attained in the hop take-off. The net change in height was the smallest of all take-offs, showing only a 0.07 m increase from touch-down to take-off. The height of the centre of mass relative to standing height at take-off into the step, 66.3%, was similar to that in the hop take-off, and lower than that observed in the long jump, 72.9%. Although the net change in height of the centre of mass during the step take-off was significantly lower than all other take-offs, a high level of association was found between the step distance and gain in height, Table 4.2.15. The coefficient of determination indicates that the gain in height of the centre of mass explains 82% of the variance in the step distance. This indicates that although triple jumpers do not raise their centre of mass through the greatest possible range, there is some evidence to indicate that those who raise theirs the furthest may attain longer step distances.

The lack of strong associations between the changes in horizontal and vertical velocity with the step distance may be due to factors associated with the landing and their ability to drive-off without losing excessive amounts of speed.

Table 4.2.15. Relationships between the step distance and changes in height, horizontal velocity and vertical velocity of the centre of mass during the step take-off.

Step Distance *vs*	r	P	R^2
Height $_{TD\text{-}TO}$	0.906	0.01	82%
Horizontal velocity $_{TD\text{-}TO}$	-0.249	NS	6%
Vertical velocity $_{TD\text{-}TO}$	0.479	NS	23%

The Jump Take-off

As athletes land from the step phase and are dropping onto the track they again experience a large negative vertical velocity at touch-down of -2.05 $m.s^{-1}$, but this is not as severe as in the step take-off. The horizontal velocity decreased through the support phase of the step dropping to 7.85 $m.s^{-1}$ for touch-down into the jump. The jump take-off showed a slightly greater loss in horizontal velocity compared to the hop and step take-offs, (-1.09 $m.s^{-1}$, NS), but was still approximately 0.3 $m.s^{-1}$ less than the loss in the long jump, (P=0.037, effect size = 1.10). The gain in vertical velocity in the jump take-off was very similar to that in the step take-off, and significantly greater than the gains in the long (P=0.004, effect size = 1.62) and hop take-offs (P=0.000, effect size = 2.46). The vertical velocity at take-off, 2.12 $m.s^{-1}$, was similar to the other triple jump take-offs, but again it was lower than in the long jump. The observation that the projection angle at take-off was greater in the jump take-off than in the hop and step is therefore predominantly due to the lower horizontal take-off velocity rather than a greater vertical velocity at take-off. The loss in speed, -1.02 $m.s^{-1}$, was similar to the loss in the step take-off and was greater than the loss experienced by long jumpers. The height of the centre of mass relative to standing height at touch-down was similar to previous take-offs, 59.3%. Due to the large negative vertical velocity at touch-down the centre of mass dropped by 0.05 m in the compression phase to a height of 0.96 m, which was the lowest position of the centre of mass in any take-off. In the extension phase the centre of mass was raised through 0.20 m which was greater than the corresponding gains in the hop and step. The net increase in height during the jump take-off was similar to that of the hop take-off, 0.15 m, and agrees with the findings of Fukashiro et al. (1981) and Bruggeman (1990), Table 4.2.13.

The relationships tested between the jump distance and the net changes in height and horizontal and vertical velocities of the centre of mass were found to produce low levels of association, Table 4.2.16. As with the step take-off, this is likely to be due to the conditions in which the athlete lands from the preceding flight phase. Factors may include the magnitude of vertical velocity at touch-down, the body position at touch-down, and the ability to control the landing and to actively drive-off into the jump.

Table 4.2.16. Relationships between the jump distance and changes in height, horizontal velocity and vertical velocity of the centre of mass during the jump take-off.

Jump Distance *vs*	r	P	R^2
Height $_{TD\text{-}TO}$	0.299	NS	9%
Horizontal velocity $_{TD\text{-}TO}$	0.582	NS	34%
Vertical velocity $_{TD\text{-}TO}$	0.536	NS	29%

The aim of the triple jumper in any of the take-offs does not appear to raise his centre of mass through the greatest possible range. The results have consistently shown that the range through which the centre of mass moves is smaller in the triple jump take-offs, and as such the height of the centre of mass at take-off is also lower. Although not always statistically significant at the $P<0.01$ level, there is also some evidence that triple jumpers aim to maintain horizontal velocity rather than generate maximum vertical velocity at take-off compared to long jumpers.

4.2.3.3 *Kinematic characteristics of the triple jump take-offs*

The kinematics of touch-down, take-off and the changes occurring during the take-off help to describe the triple jumper's technique and explain how they achieve these objectives.

In section 4.1 strong relationships were found between the angle of leg placement at touch-down, Ax_{TD}, and the changes in height and horizontal velocity from touch-down to take-off in the long jump. Larger Ax_{TD} values were found to be associated with greater increases in height, and greater losses in horizontal velocity. As the aim of the triple jumper is to preserve horizontal velocity and not to attain maximum height then Ax_{TD} is a good starting point in this discussion. The results of this study found leg plant angles of 24.1°, 21.4° and 23.7° in the triple jump take-offs, all of which are significantly smaller than the angle exhibited by long jumpers, 32.2°, (P=0.000). As the increase in height of the centre of mass is significantly less in the 3 triple jump take-offs, then the smaller angle of leg placement supports the relationship found in the long jump. The angle of leg placement is determined by the horizontal and vertical position of the centre of mass relative to the ankle joint then it is important to examine how body position influences Ax_{TD}. It can be seen in Table 4.2.12 that the height of the centre of mass relative to standing height at touch-down is similar to that in the long jump, with the exception of the step touch-down which is slightly higher. Therefore, the major influence on Ax_{TD} is the horizontal distance between the ankle and the centre of mass, which has been referred to as the touch-down distance, D_{TD} (Koh and Hay, 1990). Touch-down distance in the hop, step and jump take-offs were found to have values of 0.39, 0.36 and 0.39 m which were all significantly smaller than 0.55 m reported for the long jump. The reason why the touch-down distance is between 0.16 m and 0.19 m smaller in the triple jump take-offs can be attributed to 2 main observations:

i) the angle of the trunk in the sagittal plane is actually inclined forwards in the triple jump take-offs, (5.8°, 5.8° and 10.0°), whereas in the long jump it is inclined backwards, -7.5°. This effectively places the centre of mass in front of the hip joint as opposed to behind in the long jump take-off; and

ii) the knee is more flexed at touch-down in the triple jump take-offs, (156°, 160° and 160°), compared to 167° in the long jump. This effectively draws the ankle joint backwards and closer to the body.

The height of the centre of mass at take-off was found to be lower in all triple jump take-offs, (1.15, 1.13 and 1.16 m) compared to 1.27 m in the long jump. This indicates that triple jumpers do not aim to attain maximum vertical height at take-off, as can be seen in the lower heights of the centre of mass relative to standing height, 66% to 68% compared to 73%. There are two possible explanations as to why triple jumpers have lower centre of mass at take-off:- either they do not fully extend the hip, knee and ankle joints, or that they are less upright and the whole body is angled closer to the track. With reference to joint extension, all the take-offs exhibited similar angles of hip extension and abduction at the instant of take-off, typically around 200° and 100° respectively. With the exception of the hop take-off the knee extension angles were also similar, typically 168°. The ankle angles at take-off were also similar, around 137°, although in the step take-off slightly less than full plantar flexion was achieved, 131°. With the 2 exceptions noted it can be assumed that triple jumpers attempt to fully extend the hip, knee and ankle joints at take-off into each phase. Therefore, in relation to the height of the centre of mass at take-off, joint extension does not appear to be the limiting factor. The major cause of the relatively low heights at take-off can be attributed mainly to the alignment of the take-off leg and trunk in the sagittal plane. The long jump athletes were observed to take-off with an almost vertical trunk angle, -0.8°, whereas noticeable forward inclination angles of 6.1°, 11.0° and 11.5° were observed in the triple jump take-offs. The alignment of the take-off leg relative to the centre of mass was also inclined further forwards in the triple jump take-offs than in the long jump. Angles of leg inclination at take-off, Ax_{TO}, were found to be -36.4°, -39.4° and -34.4° in the hop, step and jump take-offs, compared to -23.6° in the long jump. These angles indicate that triple jumpers are less upright at the instant of take-off than long jumpers.

Considering that the phase distance is the sum of the take-off, flight and landing / touch-down distances, Figure 4.2.8, the benefit of inclining the body more horizontally at take-off is that it increases the take-off distance and ultimately the phase distance. Using the same definition of the take-off distance as Fukashiro et al. (1981) it is possible to quantify the contribution of the take-off distance to the phase distance. Their definition of the take-off distance was the horizontal distance between the centre of mass and the toe, which relates to the variable Tx_{TO} in Table 4.2.3. This definition gives take-off distances of 0.65 m, 0.70 m and 0.62 m which contribute 11.5%, 15.3% and 12.2% to the hop, step and jump phase distances of 5.65 m, 4.59 m and 5.09 m respectively. In comparison, a mean take-off distance of 0.44 m contributes only 5.9% to the effective distance of 7.44 m in the long jump. This suggests that it is more advantageous for triple jumpers to increase their performance through adding a further 0.18 m to 0.26 m to each of their take-off distances, than by attempting to raise the height of the centre of mass by an additional 0.11 m to 0.14 m, as exhibited in the long jump.

Although the take-off distance is a function of technique, it is also undoubtedly a function of the athlete's body height and leg length (Karayannis, 1987). Therefore, as the take-off distance is limited by body height and leg length, the only way to increase phase distances is through longer flight distances, and these are achieved through greater heights, speeds and projection angles at take-off.

The greater the height of the centre of mass during the flight phase will inevitably mean greater negative vertical velocities at touch-down in the following take-off. Therefore, the function of a lower height of the centre of mass at take-off may also be to help the athlete maintain control, or withstand a lowering of the centre of mass in the subsequent landing. The importance of this can be seen in Figure 4.2.3 where positive vertical velocity only begins to be produced when the centre of mass begins to rise, and this generally occurs just before maximum knee flexion. The function of the pivot mechanism in the early part of the compression phase is therefore to control the rate of flexion and lowering of the centre of mass. This appears to be achieved by reducing the touch-down distance and having a partially flexed knee joint. Additionally, providing the athlete has contracted the quadricep muscles, a partially flexed knee joint at touch-down may be better equipped to resist flexion than a straighter leg which is likely to create a more forceful impact. A smaller touch-down distance also means that the centre of mass will pass over the point of support earlier in the triple jump take-offs. This equates to a shorter braking phase and helps to explain how athletes avoid losing excessive amounts of horizontal velocity.

By the end of the compression phase positive vertical velocity had been attained in all triple jump take-offs, (1.06, 0.55 and 0.86 $m.s^{-1}$). These increased further to 1.37, 0.64 and 1.30 $m.s^{-1}$ by the end of the pivot / braking phase, Tx=0, and these were all lower than those attained in the long jump, 3.12 $m.s^{-1}$. However, expressed as the gain in vertical velocity from touch-down to Tx=0, results indicate that similar amounts of vertical velocity are generated in the step and jump take-offs and the long jump, (3.06 $m.s^{-1}$, 3.35 $m.s^{-1}$ and 3.30 $m.s^{-1}$ respectively). The hop take-off only showed a gain of

2.06 $m.s^{-1}$ from touch-down to Tx=0, which was lower than all other take-offs. Interestingly, the pivot / braking action was observed to end significantly earlier in the triple jump take-offs, (48.1, 45.6 and 50.3% of the support phase), than in the long jump, 66.3%. The percentage gain in vertical velocity to the end of the pivoting / braking phase was therefore smaller in the triple jump take-offs, 75.5%, 74.8% and 80.2%, compared to 93.3% in the long jump. This suggests that joint extension and the free limbs contribute relatively more to the generation of vertical velocity in the triple jump take-offs than in the long jump.

The free limbs were found to contribute 12.2%, 19.0% and 19.0% to the peak vertical momentum of the centre of mass in the hop, step and jump take-offs, compared to 10.8% in the long jump. Of these only the free limb contribution in the jump take-off was significantly different from that of the long jump ($P<0.002$, effect size = 2.36). There was some evidence that the free limbs had a greater contribution in the step take-off than in the long jump, effect size = 1.65, but this fell short of the $P<0.01$ level of significance. However, as previously noted, the free limbs do not act in isolation to the pivot mechanism, and in all take-offs some positive relative momentum was attained prior to the end of the pivot, Tx=0. The percentage contributions of the free limbs to the gain in vertical velocity from touch-down to Tx=0 were 11.8%, 5.0% and 9.5%. The contribution made by the pivot mechanism is calculated by subtracting the contributions made by the free limbs from touch-down to Tx=0, from the percentage gain in vertical velocity from touch-down to Tx=0. The pivot mechanism therefore contributes 63.7%, 69.8% and 70.7% to the total gain in vertical velocity generated between touch-down and take-off in the hop, step and jump take-offs respectively. These contributions were all found to be significantly lower than the contribution made by the pivot mechanism in the long jump take-off ($P<0.002$).

It is apparent that similarities exist between the timing of the free limbs (total) relative momentum in the hop and long jump take-offs, and also between the step and jump take-offs. This can be seen in Figures 4.1.10 and 4.2.4 where the relative momentum of the free limbs (total) peak shortly after maximum knee flexion in the long and hop take-offs, but close to take-off in the step and jump take-offs. The peak relative momentum was found to occur at 54.0%, 52.1%, 90.4% and 88.5% of the support phase in the long, hop, step and jump take-offs respectively. The timing of this peak has implications on the contribution made by the free limbs in the compression and extension phases of each take-off. The peak positive increases in free limbs relative momentum in the long and triple jump take-offs were 32.1 N.s, 22.4 N.s, 29.2 N.s and 37.6 N.s respectively, of which, 91.6%, 85.6%, 22.8% and 31.7% was generated in the compression phases. The greater contributions in the compression phases of the long and hop take-offs indicate that the free limbs assist relatively more with the pivot action than joint extension. In the step and jump take-offs the free limbs contribute relatively more to joint extension than to enhance the pivot action in the compression phase. The results of the long jump analysis (section 4.1) and observations made by Dapena and Chung (1988) indicate that greater levels of free limb activeness are likely to create more compression in the joints of the take-off leg. Considering that athletes experience larger negative vertical velocities at touch-down into the step and jump take-offs, and greater potential for flexion, it would appear that athletes place less emphasis on free limb activity in the compression phases. It could also be the case that in order to generate positive relative momentum a firm base of support needs to be established. It can be seen in Figures 4.2.4 b) and c) that the combined free limbs do not begin to generate positive relative momentum until just before maximum knee flexion in the step and jump take-offs. This point is synonymous with the time that centre of mass has finished its downward descent and begins its upward movement.

The results have shown that the profile of the lead leg relative momentum dictates the timing of the peak free limbs (total) relative momentum. The relative momentum of the lead leg reaches a peak value at maximum knee flexion in the long and hop take-offs, but in the step and jump take-offs it is closer to take-off. Figures 4.1.13 and 4.2.7 show the movement patterns of the lead leg in the long and triple jump take-offs. The most noticeable characteristic of the lead leg action in the long and hop take-offs compared to the step and jump take-offs is the extent to which the knee joint is flexed. It can be seen that the knee joint is significantly more flexed at the instant of maximum knee flexion (of the support leg) in the long and hop take-offs, 40.3° and 35.3°, compared to angles of 86.3° and 91.4° in the step and jump take-offs. It appears that relative momentum of the lead leg is more influenced by the knee flexion angle than the range of upper leg rotation in the sagittal plane. In the compression phase of the long and hop take-offs the lead leg was found to flex through approximately 50°, while only 15° flexion was observed in the step and jump take-offs. The range of upper leg rotation was similar for all take-offs, typically 87° from touch-down to take-off. The highly flexed knee angles in the long and hop take-offs could be related to the short times of support, 0.14 s, and the need to get the leg through as quickly as possible. This will decrease the moment of inertia and allow for faster movement of the limb. As support times increase in the step and jump take-offs, 0.16 s and 0.18 s, more time is available to bring the lead leg through. With longer support times, it is more beneficial to have a straighter leg, as this increases the moment of inertia and the centre of mass of the lead leg travels through a greater vertical range. This would be more beneficial for athletes aiming to generate greater amounts of vertical velocity. In the step and jump take-offs the lead leg generates its relative momentum mainly in the extension phase where the main characteristic of movement is upper leg rotation, typically around 40°. Although the upper leg rotated through 45° in the extension phase of the hop, no further increase in relative momentum was observed. This was because the lead leg extended, and as such the centre of mass of the lower leg adopted a lower vertical position.

The co-lateral arm was shown to increase its relative momentum from the hop take-off through to the jump. The results also showed corresponding increases in elbow extension angles and ranges of upper arm rotation in the sagittal plane. The same principles as described with the lead leg can also be applied to the co-lateral arm. The contra-lateral arm produced the smallest gains in relative momentum of the 3 limbs. The relatively greater lateral movement of this limb indicates that it serves to maintain balance, by keeping the centre of mass above the ankle joint in the frontal plane, Az_{TD}, as well as contributing a small amount to vertical momentum. In terms of the greatest contributions to vertical momentum, the results indicate that single arm actions are more beneficial in the hop and step take-offs while a double arm technique is most beneficial in the jump take-off.

4.2.5 Conclusion

This study has helped to identify important kinematic characteristics of the hop, step and jump take-offs, and quantify the contributions of the pivot mechanism and the free limbs to the generation of vertical velocity. The main observations were concentrated in the sagittal plane, but the 3D angles of the knee, ankle and elbow and movements in the frontal and transverse planes have allowed for a more thorough examination of the event.

By the instant that the centre of mass was directly above the toe the percentages of the total gains in vertical velocity were 75.5%, 74.8% and 80.2% in the hop, step and jump take-offs respectively. Of these, the percentages due to the pivot mechanism were 63.7%, 69.8% and 69.8% and that due to the free limb activity between touch-down and the end of the pivot was 11.8%, 5.0% and 9.5%. The total contributions of the free limbs were 12.2%, 19.0% and 19.0% for the hop, step and jump take-offs respectively. The significantly smaller contributions of the pivot mechanism to the generation of vertical velocity compared to the long jump, 83.0%, and the smaller losses in horizontal velocity were attributed to one main observation - smaller angles of leg placement at touch-down. As the heights of the centre of mass (relative to standing height) at touch-down were similar, the lower angles of touch-down were attributed to the fact that the centre of mass was closer to the point of support. As the centre of mass passes over the point of support this shorter distance facilitates a shorter pivot / braking phase and allows for a prolonged drive phase. Thus, the losses in horizontal velocity can be kept to a minimum. The smaller touch-down distances in the triple jump take-offs were explained by 2 main observations - the forward inclination of the trunk and the relatively greater flexion of the knee joint at touch-down.

Another interesting observation was the lower heights of the centre of mass at take-off. In most cases athletes demonstrated almost full joint extension, and therefore the reason for the low take-off heights were attributed to the greater angles of forward lean at take-off, Ax_{TO}, and longer take-off distances. It is apparent that triple jumpers trade greater heights at take-off for larger take-off distances. A larger take-off distance can add between 0.18 and 0.26 m directly to the phase distance, whereas a greater height at take-off will add to the flight distance. The latter will increase the height during the flight phase and consequently the force of impact in the subsequent landing. Therefore, not until athletes have sufficient strength to control the following landing should they attempt to become more upright and increase their height at take-off.

The free limbs were observed to function differently in the long and hop take-offs compared to the step and jump take-offs. It was shown that the majority of relative momentum in the long and hop take-offs is generated during the compression phase whilst in the step and jump take-offs the majority is generated in the extension phase. The implications of these observations are that the free limbs ultimately act to enhance the pivot action in the long and hop take-offs, whilst in the step and jump take-offs they function mainly to support joint extension. These similarities are undoubtedly due to the type of approach into the take-off, be it 'flat' in the long and hop, or 'drop' in the step and jump. In the flat approaches athletes resist any lowering of the centre of mass, while in the drop approach the centre of mass lowers by around 5 cm in the compression phase. These timing differences can be explained as follows. Firstly, greater activity of the free limbs in the compression phase will place greater stress on the support leg. In the long and hop take-offs where the vertical velocities at touch-down are less severe than in the step and jump take-offs additional stress can be tolerated. However, in the step and jump take-offs where a firm base of support needs to be established additional stress will almost certainly lead to greater compression. Secondly, the times of support are relatively shorter in the long and hop take-offs due to the greater horizontal velocities at touch-down. This means that athletes need to perform free limb movements more quickly, and this is achieved through greater flexion of the lead leg and co-lateral arm, i.e. greater movement of the lower segment relative to the upper segment. The effect of a more 'compact' limb inevitably leads to smaller gains in relative momentum and smaller contributions to the vertical velocity.

5.0 KINETICS AND MUSCLE MECHANICS

5.0 Kinetics and muscle mechanics

In this chapter the kinetics and muscle mechanics associated with the performance of simulated long and triple jump take-offs are examined. Its purpose is to build on the limited amount of research on ground reaction forces and to examine the distribution of these forces about the joints of the support leg, (Stefanyshyn and Nigg, 1998). It is intended that this study will identify how aspects of technique, particularly the variables associated with the generation of vertical velocity, alter the net joint moments and to investigate whether differences between long and triple jump take-offs exist. Combined with the assessment of isokinetic strength, this chapter will give an indication of the strength requirements of elite long and triple jumpers. This chapter fulfils the requirements of aims 4 and 5 in section 1.1.

5.1 Kinetics and muscle mechanics during simulated long and triple jump take-offs.

5.1.1 Introduction

To appreciate fully the physical demands placed on the musculo skeletal system during the long and triple jump take-offs it is important to examine the magnitude and direction of the ground reaction forces experienced. In order to perform the long and triple jumps successfully, athletes must adopt a technique that distributes these forces effectively about the joints of the support leg. Net joint and muscle moment analysis can provide this information, Winter (1980). Unfortunately this type of analysis does not estimate individual muscle forces about a joint, but provides the resultant moment of agonist and antagonist muscle groups and other structures acting about a joint.

Experimental evidence indicates that the force a muscle can generate depends upon the muscle length and velocity of shortening, (Frigo and Pedotti, 1978). Hence, only after the kinematics of a given active muscle are determined can conclusions be drawn concerning the force and type of work that a muscle produces during the given activity, (Hawkins and Hull, 1990). This is particularly important for bi-articular muscles as it is less clear whether the muscle is lengthening or shortening during specific movements. For these muscles the change in muscle length must take into account the effect of the joint angle of both joints that the muscle spans (Visser et al., 1990). Hawkins and Hull (1990) suggested that net joint and muscle moment data should be supported with muscle kinematic information to assess the type of contraction individual muscles are performing, i.e. whether the muscle is lengthening or shortening. Without this information, assumptions about the function of antagonistic muscle groups are often incorrect.

The inherent difficulty of measuring changes in muscle length and muscle contraction velocity directly has led to a number of studies investigating the relationship between changes in muscle-tendon length and changes in joint angle. Several approaches have been used to identify these relationships, including a mathematical and geometrical solution (Frigo and Pedotti, 1978); direct measurement on cadaveric limbs (Grieve et al., 1978; Visser et al., 1990), and those that have used both cadaveric information and geometric analysis (Pierrynowski and Morrison, 1985; Hawkins and Hull, 1990). All the methods have limitations which include over-simplification of muscle and joint geometry, assuming straight lines of muscle action, assuming fixed joint centres of rotation and the use of a limited number of subjects or cadavers. Each study has also differed in the number and choice of the muscles analysed. Generally, the geometric analyses allow for a more comprehensive analysis, but incorporate more assumptions and limitations than cadaveric investigations.

Another method of investigating the demands placed on the athlete is to remove the athlete from the dynamic situation and to assess the torque generating capabilities of isolated muscle groups. Isokinetic dynamometers allow for the accurate assessment of joint moment at controlled speeds of movement and in different modes of muscle contraction (concentric, eccentric, isometric). The limitation of this method is that it only takes into account the movement of one joint and therefore cannot assess the dynamic behaviour of bi-articular muscles and the additional power they are reported to deliver to the joints (Ingen Schenau et al., 1985; Prilutsky et al., 1995). However, the assessment of isokinetic muscle function will provide an indication to the specific muscle conditioning requirements of elite long and triple jumpers.

The overall aim of this section was to assess the demands placed on the musculo skeletal system and to quantify the strength requirements of long and triple jumpers during simulated take-offs. The objectives of this study were:

1. to examine ground reaction forces, net muscle moments and joint powers of the hip, knee and ankle joints of the support leg in simulated long and triple jump take-offs in the laboratory;
2. to examine relationships between the kinetic information and kinematic characteristics of the take-offs;
3. to describe changes in muscle-tendon length, and
4. to profile the isokinetic muscle function of elite long and triple jumpers.

5.1.2 Method

Subjects

On two separate occasions, members of the British long and triple jump squads attended the laboratory for data collection; on the first occasion, five male long jumpers and, on the second, five triple jumpers (four male, one female). The mean mass, height and lower extremity segment lengths of these athletes are summarised in table 5.1.1.

Table 5.1.1. Anthropometric characteristics of the subjects.

	Height (cm)	Body Mass (kg)	Upper Leg Length (cm)	Lower Leg Length (cm)
Mean	177.5	75.7	43.7	42.8
SD	7.1	7.4	3.6	3.8

Protocol

The testing session was divided into 3 sections: warm-up, isokinetic muscle function testing and dynamic jump testing.

Warm-Up

The warm up period consisted of a 5 minute cycle on a Monark Cycle ergometer at a self selected intensity followed by 10 to 15 minutes of stretching exercises. The choice of stretching exercises was left to the athletes as this is an integral part of their pre-competition routine. However, athletes were instructed to pay particular attention to muscles of the lower extremity. Only when the athlete felt they had done sufficient stretching did muscle function testing begin.

Isokinetic Muscle Function Testing

In order to attain accurate assessments of peak torque it was decided to carry out the isokinetic tests prior to the dynamic jump tests. In this respect the peak torque values would not be influenced by fatigue. A LIDO isokinetic dynamometer was used to measure the peak torque (gravity compensated) of the knee flexor and extensor muscle groups under 3 conditions. The first test was at a slow movement speed (angular velocity) of 1.05 $rad.s^{-1}$ (60 $°.s^{-1}$) to assess the 'absolute' concentric torque of the quadriceps and hamstring muscle groups. This was followed by a fast speed test to assess the ability of the same muscle groups to generate concentric torque at high movement speed, 5.24 rad.s^{-1} (300 °.s^{-1}). The final test concentrated on the quadriceps muscle group only and assessed the concentric and eccentric torque at an intermediate speed of 2.09 rad.s^{-1} (120 °.s^{-1}). These testing conditions were chosen to mirror the tests conducted on groups of athletes in the literature (Appen and Duncan, 1986; Ghena et al., 1991). Five repetitions were performed during each test and the peak torque value recorded. Both legs were tested, but only the data of the take-off leg in the dynamic jump tests were carried through to later analysis.

Dynamic Jump Tests

Simulation of the long and triple jump take-offs.

Two different types of running jump test were devised to simulate the characteristics of long and triple jump take-offs. In the simulation of the long jump and hop take-offs athletes were required to take a short approach (maximum length = 10.6 m), strike and take-off from a Kistler force platform, and to land on crash mats positioned several metres in front of the platform. This was termed a 'flat' approach and can be seen in figure 5.1.1a. The triple jumpers were then required to perform a second test designed to simulate the conditions of a step take-off, (figure 5.1.2 b). In this condition athletes were required to make a final step from the top section of a vaulting box (approximately 30 cm high and 3 m from the centre of the force platform) and to land with the step take-off leg on the force platform. This ensured that the athletes were dropping onto the force platform and thereby simulating the landing from the flight phase of a hop. This was termed a 'drop' approach. Due to the restrictions of space beyond the force platform (6.5 m) and the risk of injury, subjects were instructed to prioritise jumping for maximum height rather than horizontal distance. This also ensured that athletes produced the greatest possible gains in vertical velocity.

These tests were performed a short time after the isokinetic testing. Athletes were given time for more warm-up exercises prior to a familiarisation period. Familiarisation consisted of several practice trials where athletes adjusted their approach and take-off position on the box (for 'drop' approach). This ensured that the athletes were comfortable with the test (i.e. not over-stretching to strike the force platform) and that the results would be as realistic as possible. A tartan covering was connected to the force platform to simulate track conditions and to provide greater friction between the foot and surface, thereby reducing the risk of slipping (and injury). Athletes wore their own training shoes during the tests.

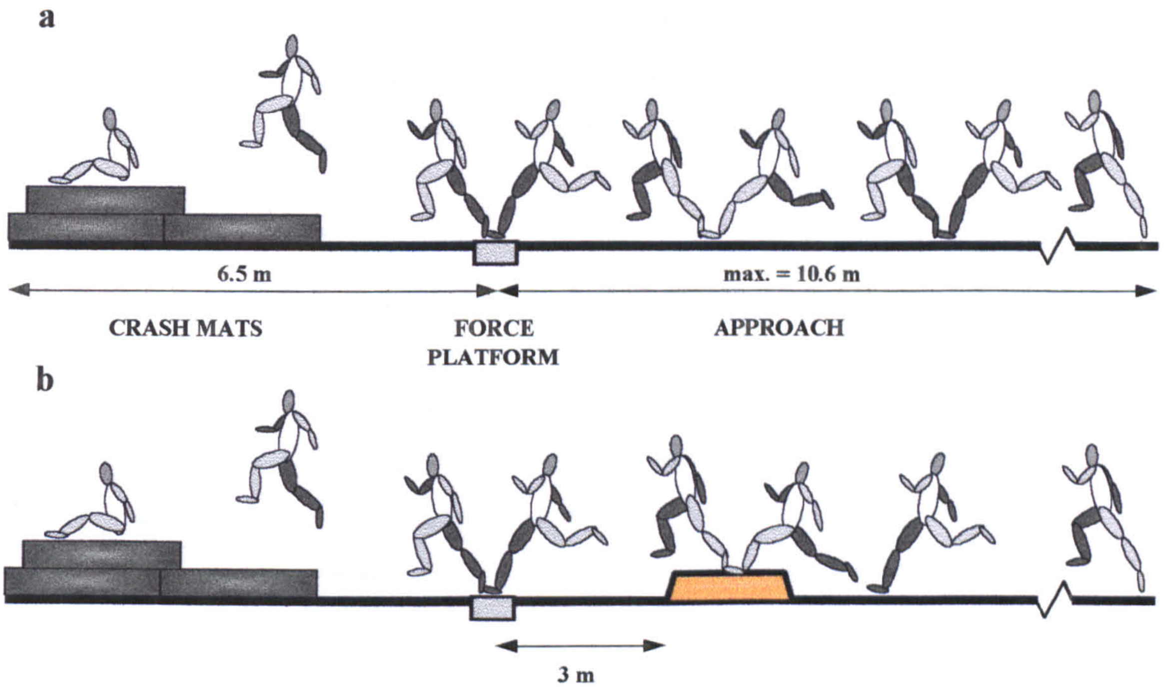


Figure 5.1.1 Diagrams illustrating (a) the 'flat' and (b) the 'drop' approaches.

Data Collection and Analysis

The location of the force platform and constraints of the laboratory meant that high quality three-dimensional cine-film could not be obtained for this study. This was mainly due to the lack of space beyond the force platform and the narrow angle between optical axes of the cameras (less than 40°). It was therefore decided to revert back to a two-dimensional analysis to assess net plantar and dorsi flexor moments of the ankle and net flexor and extensor moments of the hip and knee joints. With respect to the specific aims of this research, the limitation is that net hip adductor and abductor moments can not be assessed. This will however be an area for future study.

Cine-film and force platform data were collected simultaneously as the athletes performed the test described above. A Locam 16 mm high speed cine camera was positioned perpendicular to the runway, approximately 6 m from the force platform and set to record sagittal plane movements at a frequency of 200 Hz. The field of view was approximately 5 m, (2.5 m either side of the force platform). This enabled the take-off into the last stride and a number of frames after take-off to be analysed. Kinetic data were collected on a Kistler force platform (type 9281 B) with dimensions 0.6 m x 0.4 m. The force platform sampled at a frequency of 200 Hz for the long jumpers, but was increased to 500 Hz for the triple jumpers. This was done to facilitate a more precise synchronisation with the film data (see later), but was later reduced to 200 Hz during the synchronisation process. Force platform output included vertical and horizontal (anterior-posterior, or sagittal) ground reaction forces and centre of pressure coordinates.

The digitising system incorporated an NAC analysis projector and a TDS digitising tablet operating through an Archimedes 32 bit computer. The reference origin was located at the front of the force platform through a level corresponding to the mid-line of the take-off foot. The location of the athletes' centre of mass (CM) was calculated using an 18 point, 11 segment model incorporating the segmental mass data proposed by Dempster (1955), (Appendix I). Segmental moments of inertia about the transverse axis were estimated by geometrical solids described by Hanavan (1964). The limitations associated Dempster's (1955) segmental mass ratios and mass centre locations were discussed in section 3.1.2. Errors in segmental moments of inertia data and their effect on resultant joint moments are discussed later.

Following digitisation, the reference origin of the coordinate system was shifted to correspond with the origin of the force platform coordinate system. This ensured that the centre of pressure coordinates corresponded with the kinematic data. Kinematic and kinetic data were synchronised from the instant of touch-down on the force platform and the kinematic data interpolated to the same frequency as the kinetic data. The definition of touch-down in the kinematic data was the first frame in which there was clear contact between the foot and the ground. For the kinetic data the instant of touch-down was defined as the first data point in which the vertical force registered a value above a threshold of 50 N. Take-off was defined as the first frame in which the foot had clearly left the ground for both film and force platform data (i.e. vertical force below 50 N). Prior to synchronisation a comparison of contact times derived from film and force platform data was made. The mean difference in the two measurements for all jumps was 0.004 seconds, with a maximum difference of 0.01 s.

Centre of pressure coordinates in the first and last few frames of contact are known to have large errors (McCaw and DeVita, 1995). To reduce any obvious alignment errors, these coordinates were manually edited and located in the regions of the heel and toe at touch-down and take-off respectively. Net joint moments were then calculated using an inverse dynamics analysis, as outlined by Winter (1980).

Instantaneous changes in muscle-tendon length were calculated for 6 lower extremity muscles, (rectus femoris, vastus medialis, vastus lateralis, vastus intermedius, biceps femoris and gastrocnemius) using the equations provided by Visser et al. (1990) and Grieve et al. (1978):

$$\Delta l_{oi} = A_0 + A_1\theta_i + A_2(\theta_i)^2$$

where Δl_{oi} represents the origin to insertion length relative to the length in the reference position (as a percentage of the segment length), θ_i represents joint angle (in degrees) and $A_{0,}A_1$ and A_2 are constants.

For bi-articular muscles the changes in length were calculated as the algebraic sum of the independent changes of the joints the muscles cross. For the gastrocnemius muscle the constants determined by Grieve et al. (1978) were preferred to those by Visser et al. (1990). This was because Grieve et al. (1978) examined the length changes due to both knee and ankle angles, whereas Visser et al. (1990) only examined the effect of the knee joint angle. Both studies used cadavers and the change in muscle length due to knee flexion and extension alone were similar.

The raw kinematic data were smoothed using a Butterworth 4th order zero lag digital filter with padded end points (Smith, 1989) and a cut-off frequency of 10 Hz. Net joint moments were then calculated and smoothed using the same Butterworth filter, but adopting a cut-off frequency of 14.3 Hz. The cut-off frequencies were chosen from the results of residual analyses performed on the data sets, (Winter, 1990). Data prior to touch-down and after take-off were then deleted and the remaining support phase data were normalised to 100%. Restrictions on time meant that data on only one good trial for the long jumpers could be collected. Several trials of the triple jump take-offs were recorded and two of these were digitised. The mean of the two trials was determined and this data was carried forward for further analysis. Relationships were tested using the Pearson Product Moment Correlation coefficient and differences between take-offs were examined using paired t-tests. To control the risk of making Type I errors the alpha level was set to $P<0.01$ and the number of comparisons was restricted to 20. The familywise Type I error rate was therefore calculated to be 18%. Power and effect size statistics were also calculated to assess the risk of making Type II errors. For paired t-tests the effect size statistic is calculated as the expected mean difference divided by the standard deviation of differences (Elashoff, 1999 - nQuery Advisor Release 3.0). This provides an index of the expected size of the difference between the two jump conditions.

Assessment of errors

The reliability of the data was assessed by the mean deviation of three repeated digitisations of one take-off (Appendix VI). Peak joint angles, angular velocities, moments and joint powers were precise to less than 1°, 0.2 $rad.s^{-1}$, 14 N.m, and 87 W respectively with maximum percentage errors of 1%, 1.6%, 2.7% and 6%.

Estimations of body segmental parameters have been reported to contribute to errors in biomechanical data. The limitations of using segment mass ratios and segmental mass centre locations from cadaver studies were discussed in section 3.1.1, but net joint moments analyses also require accurate segmental mass moment of inertia values. In the current study, segmental moments of inertia are estimated by those typical of geometrical solids in the model of Hanavan (1964). For the lower leg segment Mungiole and Martin (1990) reported a 12.9% difference between Hanavan's (1964) estimate ($4.40 \pm 0.54 \times 10^{-2}$ $kg.m^2$) and their own estimate derived from a magnetic resonance imaging technique ($5.05 \pm 0.76 \times 10^{-2}$ $kg.m^2$). The effect of perturbations in segmental moments of inertia on resultant joint moments was examined by Challis (1996) for walking and maximum vertical jumping. He found that the errors in resultant joint moments introduced by errors in moment of inertia data were very small in both activities. Maximum absolute differences increased from zero about the ankle joint, to 0.2 N.m about the knee and 0.5

N.m about the hip joint. Miller (1987) noted that slight alterations in the inertia characteristics combined with the choice of cut-off frequency in data processing made only small changes of approximately ±4 N.m to the resultant knee joint moment in running trials. Challis (1996) added that the errors associated with moment of inertia estimates are much smaller than other parts of the measurement process, in particular the location of the centre of pressure coordinates.

The potential error in peak joint moments related to mis-alignment of the centre of pressure coordinates with the film data was assessed by a sensitivity analysis and manually shifting the origin forwards and then backwards. A mean error of 34 N.m was found when the origin was displaced by ± 1 cm (Appendix VII), which was similar to the mean error of 44 N.m reported by McCaw and De Vita (1995) in running trials. As the centre of pressure was displaced by ± 4 cm the error increased to around 134 N.m. The alignment of the film coordinate system and centre of pressure coordinates would be expected to be within 1 cm.

A sensitivity analysis was conducted on one long jump performance at the instant of maximum knee flexion to determine the effect of errors on the resultant joint moments. Joint centre location, segmental centre of mass location and acceleration, segmental angular acceleration, choice of segmental body mass and moment of inertia parameters, ground reaction forces and centre of pressure location were pertubated in turn to examine their individual effects (Appendix VIII). Typical errors were determined from repeated digitisations and from the literature. The greatest differences occurred as a result of joint centre and centre of pressure location, up to 38 N.m. The choice of body segmental parameters generally had only a small effect on the resultant joint moment, typically less than 6 N.m. However, in comparison to Zatsiorsky and Seluyanov's (1983) segmental moment of inertia of the upper leg, a difference of 21 N.m was found. The results agree with previous studies highlighting the importance of joint centre location and alignment of the centre of pressure. This is particularly so when the combined effects of all errors are computed. For example, if the centre of pressure is moved by 1 cm in one direction and the joint centre locations are moved by 1 cm in opposite direction, then the relative displacement of 2 cm, creates differences of between 119 N.m and 153 N.m are observed. However, reliability in digitisation and careful synchronisation of film and force data would ensure that errors be kept below 38 N.m. Considering that the error in joint angular velocity measurements are small, typically less than 1 rad.s^{-1} (Appendix VI), then the error in joint power would not be expected to be greater than 38 W (net joint moment x joint angular velocity).

5.1.3 Results

This section begins with a kinematic comparison between simulated and competition take-offs. This helps to identify strengths and weaknesses in the simulation and to account for differences in the kinetic data. Following this, the results of the kinetic and muscle kinematic analyses are presented in graphical and tabulated forms. The results of statistical analyses are presented throughout.

5.1.3.1 Simulation of the 'Flat' and 'Drop' approaches

The first requirement of this study was to devise laboratory based running-jump tests that simulate the characteristics of the long and triple jump take-offs. These take-offs were performed on a force platform in order to collect realistic kinetic data. For comparative purposes, kinematic variables specific to long and triple jump take-offs are presented in table 5.1.2. It can be seen that the major limitation of both types of simulated jump are the smaller horizontal velocity at touch-down, VX_{TD} (approximately 63% of competition jumps). The direct consequences of this are longer support times and lower relative ankle velocities. However, despite this the simulated jumps appeared to characterise the touch-down conditions quite well. The absolute velocity of the ankle, the leg placement at touch-down, (D_{TD} and A_{TD}) and the vertical velocity at touch-down, (VY_{TD}), were generally quite comparable. The reason for the larger touch-down distance, (D_{TD}), in the hop take-off was probably due to the need to gain more height than in actual competition (considering the relatively limited amount of space beyond the force platform). This is reflected somewhat in the gains in vertical velocity from touch-down to take-off. With the exception of the long jumpers, greater gains in vertical velocity were recorded for the simulated jumps; again, this is likely to be a reflection of the slower approach and the limited amount of space. Surprisingly, the knee angle at maximum knee flexion was found to be 10° and 4° more flexed in the simulated jumps than in competition for the long and triple jumpers respectively. As this data were collected out of the competitive season these results may be a reflection of the athlete's conditioning e.g. a slightly increased body mass or the training emphasis being on strength as opposed to speed or technique. Overall the results indicated that the simulation of the jumps in the laboratory were satisfactory considering the constraints of the laboratory. The main limitation was approach speed, and this should be borne in mind when comparing the results of this chapter to actual competition jumps. The effect of a slower approach speed is likely to underestimate the ground reaction forces, net joint moments and joint power.

Table 5.1.2. Kinematic comparisons between competition (Comp) and the simulated ('Flat', 'Drop') take-offs.
D_{TD} = Touch-down distance, A_{TD} = leg placement angle at touch-down,
VX = Horizontal velocity, VY = Vertical velocity.

	D_{TD} (m)	A_{TD} (deg)	Ankle Velocity Abs. ($m.s^{-1}$)	Ankle Velocity Rel. ($m.s^{-1}$)	VX_{TD} ($m.s^{-1}$)	VX loss ($m.s^{-1}$)	VY_{TD} ($m.s^{-1}$)	VY gain ($m.s^{-1}$)	Knee Angle $_{MKF}$ (deg)	Support Time (s)
LONG JUMPERS										
LJ Comp (n=14)	0.55	32.2	4.37	-5.56	9.93	-1.38	-0.18	3.54	140.2	0.14
LJ 'Flat' (n=5)	0.55	31.4	3.48	-3.14	6.62	-1.14	-0.23	3.45	130.9	0.18
Difference	0.00	-0.8	-0.89	2.42	-3.31	0.24	-0.05	-0.09	-9.3	0.04
TRIPLE JUMPERS										
Hop Comp (n=7)	0.39	24.1	3.85	-6.09	9.94	-0.92	-0.68	2.71	134.0	0.14
TJ 'Flat' (n=5)	0.48	27.1	2.30	-4.25	6.55	-1.24	-0.33	3.35	130.2	0.18
Difference	0.09	3.0	-1.55	-1.85	-3.39	-0.32	0.35	0.64	-3.8	0.04
TRIPLE JUMPERS										
Step Comp (n=7)	0.36	21.5	2.60	-6.47	9.07	-0.97	-2.43	4.10	130.6	0.16
TJ 'Drop' (n=5)	0.36	18.7	1.20	-4.15	5.35	-0.85	-2.58	4.97	126.5	0.22
Difference	0.00	-2.8	-1.40	2.33	-3.72	0.12	-0.15	0.87	-4.0	0.06

5.1.3.2 Comparison between 'Flat' and 'Drop' approaches

This section examines only the 5 triple jump athletes as they performed both types of jump. As direct comparisons can be made between the two jumps, forces, joint moments and joint power characteristics have been reported in absolute terms. Differences between key characteristics of the graphs, e.g. touch-down, peak and minimum values were examined using paired t-tests.

Ground Reaction Forces

Figure 5.1.2 shows the mean normalised vertical ground reaction force (VGRF) curves for flat and drop approaches. The graphs show a characteristic impact peak following touch-down, followed by a trough and then a further peak shortly afterwards. The first peak is commonly referred to as the 'impact peak' and this occurs within the first 15% of take-off. Results indicate that the impact peak occurs significantly earlier, and with much greater magnitude in the 'drop' than in the 'flat' approach, (both $P<0.01$). In relative terms the average impact peak was 4.5 and 7.0 x BW in the flat and drop approaches respectively. The VGRF was then observed to decrease to a minimum value at approximately 20% of support. This observation agrees with Ramey (1970) who referred to this initial period, from touch-down to trough, as the 'impact region'. The timing and magnitude of this trough was similar in both jumps. The VGRF then increases to a second peak known as the 'drive peak' before decreasing to zero at take-off. Ramey (1970) referred to the period between the trough and take-off as the 'thrust region'. The drive peak was found to occur significantly earlier in the drop approach compared to the flat approach, (33% compared to 46% of support, $P<0.01$). Although the mean drive peak was greater in the drop take-off (4.5 x BW), compared to the flat take-off (4.0 x BW) this fell short of the $P<0.01$ significance level. It would appear that the drop approach places a far greater demand on the athlete, not only in terms of the magnitude of the forces, but also on the rate of loading. This can be seen by the steeper gradients leading to the impact peak, to the trough and to the drive peak in figure 5.1.2. The average VGRF's over the support phases were 2.8 and 3.2 x BW for the flat and drop approaches respectively.

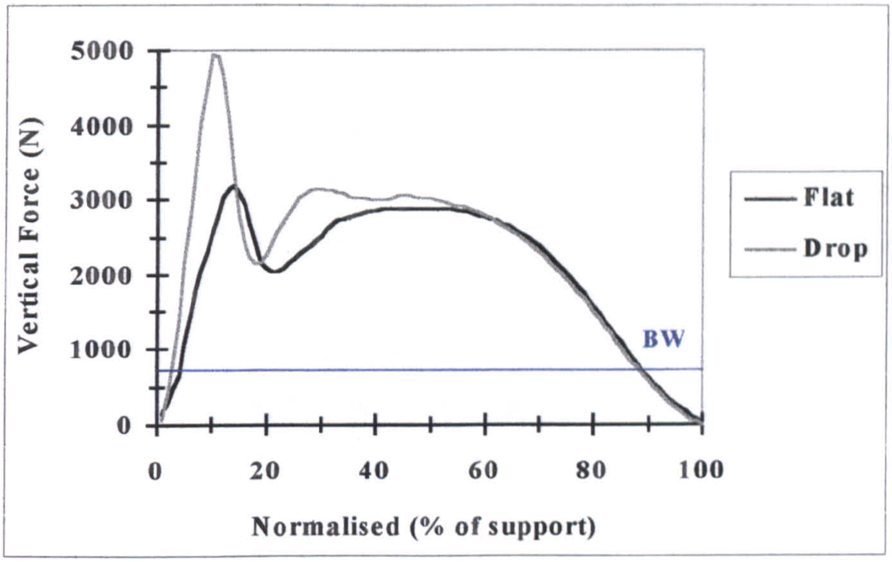


Figure 5.1.2 Graph to show the mean vertical ground reaction force in the flat and drop approach take-offs.

Table 5.1.3 Analysis of vertical ground reaction force graphs.

Vertical GRF	FLAT		DROP				Effect	Power
	Mean	SD	Mean	SD	t	P	Size	%
Force (N)								
Impact peak (N)	3250	785	5080	248	7.04	0.002	3.15	79
Trough (N)	1780	662	2090	666				
Drive peak (N)	2910	381	3240	477	3.35	0.029	1.50	
Temporal (% of support)								
t Impact Peak	13.8	1.1	10.5	0.8	-7.12	0.002	3.18	80
t Trough	21.1	2.7	18.2	0.4				
t Drive Peak	46.1	5.2	32.6	3.7	-8.45	0.001	3.57	98

The profile of the horizontal ground reaction force (HGRF) can be seen in figure 5.1.3. Both graphs are characterised as having a peak braking force early into the take-off, (10% to 15%), followed by a propulsive peak close to the instant of take-off, (around 85% to 90% of support). The magnitude of the braking peak was similar for both jumps, typically 2.4 x BW to 2.6 x BW, but tended to occur earlier into the drop take-off than in the flat. The instant at which the HGRF is zero, i.e. the point of 'crossover' is indicative of the resultant force being vertical. Therefore this point would be expected to be synonymous with the instant of Tx=0 in sections 4.1 and 4.2, i.e. when the centre of mass is directly above the toe. The results found that the instants of Tx=0 and 'crossover' occurred at 71% and 75% of support in the flat approach, and 56% and 61% of support in the drop approach. Therefore, although there is a difference of approximately 5%, these points give a good indication of when the braking phase and pivot action end. As the HGRF becomes positive the resultant GRF is directed backwards as the athlete attempts to drive the body forwards. The period between the instants of crossover and take-off can be regarded as the 'drive phase' when athletes generally recover some horizontal velocity. The observation that the instant of crossover occurs earlier in the drop than in the flat approach, ($P<0.01$), indicates that the drop approach has a relatively shorter braking phase and longer drive phase. The propulsive peak was found to be greater and to occur earlier in the drop approach, (0.5 x BW at 85% of support), than in the flat approach (0.3 x BW at 90% of support). Although these were both slightly above the $P<0.01$ level, the large effect sizes indicate that these are likely to be characteristic differences. The mean HGRF's over the take-off phases were -0.7 x BW and -0.3 x BW for the flat and drop take-offs respectively.

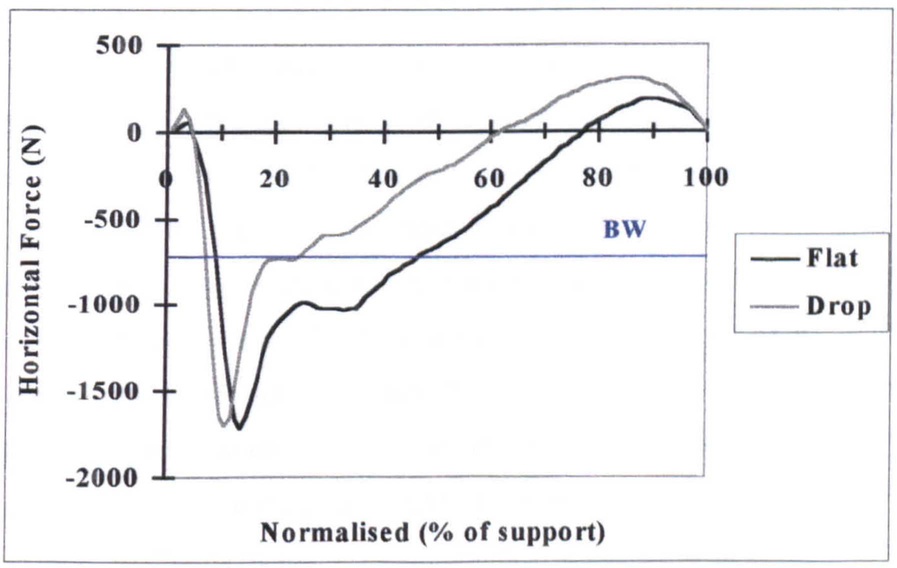


Figure 5.1.3 Graph to show the mean horizontal (braking-propulsion) ground reaction force in the flat and drop approach take-offs.

Table 5.1.4 Analysis of horizontal (braking-propulsion) ground reaction force graphs.

Horizontal (braking-propulsion) GRF	FLAT		DROP		t	P	Effect Size	Power %
	Mean	SD	Mean	SD				
Force (N)								
Braking peak (N)	-1750	531	-1860	531	-0.30	0.780	0.13	
Propulsive peak (N)	213	48	327	101	3.85	0.018	1.72	
Temporal (% of support)								
t Braking Peak	15.3	3.3	10.7	0.6	-2.92	0.043	1.31	-
t Crossover	75.9	6.0	62.6	6.1	-9.04	0.001	4.04	95
t Propulsive Peak	90.0	1.8	84.7	4.4	-4.50	0.011	2.01	55

The horizontal and vertical GRF's reported above are a reflection of the athlete's technique and body alignment during the take-off phase. Figure 5.1.4 shows a sequence of kinetograms with resultant GRF (RGRF) of an athlete performing a 'flat' approach take-off. The scale of the GRF in Frame 1 has been adjusted to 1 m = 50 N to make the force line visible. In all other frames the scale is 1 m = 2000 N. It can be seen in Frame 1 (touch-down) that the GRF is almost vertical and its line of action goes almost directly through the ankle joint. Immediately after touch-down the RGRF is directed backwards, the line of action of which bisects the ankle, knee and hip joints, and the centre of pressure, or point of force application shifts from the heel region towards the forefoot, (Frame 5). With respect to the direction of the RGRF about each joint, the line of action passes in front of the ankle joint throughout the entire take-off. In the later part of the take-off the RGRF passes to the rear of the hip (between Frames 17 and 27) and to the front of the knee joint (Frame 27). At the instant of 'crossover', the RGRF is vertical and the HGRF is zero. At this instant (Frame 27), the centre of mass is marginally in front of the point of force application, and is directly above the toes. It can be seen that the peak braking force (HGRF) and the peak 'impact' vertical force (VGRF) coincide with the peak hip moment (Frame 6) and that the peak knee moment occurs around maximum knee flexion (MKF, Frame 15). The peak moment about the ankle joint was found to occur in Frame 17.

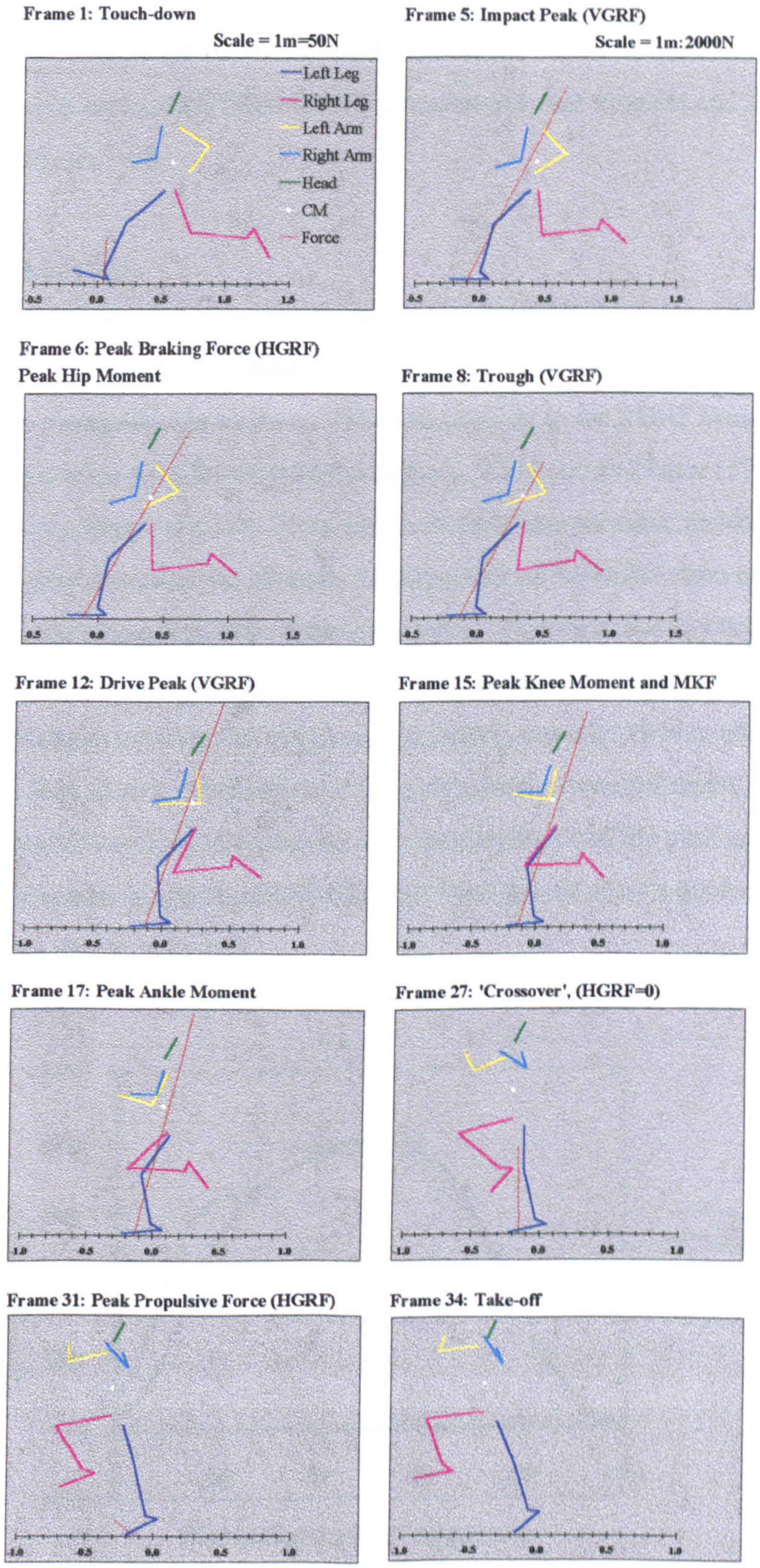


Figure 5.1.4 Kinetograms and resultant ground reaction force (RGRF) at critical instants in a 'flat' approach take-off.

Joint Moments

Figures 5.1.5 to 6 show the net moments of force about the ankle, knee and hip joints. The sum of these moments is referred to as the total extensor moment and this is presented in figure 5.1.8.

<u>Ankle Moment</u>

It can be seen in figure 5.1.5 that the net moment about the ankle joint is positive throughout the whole take-off phase. The positive value indicates that the ankle joint experiences a plantar-flexing moment. This is mainly due to the RGRF being located to the front of the ankle joint for most of the support. However, as Winter (1990) noted, the net moments about each joint takes into account segmental mass, inertia and acceleration characteristics and, as such, the alignment of the RGRF does not indicate whether the joint moments will be flexor or extensor. However, this is more important for the analysis of the knee and hip joints. At touch-down the ankle moment is relatively small, and similar in both the flat and drop approaches, typically 20 N.m and 53 N.m. Both graphs then show a steady increase to reach a peak extensor moment approximately 45% to 55% into the take-off. The magnitude of the peak ankle moment is also similar reaching approximately 400 N.m. Both graphs show a gradual reduction, tapering off to zero by take-off.

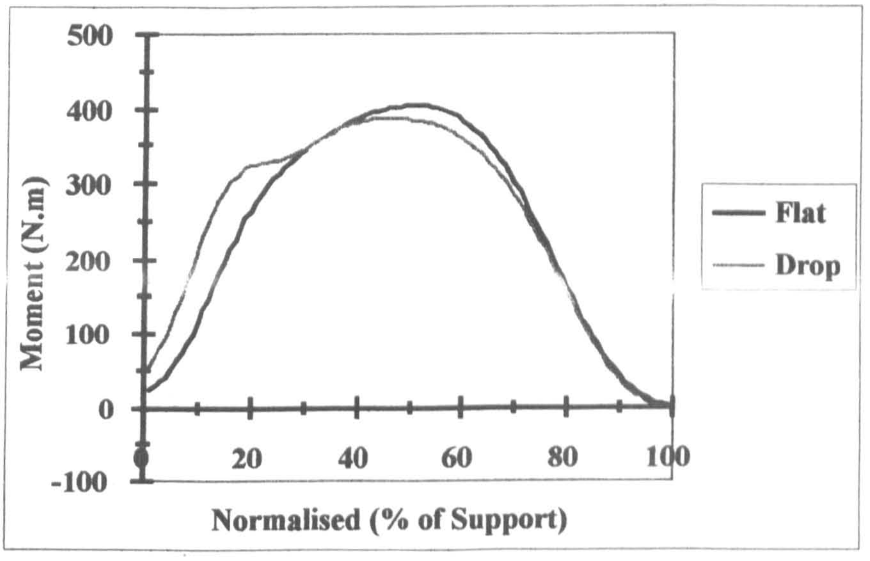


Figure 5.1.5 Graph to show the mean ankle moment in the flat and drop approach take-offs.

Table 5.1.5 Analysis of the ankle moment graphs.

Ankle Moment	FLAT		DROP				Effect	Power
	Mean	SD	Mean	SD	t	P	Size	%
Moment (N.m)								
Touch-down	20	22	53	21				
Peak	403	38	387	80	-0.49	NS	0.22	
Take-off	-1	3	-3	4				
Temporal (% of support)								
t Peak	50.8	3.1	46.6	3.1				

Knee Moment

Figure 5.1.6 shows the profile of the knee joint moment for both flat and drop approaches. It can be seen that the moment is negative at touch-down indicating a net flexor moment. The results indicate that the net knee flexor moment at touch-down in the flat take-off (-110 N.m) is greater than in the drop approach (-46 N.m). Although statistically this fell short of the $P<0.01$ significance level, the large effect size of 1.52 indicates that this is likely to be a characteristic difference. Shortly after touch-down the moment becomes extensor (positive), reaching a peak approximately 49% into the support phase of the flat approach and 39% in the drop take-off. The magnitude of the peak knee moment was also found to be similar recording mean values of 233 N.m and 296 N.m. At take-off the moment drops slightly below zero indicating a small flexor moment, and again this is of similar magnitude in both take-offs.

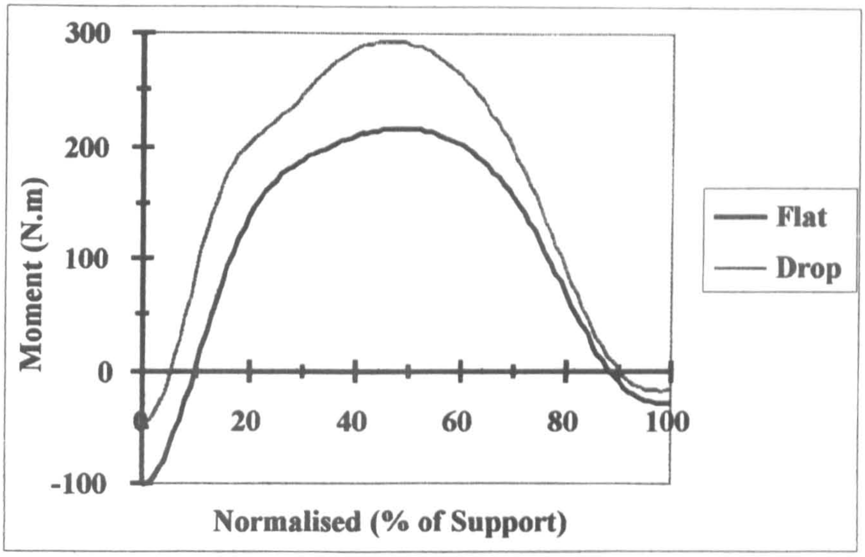


Figure 5.1.6 Graph to show the mean knee moment in the flat and drop approach take-offs.

Table 5.1.6 Analysis of the knee moment graphs.

Knee Moment	FLAT		DROP				Effect	Power
	Mean	SD	Mean	SD	t	P	Size	%
Moment (N.m)								
Touch-down	-110	36	-46	39	3.41	0.027	1.53	
Peak	233	77	296	134	1.82	0.140	0.81	
Take-off	-26	14	-15	14				
Temporal (% of support)								
t Peak	49.8	9.0	39.2	14.2				

Hip Moment

Figure 5.1.7 shows the moment of force about the hip joint. In both the flat and drop approach take-offs the hip has a large positive extensor moment at touch-down, and is significantly greater in the flat take-off, 248 N.m, than in the drop, 84 N.m, ($P<0.01$). The net hip moment reached a peak around 20% to 28% of support and was similar in magnitude for both flat and drop take-offs, 292 N.m and 249 N.m respectively. Between 60% to 70% of support the moment becomes flexor, and this reaches a peak towards the end of the take-off. At take-off the net flexor moment is similar, -69 N.m and -93 N.m for the flat and drop take-offs respectively.

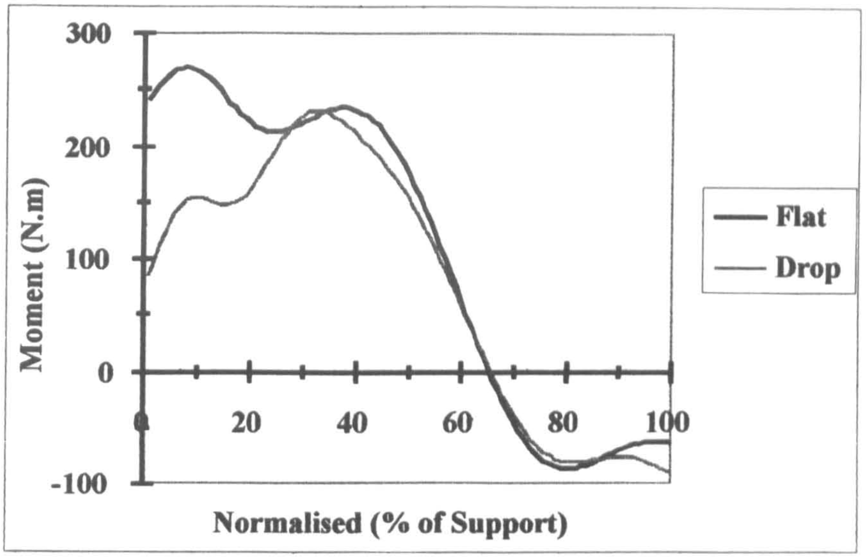


Figure 5.1.7 Graph to show the mean hip moment in the flat and drop approach take-offs.

Table 5.1.7 Analysis of the hip moment graphs.

Hip Moment	FLAT		DROP		t	P	Effect Size	Power %
	Mean	SD	Mean	SD				
Moment (N.m)								
Touch-down	248	65	84	67	-5.93	0.004	2.65	80
Peak	292	74	249	48	-0.83	0.450	0.37	
Take-off	-69	38	-93	35				
Temporal (% of support)								
t Peak	20.4	16.1	28.6	10.9				

Total Extensor Moment

The sum of the ankle, knee and hip joint moments is referred to as the 'support' or 'total extensor' moment and this is presented in figure 5.1.8. This graph represents a total limb pattern to push away from the ground, (Winter, 1990). The results indicate that for approximately 85% of support in both types of take-off the net moment is extensor, and in the last 15% it is flexor. The peak extensor moment appeared to occur slightly earlier in the drop take-off, 39.6%, than in the flat approach, 42.6%, and the magnitude of the peak moment was similar with values of 881 N.m and 833 N.m respectively. At the instant of take-off net flexor moments were exhibited in both types of take-off with mean values of -95 N.m and -111 N.m.

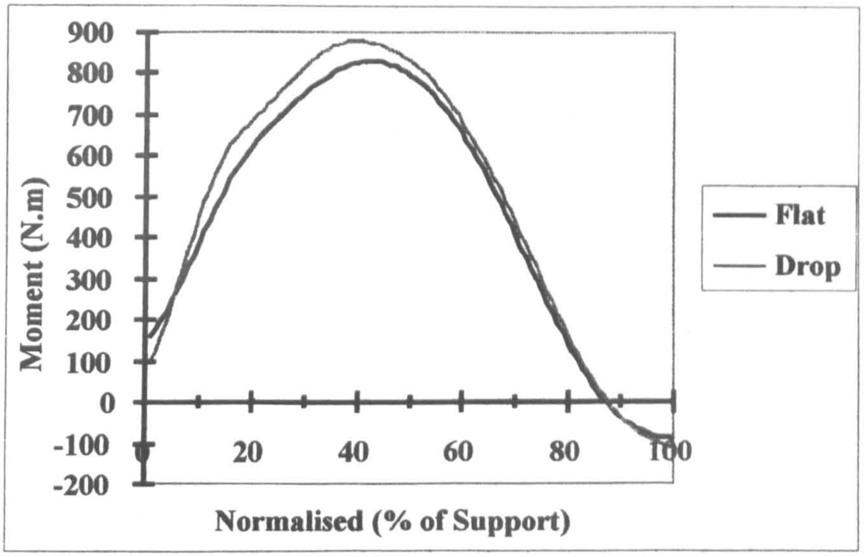


Figure 5.1.8 Graph to show the mean total extensor moment in the flat and drop approach take-offs.

Table 5.1.8 Analysis of the total extensor moment graphs.

Total Extensor Moment	**FLAT**		**DROP**	
	Mean	**SD**	**Mean**	**SD**
Moment (N.m)				
Touch-down	158	60	91	43
Peak	833	128	881	129
Take-off	-95	28	-111	29
Temporal (% of support)				
t Peak	42.6	2.3	39.6	2.3

Joint Angular Velocities

Ankle Angular Velocity

Figure 5.1.9 shows the angular velocity of the ankle joint in flat and drop approaches. Positive values indicate that the ankle joint is plantar-flexing and negative values indicate dorsi-flexion. The graphs follow a similar trend, characterised by having positive angular velocity at touch-down, becoming negative as the ankle joint compresses and back to positive as the ankle joint plantar flexes in the extension phase. The minimum angular velocity, or dorsi-flexion velocity, was similar in magnitude, -6 rad.s^{-1}, but was found to occurred slightly earlier in the drop approach than in the flat, (25.0% and 32.5% of support respectively). The minimum ankle angle, denoted by zero angular velocity, was found to occur between 55% and 60% of support in both take-offs. As the ankle plantar-flexed in the extension phase it was found to reach a peak angular velocity of approximately 15 $rad.s^{-1}$ and this occurred between 86% and 89% of support. Peak plantar flexion velocity was similar in magnitude and timing between flat and drop approaches.

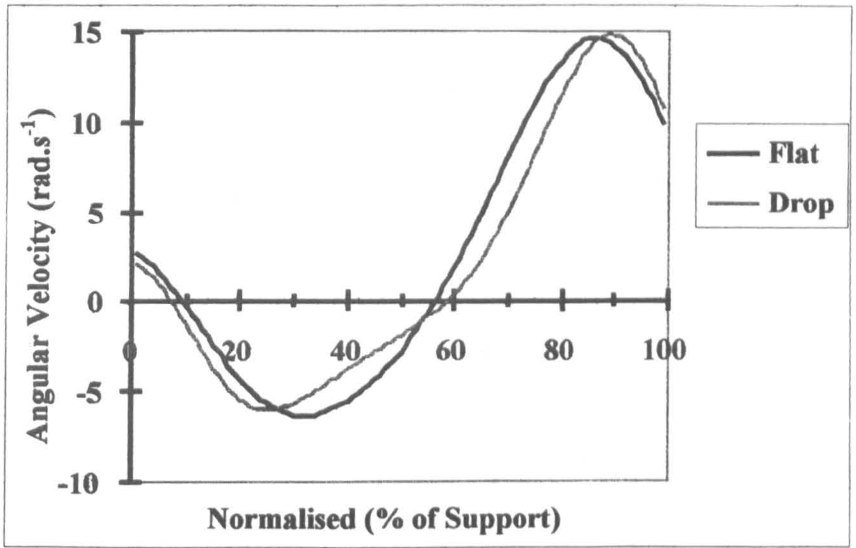


Figure 5.1.9. Graph to show the mean ankle angular velocity in the flat and drop approach take-offs.

Table 5.1.9 Analysis of the ankle angular velocity graphs.

Ankle Angular Velocity	FLAT		DROP	
	Mean	**SD**	**Mean**	**SD**
Angular Velocity ($rad.s^{-1}$)				
Touch-down	3.0	1.4	2.2	1.9
Minimum	-6.5	0.5	-6.2	0.6
Peak	15.2	0.9	15.0	1.0
Take-off	9.4	2.0	10.0	2.0
Temporal (% of support)				
t Minimum	32.5	2.9	25.0	2.6
t Peak	86.2	2.2	89.2	2.4

Knee Angular Velocity

Figure 5.1.10 shows the angular velocity of the knee joint. As with the ankle joint, the knee shows a flexion peak followed by an extension peak, and the graphs of the flat and drop approach take-offs are almost identical. At touch-down the knee has negative angular velocity which indicates a small amount of flexion prior to contact. The flexion angular velocity was found to peak (Minimum in table 5.1.10) around 17% of support in both take-offs. The peak flexion angular velocity was slightly greater in the drop approach take-off, 8.9 rad.s^{-1}, than in the flat, -7.7 rad.s^{-1}. The knee stopped flexing between 45% and 50% of support, denoted by a zero angular velocity, which is consistent with the results presented in sections 4.1 and 4.2. The knee joint can then bē seen to reach a peak extension velocity around 80% of support in both take-offs and the magnitude of this reaches approximately 11 rad.s^{-1}. As the knee approaches almost full extension by take-off, typically 170°, the angular velocity can be seen to decrease to zero.

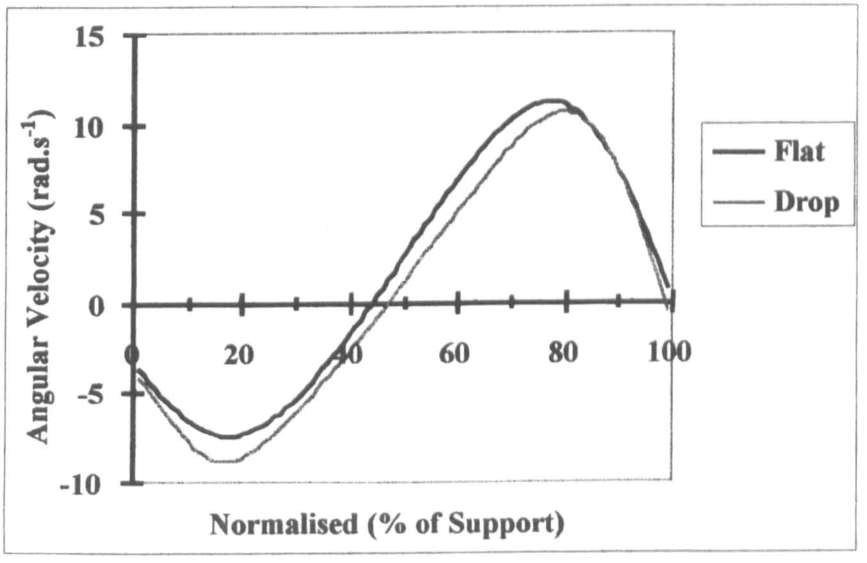


Figure 5.1.10 Graph to show the mean knee angular velocity in the flat and drop approach take-offs.

Table 5.1.10 Analysis of the knee angular velocity graphs.

Knee Angular Velocity	**FLAT**		**DROP**	
	Mean	**SD**	**Mean**	**SD**
Angular Velocity (rad.s^{-1})				
Touch-down	-3.3	1.9	-4.0	1.2
Minimum	-7.7	0.4	-8.9	0.8
Peak	11.5	1.0	11.1	1.5
Take-off	0.2	3.0	-1.6	4.1
Temporal (% of support)				
t Minimum	17.7	2.7	17.0	1.2
t Peak	78.1	5.3	79.4	3.2

Hip Angular Velocity

Figure 5.1.11 shows the angular velocity of the hip joint. It can be seen that both types of take-off demonstrate positive angular velocity at touch-down. This is indicative of the athlete extending the hip and sweeping the leg backwards prior to touch-down. This supports the findings of the kinematic analyses in the previous chapters. From this initial positive value, the angular velocity then decreased to a minimum value in the compression phase. The mean minimum angular velocity in the flat approach was positive, 0.3 rad.s^{-1}, whilst in the drop take-off it was negative, -3.3 rad.s^{-1}. The negative value indicates that the athletes experienced hip flexion, which was not observed in the kinematic analyses in chapters 4.1 and 4.2. Indeed while the mean minimum angular velocity was positive in the flat approach, 3 of the 5 athletes actually flexed, while all flexed in the drop take-off. Hip flexion ceased around 40% of support in the drop take-off, which was prior to the end of knee flexion. The hip then entered a period of extension, denoted by positive angular velocity, and reached a peak around 75% to 80% of support. Hip extension angular velocity appeared to be greater in the flat take-off, 11.8 rad.s^{-1}, than in the drop take-off, 10.5 rad.s^{-1}. The angular velocity then decreased in the late extension phase as the athletes characteristically hyper-extend the hip, reaching angles of around 188°.

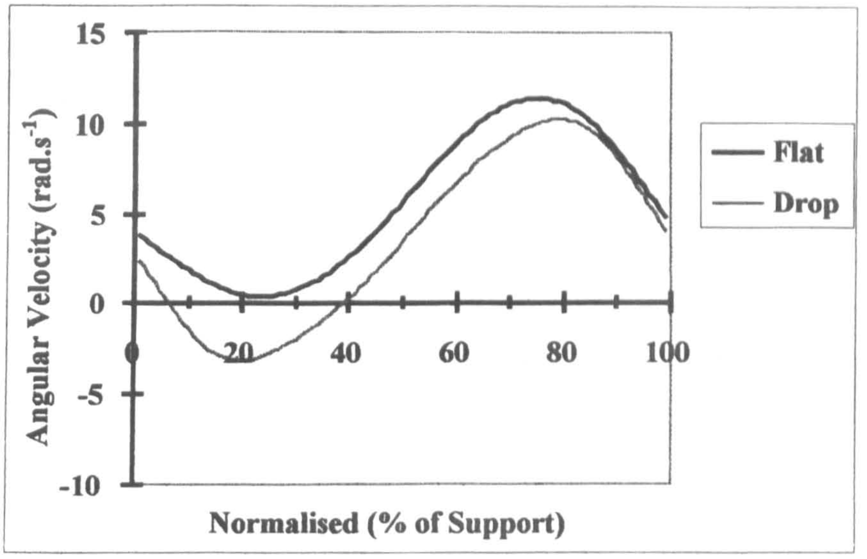


Figure 5.1.11 Graph to show the mean hip angular velocity in the flat and drop approach take-offs.

Table 5.1.11 Analysis of the hip angular velocity graphs.

Hip Angular Velocity	**FLAT**		**DROP**	
	Mean	**SD**	**Mean**	**SD**
Angular Velocity ($rad.s^{-1}$)				
Touch-down	3.8	1.0	2.4	1.1
Minimum	0.3	1.1	-3.3	0.7
Peak	11.8	1.1	10.5	1.3
Take-off	4.5	1.9	3.4	2.5
Temporal (% of support)				
t Minimum	21.2	3.8	19.8	2.1
t Peak	76.3	5.3	79.1	4.3

Joint Power

The product of the joint moment and joint angular velocity at any instant in time gives the joint power. Figures 5.1.12 to 14 show the joint power curves of the ankle, knee and hip joints in the flat and drop take-offs. In these figures, positive power indicates that the net muscle activity is concentric, while negative power represents a net eccentric action about the joint.

Ankle Power

The analysis shows that the musculature around the ankle joint works eccentrically for the first 56% of support, after which muscle activity becomes concentric. Both graphs show a peak negative power of over 2000 W, but appears to occur significantly earlier in the support of the drop take-off, 27%, compared to 35% in the flat take-off. The peak positive, or concentric power of the ankle was found to occur around 75% of support in both take-offs. The results indicated that athletes generated around 2600 W of positive power in the flat approach take-off, compared to 1916 W in the drop take-off. Although this difference was not significant, an effect size of 1.0 indicates that further study may find this to be a characteristic difference.

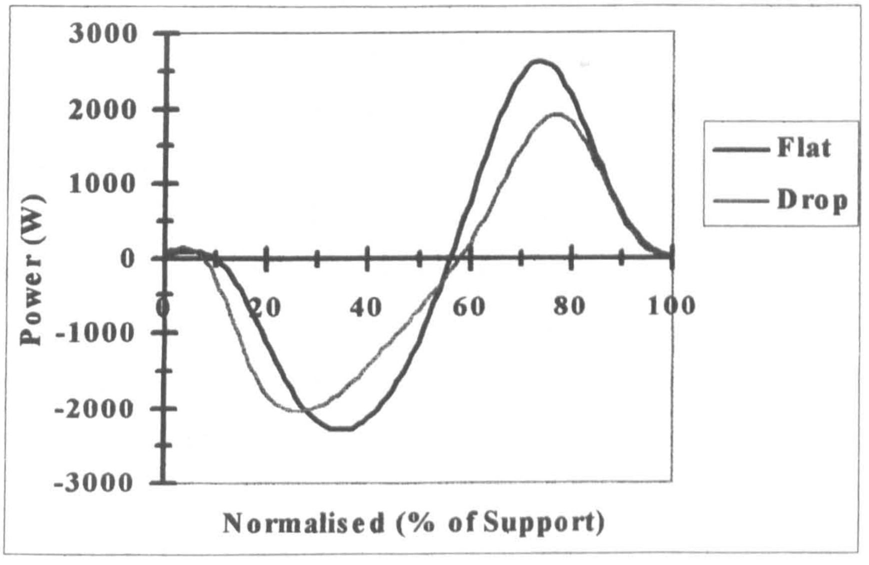


Figure 5.1.12 Graph to show the mean ankle joint power in the flat and drop approach take-offs.

Table 5.1.12 Analysis of the ankle joint power graphs.

Ankle Power	FLAT Mean	FLAT SD	DROP Mean	DROP SD	t	P	Effect Size	Power %
Power (W)								
Touch-down	54	67	103	144				
Minimum	-2320	274	-2090	626	0.65	0.550	0.29	
Peak	2600	474	1920	634	-2.24	0.089	1.00	
Take-off	-5	35	-17	33				
Temporal (% of support)								
t Minimum	35.0	3.2	27.0	3.9				
t Peak	73.8	2.5	77.2	1.3				

Knee Power

The power of the knee joint can be seen in figure 5.1.13. As with the ankle joint, the knee shows an initial eccentric phase which is followed by a concentric phase when the knee extends. The transition from eccentric to concentric (negative to positive) was found to occur around 40% to 50% of support, which relates to the instant of maximum knee flexion. There was some evidence to indicate that the knee joint generates more eccentric power in the drop take-off (-1830 W) than in the flat (-1150 W) ($P<0.029$, effect size = 1.49). The timing of this peak was similar, occurring around 20% and 25% of support. A peak concentric knee power of around 1730 W was found to occur at approximately 70% of support in both take-offs.

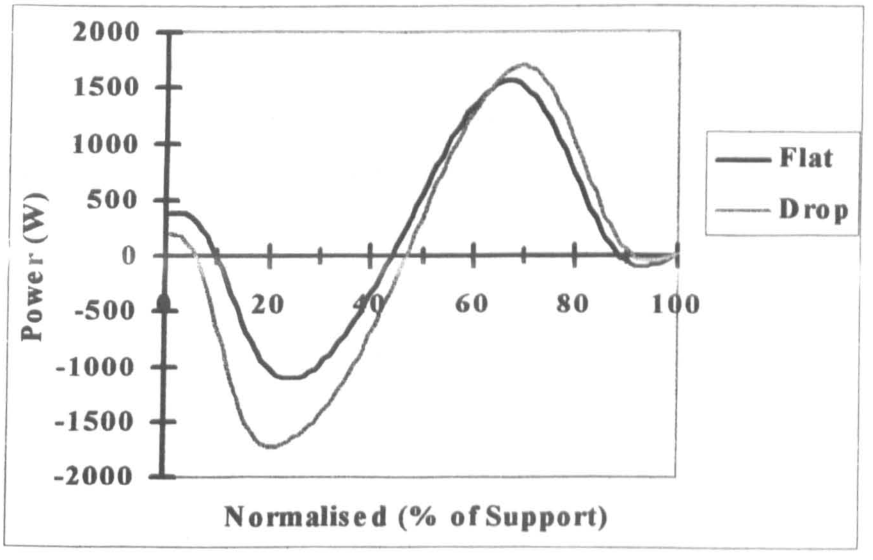


Figure 5.1.13 Graph to show the mean knee joint power in the flat and drop approach take-offs.

Table 5.1.13 Analysis of the knee joint power graphs.

Knee Power	FLAT		DROP				Effect	Power
	Mean	SD	Mean	SD	t	P	Size	%
Power (W)								
Touch-down	345	198	196	195				
Minimum	-1140	365	-1830	735	-3.33	0.029	1.49	
Peak	1740	583	1730	917	-0.03	0.97	0.02	
Take-off	11	95	13	75				
Temporal (% of support)								
t Minimum	24.4	1.8	20.8	3.6				
t Peak	67.8	4.9	70.0	2.7				

Hip Power

The hip power graphs in figure 5.1.14 highlight a few noticeable differences between the two types of take-off. At touch-down the hip joint possesses more power in the flat approach, 939 W compared to 163 W in the drop take-off. While both graphs follow similar trends, the results indicate that the compression phase in the flat take-off is concentric while in the drop take-off it is eccentric. This can be seen by the mean minimum power values of 48 W and -665 W respectively, ($P<0.01$). This finding is explained by the negative hip angular velocity in the compression phase as previously noted. In the drop take-off the eccentric phase ends at approximately 40% of support, after which the net muscle activity becomes concentric. Peak concentric hip power occurs around 50% to 53% of support in both take-offs, and reaches magnitudes of 1050 W in the flat approach and 638 W in the drop take-off, (NS). Between 60% and 70% of support the net muscle activity becomes eccentric, and this continues until take-off. Eccentric activity reaches peak values of -1150 W and -1040 W between 81% and 84% of support in the flat and drop take-offs respectively.

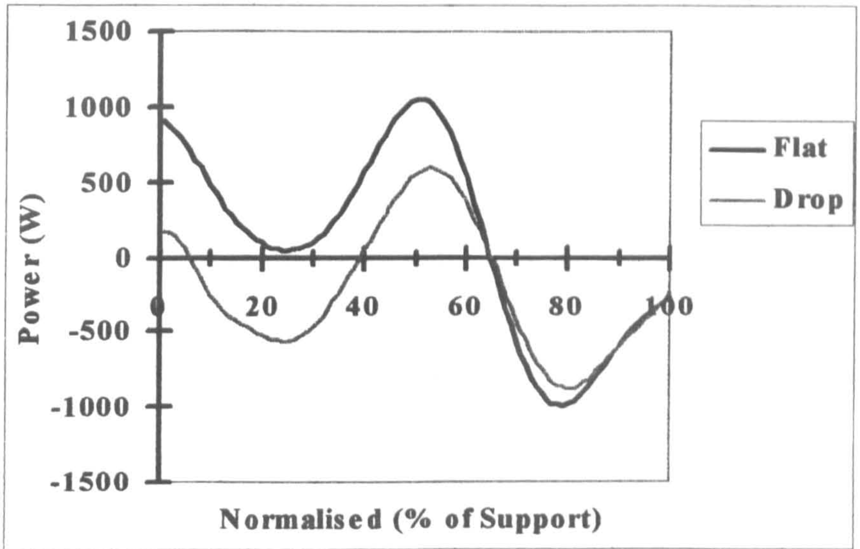


Figure 5.1.14 Graph to show the mean hip joint power in the flat and drop approach take-offs.

Table 5.1.14 Analysis of the hip joint power graphs.

Hip Power	FLAT		DROP				Effect	Power
	Mean	SD	Mean	SD	t	P	Size	%
Power (W)								
Touch-down	939	345	163	159				
Minimum1	48	265	-665	230	-5.54	0.005	2.48	74
Peak	1050	529	638	425	-1.23	0.290	0.55	
Minimum2	-1150	813	-1040	755				
Take-off	-312	259	-224	190				
Temporal (% of support)								
t Minimum 1	24.8	3.7	24.2	6.7				
t Peak	50.8	4.0	53.4	3.4				
t Minimum 2	81.2	4.3	84.0	8.5				

The phasing of the peak joint powers was found to follow a consistent pattern, starting from the hip around 50% of support, followed by the knee around 70% and then the ankle around 75% of support. This can be seen in the mean graph of the 'flat' approach take-offs in figure 5.1.15. However, although the temporal flow of power was consistent in all flat and drop take-offs analysed, the magnitude of the peak powers did not always increase in the same order. In the flat approach one athlete produced a greater hip power than the knee, and another athlete produced greater knee power than the ankle. In the drop take-off 2 athletes produced greater knee power than ankle power and one athlete generated more hip power than knee power. The lack of a consistent pattern amongst the athletes suggests that the magnitude of joint power may be a function of technique or be related to the muscular strength about each joint. Another explanation would be the effect of poor synchronisation and mis-alignment of the centre of pressure location with the film data. However, great care was taken to ensure that this was not a major factor, and joint power was expected to be accurate to within 38 W.

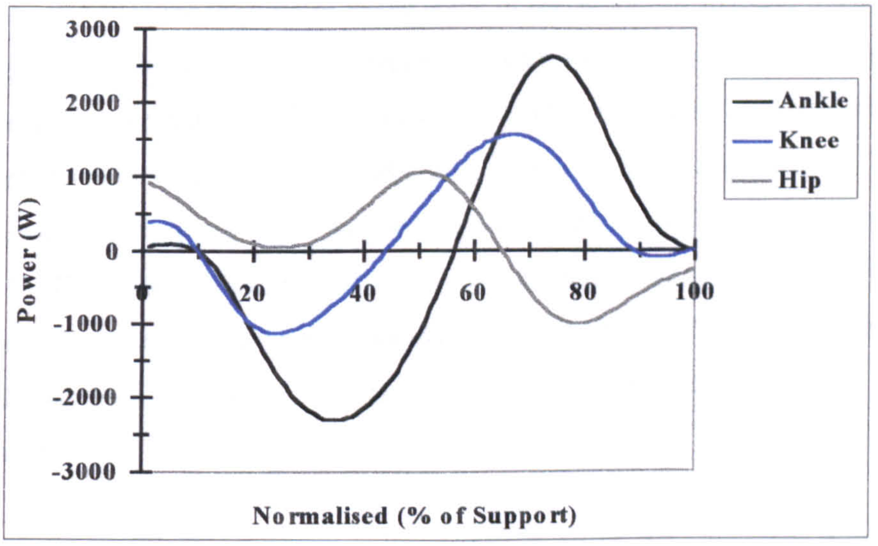


Figure 5.1.15 Graph to show the mean flow of joint power in the flat approach take-off.

5.1.3.3 Relationships between Ground Reaction Forces, Net Joint Moments and the Kinematics of take-off.

As an extension to the pivot model (figure 1.2) it is theorised that differences in technique will have an affect on the magnitude of ground reaction forces and their distribution about the joints of the lower extremity. The associations between variables relating to the athlete's body positioning throughout the take-off and net joint moments need to be identified if the biomechanist is to offer advice on the strength requirements associated with an individual's technique.

As both long jumpers and triple jumpers performed the 'flat' approach take-off this has effectively given a sample of 10 athletes. Data from both long and triple jumper's have therefore been combined for this section. To control the effects of anthropometric differences between the athletes the horizontal and vertical ground reaction force data were normalised to the athlete's body weight, and the joint moments were normalised to body weight multiplied by body height. This makes the values dimensionless.

It has been shown in the previous chapters that long and triple jumpers generate vertical velocity at the expense of losing some of the horizontal velocity developed in the approach. Using the impulse - change in momentum relationship, the average horizontal and vertical ground reaction forces (GRF) can be used to assess the changes in velocity during the take-off phase. Indeed a very strong negative relationship was found between the average horizontal and vertical GRFs, ($r=-0.919$, $P<0.01$). This indicates that 84.5% (R^2) of the variance in the average vertical GRF can be explained by the variance in the average horizontal GRF, and therefore provides supporting evidence of a trade-off between horizontal and vertical movement.

The technique variables tested for their relationships with the average horizontal and vertical GRFs and the average net joint moments were selected from the pivot model described earlier. It was decided to focus on the movement of the knee joint rather than the ankle and hip joints as the previous sections have highlighted the knee to be more significant. The hip extension angle at touch-down was not selected because it was felt that the angle of leg placement at touch-down, A_{TD}, accounted for differences in trunk angle and therefore the hip extension angle, section 4.2. The angle of the foot at ground contact was not measured in this study as it was felt that the knee angle and leg placement angle at touch-down would have a greater affect on the data. However, all athletes made contact with the heel and within two frames the foot was firmly planted on the force platform.

The relationships between each of these parameters and the average ground reaction forces and average joint moments can be seen in table 5.1.15.

Table 5.1.15 Relationships between kinematic characteristics and average GRF's and joint moments in the flat approach take-off (R^2 values given in brackets).

	Average Force		Average Joint Moments		
Kinematic Variable	Horizontal	Vertical	Ankle	Knee	Hip
Leg Placement Angle, A_{TD}	-0.597 (35.6%)	0.396 (15.7%)	-0.323 (10.4%)	0.009 (0%)	0.485 (23.5%)
Knee Angle $_{TD}$	-0.706* (49.8%)	0.563 (31.7%)	0.212 (4.5%)	-0.555 (30.8%)	0.468 (21.9%)
Knee Angle $_{MKF}$	-0.285 (8.1%)	0.465 (21.6%)	0.440 (19.4%)	-0.869** (75.5%)	0.339 (11.5%)
Knee Angle $_{TO}$	-0.539 (29.1%)	0.409 (16.7%)	0.317 (10.0%)	-0.554 (30.7%)	0.537 (28.8%)
Relative Ankle Velocity $_{TD}$	-0.199 (4.0%)	0.017 (0%)	-0.451 (20.3%)	0.151 (2.3%)	0.341 (11.6%)

*$P<0.05$; ** $P<0.01$

A negative relationship was found between the leg placement angle at touch-down and the average horizontal force. The coefficient of determination indicates a moderate level of association, 35.6%, and implies that greater angles of leg placement at touch-down are related to greater losses in horizontal velocity. The knee angle at touch-down was found to explain almost half of the variance in the average horizontal force, 49.8% and almost a third of the variance in the average vertical force, 31.7%. The negative relationship between the knee angle at touch-down and the average horizontal force indicates that more extended knee joints are associated with greater losses in horizontal velocity. Likewise, the positive relationship with the average vertical force suggests that greater knee extension angles at touch-down are associated with greater gains in vertical velocity. The knee angle at maximum knee flexion was found to explain 21.6% of the variance in the average vertical force. Although 78.4% of the variance remains unexplained, the positive relationship indicates that less knee flexion is moderately associated with greater gains in vertical velocity. These results support the findings of sections 4.1 and 4.2.

With respect to the relationships between technique and average joint moments, two main observations can be made. Firstly, the angle of leg placement at touch-down was found to have a positive relationship and a moderate level of association with the average hip joint moment, accounting for 23.5% of the variance. Secondly, the knee angle at the instants of touch-down, maximum knee flexion and take-off were found to exhibit negative relationships with the average knee moments and positive relationships with the average hip joint moments. This indicates that the angle of the knee may be a critical factor in distributing the forces about the knee and hip joints. However, this could only be proven through an intervention study. The results found here indicate moderate levels of association between the knee angle at touch-down and the average knee and hip joint moments, accounting for 30.8% and 21.9% of their variances respectively. At maximum knee flexion, the knee angle was found to have a high level of association with the average knee moment, accounting for 75.5% of the variance. This suggests that greater angles of knee extension in the mid-part of the take-off are highly associated with greater gains in vertical velocity. At take-off, the knee joint angle was found to explain approximately 30% of variances in both the average knee and hip joint moments. The results found here provide a platform for an intervention study, to examine the effects of manipulating the leg placement angle at touch-down and the knee extension angle on the net knee and hip joint moments.

5.1.3.4 Muscle Kinematics

Changes in muscle-tendon length

Figures 5.1.16 and 17 show the changes in muscle-tendon length of the vasti, biceps femoris, rectus femoris and the gastrocnemius muscles in the flat and drop take-offs respectively. The muscle-tendon lengths are derived using the equations of Grieve et al. (1978) and Visser et al. (1990) and are expressed as percentages of segment length. For the vasti muscles the average change in length of the vastus intermedius, medialis and lateralis have been reported as these changes are only associated with changes in the knee joint angle. For the bi-articular muscles the length change represents the effects of angular changes in both joints that the muscle spans. A positive change in muscle-tendon length is representative of a stretched muscle-tendon complex, while a negative change in length indicates that the muscle-tendon complex is shorter than the segment.

A dominant characteristic of the flat approach take-off in figure 5.1.16 is the shortening of the biceps femoris (BF) throughout the entire take-off phase. At the instant of touch-down it is stretched by approximately 16% of segment length, which is due to the leg extension in front of the body (and thereby hip flexion) and an extended knee joint. As the knee flexes and the hip extends after touch-down the biceps femoris shortens. The characteristic hyper-extension of the hip at take-off ensures that the muscle-tendon complex is shorter than segment length, -2%. The length changes in the vasti muscles (VAS) reflect the behaviour of the knee joint. At touch-down some knee flexion means that the muscle-tendons are stretched by 4%. As the knee flexes following impact the length increases to 8% at approximately 45% of support. As the knee extends in the extension phase the muscle-tendon complex then shortens and leaves the ground with a small stretch of 1%. As the length of the rectus femoris (RF) muscle is influenced by changes in the hip and knee joint angles its profile is different to the vasti muscles. At touch-down there is virtually zero length change which increases to 5% around 55% of support. The lengthening phase of the rectus femoris therefore lasts around 10% longer than for the vasti muscles. In the final 45% of take-off the rectus femoris then shortens to approximately 3% of segment length. The effect of knee flexion in the first 15% of support causes the gastrocnemius (GA) to shorten to 2% of segment length. Between 15% and 62% of support ankle dorsi-flexion becomes more dominant and as a result the muscle-tendon complex lengthens to 2%. In the final 38% of support ankle plantar-flexion overrides the effect of knee extension and the gastrocnemius shortens to 6% of segment length.

It cannot be stated from muscle length information whether the muscle is contracting concentrically or eccentrically. Length changes can be due to the tendon increasing or decreasing in length, the muscle increasing or decreasing in length (which in turn can be elastic or contractile components), or a combination of both. The usefulness of this information is in identifying the stretch-shorten characteristics of individual muscles, regardless of which structure undergoes the stretch. For example, from the graphs in figure 5.1.16 it is apparent that the biceps femoris muscle could not benefit from the stretch-shorten cycle because it does not undergo an initial stretch. The vastii, rectus femoris and the gastrocnemius muscles, however, are likely to benefit from this mechanism because they have an initial lengthening phase that precedes the shortening phase. The timing and phasing of the transition from stretch to shorten is also of interest. For example, this transition occurs at 45% of support for the vastii muscles, at 55% of support for the rectus femoris and 62% of support for the gastrocnemius. This indicates that the benefits of the stretch-shorten cycle, namely the generation of additional muscle force and power, will be delivered sequentially in the extension phase.

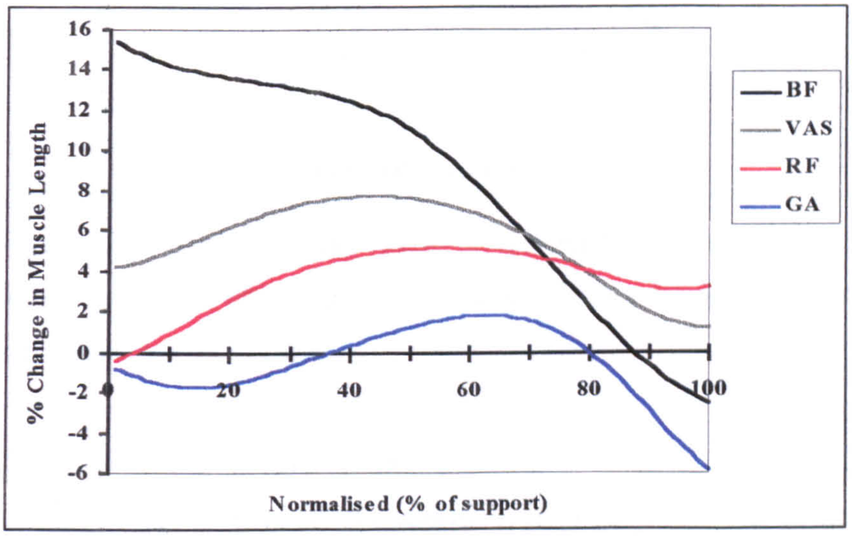


Figure 5.1.16 Graph of mean muscle-tendon length changes in the flat approach take-off (BF = biceps femoris, RF = rectus femoris, VAS = vasti muscles, GA = gastrocnemius).

The profile of the mean muscle length changes in the drop take-off can be seen in figure 5.1.17. Generally, the profiles of the muscle length changes are similar to those observed in the flat approach, but there is one noticeable difference. In the first 40% of support the biceps femoris lengthens from 10% to 12% of segment length. This is likely to be due to the observation that athletes flexed at the hip joint after touch-down. Following this initial lengthening phase, the muscle-tendon complex then shortens through to take-off. The vastii and rectus femoris muscles exhibited similar stretch-shorten profiles to the flat approach take-off, with average increases in length of 8% and 6% respectively. The gastrocnemius showed a similar stretch-shorten profile to the flat approach take-off, but the stretch was greater lengthening to 4% of segment length. With the exception of the biceps femoris, which also had a stretch-shorten cycle, the transition from stretch to shorten occurred at similar times to the flat approach take-off.

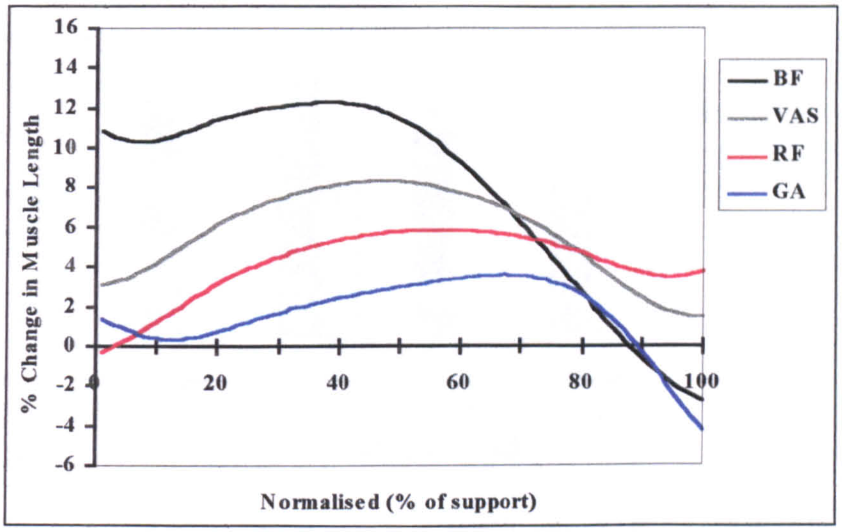


Figure 5.1.17 Graph of mean-tendon muscle length changes in the drop approach take-off (BF = biceps femoris, RF = rectus femoris, VAS = vasti muscles, GA = gastrocnemius).

5.1.3.5 Isokinetic Muscle Torque

The mean peak torque results of all the athletes in the 3 test conditions are presented in figure 5.1.18. It can be seen that the graph follows the typical Hill model where muscle torque decreases with increasing speed of movement. For the quadriceps muscle group the mean peak concentric torque (relative to body mass) was observed to decrease from 4.14 N.m/kg at an angular velocity of 1.04 rad.s^{-1} (60 °.s^{-1}) to 2.40 N.m/kg at an angular velocity of 5.24 rad.s^{-1} (300 °.s^{-1}). Similarly the mean peak concentric torque of the hamstring muscles decreased from 2.40 N.m/kg at 1.04 rad.s^{-1} to 1.66 N.m/kg at 5.24 rad.s^{-1}. This equates to a 42% decrease in the peak torque of the quadriceps and a 31% decrease in the peak torque of the hamstrings as the test angular velocity increases from 1.04 rad.s^{-1} to 5.24 rad.s^{-1}. This is reflected in the reciprocal muscle group ratios (hamstrings to quadriceps ratio) which were found to increase from 0.58 to 0.69 as the speed of movement increased from 1.04

rad.s^{-1} to 5.24 rad.s^{-1}. The mean peak eccentric torque of the quadriceps muscles, 4.30 N.m/kg, was found to be 1.3 times greater than the peak concentric torque, 3.29 N.m/kg, at the same test angular velocity of 2.09 rad.s^{-1} (120 °.s^{-1}).

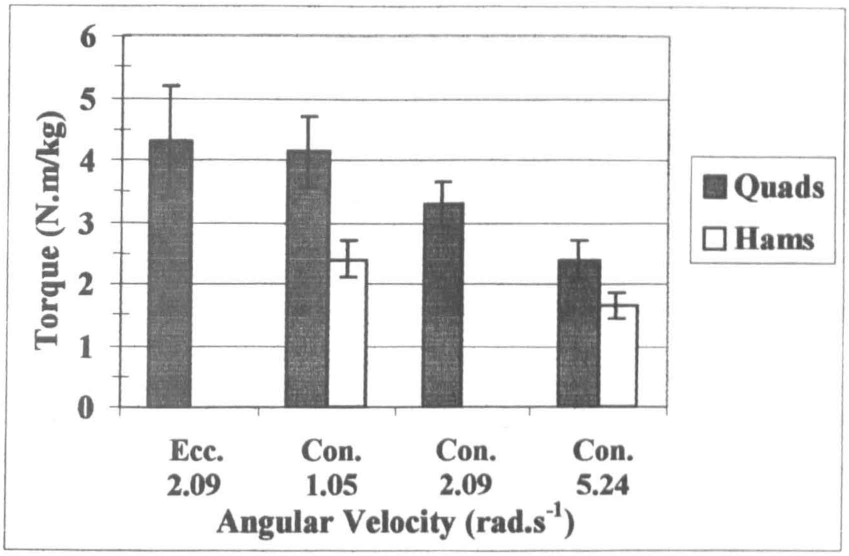


Figure 5.1.18 Mean and SD peak isokinetic torque values (relative to body mass) for quadriceps and hamstring muscles at various angular velocities.

5.1.4 Discussion

The results of this study have shown that, despite the lower approach velocities, the laboratory simulation of flat and a drop approach take-offs can be used to replicate the conditions of landing and take-off in the long and triple jumps. Due to the sub-maximal nature of these take-offs, estimated to be approximately 63% of competition speeds, the peak and average ground reaction forces are lower than others reported in the literature for long and triple jump take-offs performed in competition.

Based on kinematic data, Bruggemann (1990) and Hay and Miller (1985) calculated the average horizontal and vertical forces in the triple jump take-offs in high level competition. Average horizontal forces were reported to range between -0.5 and -1.0 x BW in all take-offs, while average vertical forces were reported to range between 3.20 and 3.77 x BW in the hop, 3.80 and 4.35 x BW in the step and between 3.70 and 4.21 x BW in the jump take-off. The average horizontal and vertical forces found in the present study were -0.67 and 2.80 x BW for the flat approach take-off and -0.34 and 3.17 x BW for drop take-off. These values indicate that the simulation take-offs approximate the conditions of high level competition performance by around 75% to 85%.

The main reason for the lower average forces appears to be more related to the impact than the drive phase. The peak vertical impact force in the 'flat' take-off was found to be between 2.4 kN and 5.1 kN, which is comparable to the data of Bedi and Cooper (1977) who also examined short approach long jump take-offs. However, for full approach take-offs the peak vertical impact force has been reported to be in the range of 7.2 kN to 12.3 kN (Bosco et al., 1976; Fischer, 1975; Luhtanen and Komi, 1979; Kyrolainen et al., 1997). The latter studies also reported peak thrust or drive forces in the range of 2.5 kN to 3.9 kN, which is similar to the range observed in the present study, 2.5 kN to 4.0 kN. This indicates that the severity of the impact in short approach take-offs is approximately 50% of that in full approach take-offs, but the peak drive force is representative of those exhibited in full approach take-offs. For the drop approach take-off, which was used to simulate the step and jump take-offs, the mean peak vertical impact force was 7.0 x BW. This value is approximately 70% of the values reported by Ramey and Williams (1985) in the step and jump take-offs, 10.3 x BW and 9.2 x BW respectively. Short approach take-offs would therefore appear to offer a safer alternative to full approach take-offs. There is a reduced risk of injury through lower impact forces, while at the same time the average ground reaction force and the peak drive-off force are sufficiently high enough to provide a high level of comparison.

However, as the speed of approach and the forces of impact are lower in the simulation take-offs, this would effectively lead to an underestimation of the peak and average net joint moments about the ankle, knee and hip. Table 5.1.16 compares the peak joint moments found in the present study with other studies investigating running and jumping activities. The present study found results similar to those of Stefanyshyn and Nigg (1998) who also analysed running jump activities, although the upper limits of the ranges are slightly greater in the ankle and knee moments. Compared to standing horizontal and vertical jumps (Bobbert and van Ingen Schenau, 1988; Robertson and Flemming, 1987; and Horita et al., 1991) the introduction of a running approach leads to greater moments about the ankle, knee and hip joints. However, the knee and hip moment values have a large range, which suggests that technique may be a large factor. The results of Thorpe et al. (1998) support this view. They found that as athletes aim for distance rather than height they experience a greater hip moment and this is accompanied by a corresponding decrease in the moment about the knee.

It can be seen in table 5.1.16 that the peak ankle moment in both the flat and drop approach take-offs exhibited high values within a relatively small range. Indeed, 6 of the 10 athletes performing the flat approach take-off and 3 of the 5 performing the drop approach were found to experience the largest moment about the ankle joint. Interestingly, 4 of the 5 long jumpers performing the flat approach take-off experienced their greatest moment about the hip joint, while in the drop take-off 2 triple jumpers exhibited their greatest moment about the knee joint. These observations indicate that strength around the ankle joint is particularly important to long and triple jumpers, although depending on aspects of technique, strength about the knee and hip joints cannot be neglected.

Table 5.1.16. Comparison of peak joint moments with other activities.

Author(s)	Year	Activity	Peak Moments		
			Ankle	Knee	Hip
Standing Jumps					
Bobbert and van Ingen Schenau	1988	Standing Vertical Jump	275	325	375
Robertson and Flemming	1987	Standing Vertical Jump	225	175	300-375
Thorpe et al.	1998	Standing Vertical Jump	151	213	193
Robertson and Flemming	1987	Standing Long Jump	300	150	400
Horita et al.	1991	Standing Long Jump	275	150	425
Thorpe et al.	1998	Standing Long Jump	157	76	251
Running Jumps					
Stefanyshyn and Nigg	1998	Running Vertical Jump	250-400	150-300	300-500
Stefanyshyn and Nigg	1998	Running Long Jump	250-400	250-300	400-650
Present Study		Running 'Flat' Approach	345-470	140-400	160-550
		Running 'Drop' Approach	295-460	130-450	200-320

The results of this study have found several relationships and trends to indicate that touch-down technique and the amount of knee flexion can lead to greater or lesser average forces. The extension of the leg in front of the body at touch-down, A_{TD}, and the knee extension angle at touch-down were found to be associated with greater average horizontal (sagittal) ground reaction forces and also greater average hip joint moments. In addition, greater knee extension angles at touch-down were also found to be related to smaller average knee joint moments. Indeed, greater angles of knee extension throughout the entire take-off were associated with smaller average knee joint moments. This was particularly so in its most flexed position, which was found to explain 75.5% of the variance in the average knee joint moment. From a mechanical perspective, this would imply that the resultant ground reaction force passes closer to the knee joint centre, producing smaller moment arms and joint angular velocities. However, smaller average knee joint moments were also found to be related to greater average hip joint moments, ($r = -0.739$, $R^2 = 54.6\%$). This suggests that for the athletes in this study, those who adopt a technique to reduce the average knee moment are likely to experience greater average hip joint moments. Therefore, in order to benefit from greater knee extension angles throughout the take-off it could be speculated that athletes must possess greater strength around the hip joint.

Although the drop take-off exhibited greater peak vertical impact and drive forces and greater peak horizontal propulsive forces than in the flat approach, no significant differences were found in the magnitude of the peak joint moments. The only apparent and significant differences between the two take-offs were the smaller knee moment at touch-down (effect size = 1.53) and greater hip joint moment at touch-down (effect size = 2.65) in the flat approach take-off. From the previous discussion this is likely to be related to the athlete's body position at the instant of touch-down, and in particular the knee angle and the angle of leg placement, A_{TD}. It can be seen in table 5.1.2 that athletes touch-down with greater knee flexion, and with greater angles of leg placement in the flat approach take-off, (154.2° and 27.1° respectively), than they would in a drop approach, (161.1° and 18.7°). These observations provide some evidence to support the notion that greater knee extension angles at touch-down create smaller knee joint moments and greater leg placement angles at touch-down lead to greater hip joint moments.

For comparison with Stefanyshyn and Nigg (1998), the amount of energy absorbed and generated at the ankle, knee and hip joints were calculated by numerical integration of the power graphs, table 5.1.17. The ankle joint was found to absorb and generate the greatest amount of energy in both 'flat' and 'drop' take-offs, agreeing with the observations of Stefanyshyn and Nigg (1998). However, in both types of jump and for all athletes, the knee was found to generate more energy than it absorbed. This is in complete disagreement with Stefanyshyn and Nigg's study where all four of their subjects generated less than they absorbed. Some athletes in the present study actually generated more energy in the knee joint than in the ankle. These observations may be indicative of differences in skill level and, or technique. The amount of energy absorbed and generated at the hip joint during the flat approach take-off was very similar to the range reported by Stefanyshyn and Nigg (1998). Most athletes generated more energy at the hip than they absorbed. However, this observation reversed for the drop approach take-off, where all five athletes absorbed more energy than they generated. This can be related to two main observations; smaller hip joint moments were experienced due to smaller angles of leg placement at touch-down, A_{TD}, and secondly, all athletes flexed at the hip creating negative angular velocities. This will lead to greater amounts of negative power and greater energy absorption. This supports the earlier views that the hip extensor muscles are very important for successful take-offs. If greater amounts of energy are to be generated at the hip joint, athletes need to plant the leg further in front of the body, but have sufficient strength in the hip flexors to resist flexion.

Table 5.1.17. Comparison of joint energy absorbed and generated in long and triple jump take-offs.

	Stefanyshyn and Nigg (1998) Long Jump (n=4)			**Present Study 'Flat' Approach (n=10)**			**'Drop' Approach (n=5)**		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Ankle									
Absorb (J)	133.4	± 32.4	100-160	128.2	± 27.0	101-184	133.9	± 28.2	93-160
Generate (J)	103.9	± 15.3	85-120	96.0	± 15.0	69-120	88.5	± 30.2	58-133
Knee									
Absorb (J)	79.6	± 3.4	75-83	48.4	± 22.6	25-100	48.4	± 22.6	38-143
Generate (J)	52.0	± 8.3	42-62	86.0	± 35.5	50-160	86.0	± 35.5	39-163
Hip									
Absorb (J)	28.1	± 15.3	7-40	47.8	± 33.6	2-90	73.5	± 25.8	49-116
Generate (J)	55.8	± 43.2	29-120	68.7	± 26.4	40-114	25.6	± 18.7	9-58

The profiling of isokinetic knee and hip joint strength provides an indication as to whether athletes would be best suited to maximising the strengths of their hip or of their knee musculature. Greater strength capabilities will indicate the potential to withstand greater joint moments, and ultimately from a technical point of view whether they should aim to have greater or lesser knee extension and angle of leg placement at touch-down. For example, an athlete who has good strength about the knee, but poor strength about the hip would be best suited to a technique that aims to maintain horizontal velocity. In contrast, an athlete with relatively greater hip joint strength will have greater ability to generate vertical velocity through an extended knee joint and leg plant in front of the body.

Although isokinetic strength of the hip joint was not assessed in this study, the data collected on the knee joint serves to provide normative data as to the knee joint strength required by elite long and triple jumpers. It is evident from comparisons made with other studies that long and triple jumpers possess greater quadriceps and hamstrings muscle strength than sprinters (Appen and Duncan, 1986) and male university athletes in general (Ghena et al., 1991), table 5.1.18. This is apparent both in absolute terms and relative to body mass, at all speeds of movement and in both concentric and eccentric modes of contraction. The reciprocal muscle group ratio (Hamstrings / Quadriceps) at the slow speed of movement (1.05 rad.s^{-1}) was found to be similar to those found in the studies of

Appen and Duncan (1986) and Ghena et al. (1991). However, at the faster speed of movement, 5.24 rad.s^{-1}, the greater ratio of 0.69 indicates that long and triple jumpers have relatively greater hamstrings strength (compared to the quadriceps) than the group of male athletes, 0.61 (Ghena et al., 1991). This is likely to be a function of the long and triple jumpers' need to generate high speed on the runway, to sweep the leg backwards in a 'pawing' action at touch-down and to extend the hip immediately after impact. The comparison with Ghena's data also reveals that the long and triple jumpers possess greater eccentric strength of the quadriceps than the group of male athletes, 4.30 compared to 3.41 times body mass. This indicates that the ability to resist compression of the knee is a specific requirement for success in the long or triple jumps, as suggested earlier in the discussion.

Table 5.1.18 Comparison of isokinetic strength profiles for long and triple jumpers with other studies on male athletes. (Con = concentric, Ecc = eccentric, abs = absolute, rel = relative)

Author(s)		Quadriceps (N.m)				Hamstrings (N.m)		Hams / Quads Ratio	
		Con 1.05 rad.s^{-1}	Con 2.09 rad.s^{-1}	Con 5.24 rad.s^{-1}	Ecc 2.09 rad.s^{-1}	Con 1.05 rad.s^{-1}	Con 5.24 rad.s^{-1}	1.05 rad.s^{-1}	5.24 rad.s^{-1}
Present Study	abs	312	250	181	325	181	125	0.58	0.69
	rel	4.14	3.29	2.40	4.30	2.40	1.66		
Appen and Duncan (1986) (male sprinters)	abs	234		118		128	78	0.55	0.66
Ghena et al. (1991)	abs	260	219	146	260	142	88	0.55	0.61
(male athletes)	rel	3.40	2.87	1.91	3.41	1.86	1.16		

In relation to the peak knee extensor moments in the flat approach take-off, the peak concentric and eccentric isokinetic torque values were found to exhibit similar values. Relative to the athletes body mass, the peak knee extensor moment in the flat approach take-off was 3.20 ± 0.97 N.m/kg and had a range of 2.13 to 5.22 N.m/kg. In comparison, the mean peak concentric torque at the angular velocity of 2.09 rad.s^{-1} was 3.29 ± 0.36 N.m/kg (range of 2.78 to 3.95 N.m/kg) and the mean peak eccentric torque was 4.30 ± 0.9 N.m/kg (range of 2.83 to 5.8 N.m/kg). Relationships were tested between the peak knee extensor moment and the peak concentric and eccentric torque measures, but these were found to be non-significant, ($r = 0.336$ and 0.063, respectively). This can be attributed to two main factors. Firstly, it is important to remember that the peak knee extensor moment is the net moment and includes the contractions of the biceps femoris and gastrocnemius as well as the quadriceps muscles. This is particularly important in dynamic multi-joint activities where these muscles have an active role in addition to their role as a joint stabiliser. The moment produced by the quadriceps muscles is therefore likely to be greater than the net knee extensor moment, (Thorpe et al., 1998). Secondly, differences in the technique of leg placement and knee extension angles at touch-down will affect the relationship due to their affect on the distribution of moments about the knee and hip joints. Although the isokinetic test velocity of 2.09 $rad.s^{-1}$ was much lower than peak knee flexion and extension velocities experienced in the flat approach take-off, (typically 7.3 $rad.s^{-1}$ and 15.6 $rad.s^{-1}$), the values obtained provide close approximations to the knee moments experienced in dynamic performance.

5.1.5 Conclusion

This study has enabled an assessment to be made of the demands placed on the musculo skeletal system in long and triple jump take-offs. Although the study was limited to simulated take-offs in the laboratory, the results indicated that the simulated jumps were good representations of competition performances. The major limitations were the reduced approach speed, estimated to be 63% of competition speeds, and the smaller impact forces, estimated to be around 50% of full approach take-offs. However, average ground reaction forces were greater than 75% of high level competition, and the peak drive-off forces were similar to full approach take-offs.

The peak vertical impact force in the drop take-off was found to be significantly greater and to occur significantly earlier in the take-off compared to the flat approach. These results indicate that drop landings, i.e. into the step and jump take-offs, are more severe than in flat approaches in terms of the magnitude of impact forces and in the rate of loading. The peak vertical drive-off force was similar in magnitude, but was found to occur significantly earlier in the drop approach take-off. The peak horizontal braking forces were similar in both take-offs, but a large effect size statistic of 1.72 indicated that the peak drive-off force could be greater in the drop take-off. The results also highlighted that the braking phase ends earlier in the drop take-off than in the flat approach take-off. Peak ankle, knee and hip joint moments were similar in both take-offs. This indicates that athletes adapt their technique from flat approach to drop approach take-offs and this enables them to keep the forces within controllable limits. Kinematic differences between the take-offs indicate that the changes in technique are likely to be a smaller angle of leg placement and a more flexed knee joint at touch-down when performing the drop take-off.

Relationships between aspects of technique and average joint moments in the flat approach take-off found some association between the angle of leg placement and the knee angle throughout the take-off with the average knee and hip joint moments. The knee angle at maximum knee flexion was found to explain 75.5% of the variance in the average knee moment, suggesting that athletes who have the ability to keep the knee extended produce smaller average knee moments. A relationship was also found between the average knee and hip joint moments, suggesting some interaction between the two. The findings provide a base for an intervention study to examine the effect of these variables on joint moments.

Examination of the muscle-tendon lengths during the simulated jumps found that the vasti muscles, the rectus femoris and gastrocnemius underwent stretch-shorten cycles in both take-offs. The biceps femoris was observed to shorten throughout the entire take-off phase in the flat approach take-off, but due to some hip flexion in the drop take-off the biceps femoris actually underwent a stretching phase. There appeared to be sequential order to the shortening phase of muscles - the biceps femoris early in the take-off, the vasti muscles around 45% of support, rectus femoris at 55% of support and then the gastrocnemius around 62% of support. The results indicate that the vasti, rectus femoris and gastrocnemius muscles in particular may generate greater force and power due to the initial pre-stretch and this occurs in sequentially throughout the take-off.

By profiling the isokinetic strength of the quadriceps and hamstring muscle groups normative data now exists for a group of elite long and triple jumpers. In order to perform long and triple jump take-offs successfully, athletes require both eccentric and concentric strength of the quadriceps muscle group. Results indicated that eccentric strength of the quadriceps was particularly important when compared to other groups of athletes in the literature. A mean peak eccentric torque of 325 N.m (4.30 times body mass) at a movement speed of 2.09 $rad.s^{-1}$ was found and this reflects the athletes need to resist knee flexion in the compression phase. Concentric quadriceps strength is related to the athletes need to drive-off in the extension phase of the take-off. Results indicated that long and triple jumpers should be able to generate peak concentric quadriceps torques of 312 N.m (4.14 x body mass), 250 N.m (3.29 x body mass) and 181 N.m (2.40 x body mass) at movement speeds of 1.05 $rad.s^{-1}$, 2.09 $rad.s^{-1}$ and 5.24 $rad.s^{-1}$ respectively. In relation to the quadriceps strength, the hamstrings muscle group should be able to generate at least 58% of quadriceps torque at slow movement speeds (1.05 $rad.s^{-1}$) and 69% of that at fast movement speeds (5.24 $rad.s^{-1}$). This equate to mean peak hamstring torques of 181 N.m (2.40 times body mass) and 125 N.m (1.66 times body mass) at slow and fast movement speeds respectively.

6.0 Summary and Conclusions

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6.1 Summary

The aims of this programme of research were to examine the three-dimensional kinematics and kinetics of the long and triple jump take-offs with the specific purpose of investigating how athletes generate vertical velocity. Although previous research into this area has used three-dimensional analysis techniques, very few studies have gone further than just reporting the medio-lateral component of velocity at take-off. One notable exception was Fukashiro et al. (1993) who examined hip, shoulder and trunk rotation in the transverse plane. The three-dimensional movements of the support leg, trunk and free limbs in all three planes of movement have now been analysed in sections 4.1 and 4.2 for the long, hop, step and jump take-offs. While it is acknowledged that the dominant features of these take-offs still occur in the sagittal plane some interesting characteristics were noted in the frontal and transverse planes. In all the take-offs it was observed that the centre of mass always remained within a very small deviation from the ankle joint when viewed in the frontal plane, i.e. the centre of mass was above the point of support. This would be expected in order for the athlete to maintain balance, but such a characteristic has not been quantified in the literature. The magnitude of hip adduction and abduction in the frontal plane was also examined. While the compression movements about the hip were small relative to those of the knee joint following touch-down it is very useful to quantify for several reasons. Excessive adduction of the hip will cause greater medio-lateral movement of the body and this will result in compensatory movements of the free limbs, and a loss in horizontal velocity. In the transverse plane, the amount of trunk rotation from touch-down to take-off was also very interesting. Fukashiro et al. (1993) noted that Mike Powell had a technique where his trunk rotation was mainly produced by rotation of his hips, while Carl Lewis' trunk rotation was mainly supported by his shoulder rotation. Fukashiro et al. (1993) claimed that Powell's greater hip rotation facilitated greater gains in vertical velocity. The results of the triple jump analysis supported this observation. Similar ranges of hip and shoulder rotation were found in the hop and step take-offs, but in the jump take-off, where greater vertical velocity is required, athletes demonstrated greater hip rotation than shoulder. This could be linked to the observation that greater lead leg relative momentum was developed in the jump take-off compared to the hop take-off.

With respect to the mechanisms for generating vertical velocity, Lees et al. (1994) proposed that a pivot mechanism acts solely in the compression phase and the free limbs, stretch-shorten cycle enhancement and concentric muscular contractions act in the extension phase. The findings of this research found this to be an over-simplification of the take-off phase. The free limbs were found to generate most of their positive relative momentum in the compression phases of the long jump and hop take-offs. In the step and jump take-offs the positive relative momentum was generated in the extension phases. The mean free limbs relative momentum increased throughout each phase of the triple jump, generating 22.4 N.s, 29.2 N.s and 37.6 N.s respectively, although this fell short of statistical significance (P=0.016). The percentage contribution, relative to the peak vertical momentum of the centre of mass, was 12.2%, 19.0% and 19.0% for the hop, step and jump take-offs, compared to 10.8% (32.1 Ns) in the long jump. The lead leg was observed to be the greatest contributor in the long, step and jump take-offs, but in the hop take-off the co-lateral arm actually produced a greater increase in positive relative momentum than the lead leg. In all take-offs, the co-lateral arm produced greater increases in positive relative momentum than the contra-lateral arm. The action of the contra-lateral arm was classified into 'single' or 'double' techniques, based on the direction of the net upper arm movement in the sagittal plane. Single arm actions, i.e. movement in the opposite direction to the co-lateral arm, appeared to produce greater increases in positive relative momentum than double arm actions in the hop and step take-offs. In the jump take-off, however, the double arm technique appeared to produce greater increases in positive relative momentum than the single arm technique.

The concept of the pivot mechanism was investigated further and attempts were made to link the definition of Bosco et al. (1976) with that of Lees et al. (1994). The former was based on force platform and kinematic information and defined it to end when athlete's centre of mass was directly above the centre of pressure. Lees et al. (1994) defined the end of the pivot action to end at the instant of maximum knee flexion and was determined by kinematic data. Taking the definition that the pivot ends when the centre of mass is directly above the point of support, results indicated that the instant of maximum knee flexion was not consistent. The instant that the centre of mass was directly above the toe of the support foot was more appropriate and consistent. It was referred to the instant of Tx=0, when the horizontal distance between the centre of mass and the toe was zero. Using this definition the pivot was found to end in the mid-part of the extension phase in the long jump and just after maximum knee flexion in the triple jump take-offs. It became apparent that two different concepts have been used to define the action of the pivot mechanism, one relating to compression and extension, the other relating to braking and drive-off characteristics. When the centre of mass is behind the point of support then the athlete would be braking and drive-off would begin when the centre of mass passes in front of the point of support. There are advantages and disadvantages for both interpretations. The braking and drive-off definition is probably the better indicator of the pivoting effect, but this cannot distinguish between the effect of knee compression and extension. At the instant of maximum knee flexion the athlete's centre of mass is behind the toe, in which case the pivoting action has not been completed, but the roles of knee flexion and extension can be separated. The gain in vertical velocity due to the pivot mechanism (from touch-down to Tx=0) less the contribution of the free limbs were 83.0%, 63.7%, 69.8% and 70.7% for the long and triple jumps take-offs respectively. The time in which the body spent pivoting, as a percentage of support time, was 66% in the long jump and between 45% to 50% in the triple jump take-offs. As the centre of mass spent more time behind the point of support in the long jump take-off, it is not surprising that the greater losses in horizontal velocity were experienced compared to the hop take-off in particular.

Aspects of technique relating to the pivot model (figure 1.2) were examined for their association with the gain in vertical velocity and loss in horizontal velocity in the long jump take-off. A model of performance has been established which indicates that the angle of leg placement, Ax_{TD}, is associated with raising the height of the centre of mass and with the loss in horizontal velocity. Greater gains in vertical velocity are related to three main characteristics - a low centre of mass and an extended knee joint at touch-down and the ability to resist knee flexion. In addition, greater losses in horizontal velocity were associated with greater hip adduction, less hip extension and greater gains in height from touch-down to take-off.

The comparison of the triple jump take-offs with the long jump highlighted several main differences that relate to the above model. Triple jumpers do not raise their centre of mass through as large a range as do long jumpers, and this is mainly due to their lower height at take-off. Triple jumpers have smaller angles of leg placement at touch-down, Ax_{TD}, in all the triple jump take-offs, typically between 21° and 24° compared to 32° in the long jump. This can be attributed to the greater flexion of the hip and knee joints and forward inclination of the trunk at touch-down in the triple jump, compared to greater hip and knee extension and backward inclination of the trunk in the long jump. Consequently the centre of mass is closer to the point of support and the braking phase ends earlier in the triple jump take-offs than in the long jump.

The angle of leg placement and the knee angles at touch-down, maximum knee flexion and take-off were examined for their relationship with the mean horizontal and vertical ground reaction forces and the mean net joint moments during laboratory simulated take-offs. The results indicated that greater leg placement angles at touch-down are related to greater losses in horizontal velocity (R^2=35.6%), and greater knee extension at touch-down are associated with greater losses in horizontal velocity (R^2=49.8%) and greater gains in vertical velocity (R^2=31.7%). Results also indicated that the knee extension angle at touch-down is associated with smaller average knee and greater average hip joint moments (R^2=30.8% and 21.9% respectively). Athletes who experienced the deepest angles of knee flexion were also found to experience greater knee joint moments (R^2=75.5%) and smaller average vertical forces (R^2=21.6%). Therefore, the results provide some evidence to support the pivot model, indicating that greater average vertical forces (and vertical velocity) is associated with the ability to keep the knee as extended as possible throughout the entire take-off phase. The assessment of isokinetic knee joint strength revealed that compared to other groups of athletes elite long and triple jumpers have a specific requirement for eccentric strength, which supports the need to resist knee flexion.

6.2 Conclusions

In relation to the purpose and aims of this research set out in section 1.2, studies have been conducted to address those issues and to widen the knowledge base in the biomechanics of long and triple jump performance. The specific purpose of the research was to identify factors that influence the generation of vertical velocity in the long and triple jump take-offs, as outlined in the theoretical model, figure 1.2.

With respect to aim 1, studies in section 3 demonstrated that accurate kinematic data of the long jump take-off can be obtained when using a cine-based digitising system operating at 100 Hz. Video-based systems with their lower sample frequency of 50 Hz and inferior resolution capacity produce less accurate information, especially in velocity measures.

With respect to aim number 2, the three-dimensional kinematic characteristics of the long and triple jump take-offs were identified in sections 4.1 and 4.2. This helped to identify factors that are associated with the pivot mechanism and the athlete's ability to generate vertical velocity. The contribution made by the pivot mechanism to the generation of vertical velocity was significantly greater in the long jump take-off, 83.0%, compared to 63.7%, 69.8% and 70.7% in the hop, step and jump take-offs respectively. However, the contribution of the pivot mechanism was similar for each of the triple jump take-offs.

With respect to the variables outlined in the theoretical model, the angle of leg placement at touch-down was not found to be associated with the gain in vertical velocity from touch-down to take-off for long jumpers in section 4.1.

The amount of knee flexion from touch-down to its minimum angle had a negative relationship with the gain in vertical velocity from touch-down to take-off. However, this was only as part of a multiple regression relationship which included the height of the centre of mass and the knee extension angle at touch-down, R^2(adj)=72.7%.

In all long and triple jump performances analysed, none exhibited hip flexion following touch-down. A coefficient of determination of R^2=37.0% provides some evidence to suggest that greater ranges of hip extension from touch-down to take-off has a negative association with the gain in vertical velocity.

The amount of hip adduction from touch-down to its minimum angle was not found to be associated with the gain in vertical velocity. However, there was some evidence to suggest that greater hip adduction is associated with greater losses in horizontal velocity, R^2=64.1%.

With respect to aim 3, the free limbs were found to contribute 10.8%, 12.2%, 19.0% and 19.0% to the gain in vertical velocity from touch-down to take-off in the long and triple jump take-offs respectively. A significant difference was found between the contribution of the free limbs in the long jump and the jump take-off. Observations made in sections 4.1 and 4.2 indicated that the free limbs functioned differently in the long and hop take-offs compared to the step and jump take-offs. The free limbs were found to generate a large proportion of their relative momentum in the compression phases of the long and hop take-offs, while in the step and jump the majority was generated in the extension phases.

With respect to aim 4, the demands placed on the musculo skeletal system during simulated 'flat' and 'drop' approach take-offs were examined in chapter 5. The peak vertical impact force was found to be significantly greater in the 'drop' take-off, 5080 N, than in the 'flat' approach take-off, 3250 N. There was no significant difference in the peak horizontal braking force between the two take-offs. Peak net joint moments about the ankle joint were not significantly different between 'flat' and 'drop' take-offs with values of 403 N.m and 387 N.m respectively. The peak net joint moments about the knee were also similar for both take-offs, 233 N.m and 296 N.m respectively. The peak net joint moments about the hip were 292 N.m and 249 N.m for the 'flat' and 'drop' take-offs and these too were not significantly different. The results indicate that athletes adapt their techniques from 'flat' to 'drop' approaches in order to distribute the forces effectively and to keep the net moments within controllable limits.

With respect to aim 5, isokinetic strength of the knee joint was profiled. Compared to other athletic groups in the literature, it was found that long and triple jumpers have a specific need for eccentric quadriceps strength. Results indicate that this must be in the order of 325 N.m (4.30 x body mass) at a test angular velocity of 2.09 $rad.s^{-1}$.

The overall findings of this thesis indicate that the pivot mechanism is the greatest contributor to the generation of vertical velocity in all the take-offs. Its effectiveness is dependent on the touch-down characteristics of the support leg, and the ability to resist knee flexion in particular. These characteristics dictate how the ground reaction force will be distributed about the joints of the support leg. It is apparent that strength about the ankle joint is paramount, but differences in technique are likely to place different demands on the knee and hip joint musculature. It is important therefore that athletes have sufficient strength about the relevant joints to cope with their individual leg placement characteristics. From a developmental perspective, young athletes who generally 'run-through' the board will benefit from good knee and ankle joint strength. As they progress and pay more attention on technique, i.e. lowering the centre of mass and extending the leg in front of the body, greater emphasis will be required on the development of strength about the hip joint.

6.3 Recommendations for further research

The net joint moments calculated in this study were limited to the sagittal plane and therefore do not take into account the abduction / adductor moments of the hip and inversion / eversion moments of the ankle. In order to obtain a more thorough insight into the strength requirements of long and triple jumpers, three-dimensional joint moment analyses need to be conducted. A further limitation was the sub-maximal nature of the simulated take-offs, estimated to be approximately 63% of competition approach speeds. Although this was limited to the size of the laboratory, full approach take-offs need to be analysed in order to appreciate the demands of competition performances.

Evidence was provided that relates greater flexion of the knee joint with greater average knee moments, and greater angles of leg placement with greater average hip moments. An intervention study now needs to be conducted to assess the affects of changing these variables on the ground reaction forces and joint moments. This should provide an indication to the specific strength requirements for given touch-down conditions. In addition, the profiling of isokinetic, knee and hip joint strength would provide an indication as to whether athletes would be best suited to maximising the strengths of their hip or of their knee musculature. Greater strength capabilities will indicate the potential to withstand greater joint moments, and ultimately from a technical point of view whether they should aim to have greater or lesser knee extension and angle of leg placement at touch-down.

The theoretical model presented in figure 1.2 outlined that stretch-shorten cycles may assist in the generation of vertical velocity through enhanced force and power production of muscles and tendons. Predictive equations used to estimate muscle-tendon lengths have indicated that several muscles undergo stretch-shorten cycles, namely the vasti group, the rectus femoris and the gastrocnemius. However, these equations cannot differentiate between the lengthening and shortening characteristics of the muscle and tendon, and as such whether the muscle contracts concentrically or eccentrically. Before it is possible to quantify the contribution of stretch-shorten enhancement EMG studies need to be conducted to determine the nature of muscle contractions in long and triple jump take-offs. It could also be possible to use EMG data in a muscle model to determine individual muscle forces.

The present study was limited to investigating the triple jump as separate take-offs. In reality there will be some 'knock-on' effects from one take-off to the next, that is the effect of the hop phase on the step take-off and the step phase on the jump take-off. Interactions between the triple jump take-offs could be addressed by incorporating angular momentum into the model.

References

References

Abdel-Aziz, Y.I. and Karara, H.M. (1971). Direct linear transformation from comparator co-ordinates into space co-ordinates in close range photogrammetry. In *Proceedings of the Symposium on Close range Photogrammetry*, pp. 1-18. Falls Church: American Society of Photogrammetry.

Ae, M. and Shibukawa, K. (1980). A biomechanical method for the analysis of the contribution of the body segments in human movement. *Japanese Journal of Physical Education*, 25(3), 233-243.

Angulo, R.M. and Dapena, J. (1992). Comparison of film and video techniques for estimating three-dimensional co-ordinates within a large field. *International Journal of Sports Biomechanics*, 8, 145-151.

Alexander, R. McN. (1990). Optimum take-off techniques for high and long jumps. *Philosophical Transactions of the Royal Society, London*, 329, pp. 3-10.

Allard, P., Stokes, I.A.F. and Blanchi, J.P. (1995). Three-dimensional analysis of human movement. Human Kinetics. Champaign, IL.

Appen, L. and Duncan, P.W. (1986). Strength relationships of the knee musculature: effects of gravity and sport. *The Journal of Orthopeadic and Sports Physical Therapy*, 7 (6), pp. 232-4.

Atkinson, G. and Nevill, A.M. (1998). Statistical methods for assessing measurement errorr (reliability) in variables relevant to sports medicine. *Sports Medicine*, 26 (4), pp. 217-238.

Aura, O. and Komi, P.V. (1987). Coupling time in stretch-shortening cycle: influence on mechanical efficiency and elastic characteristics of leg extensor muscles. In: *Biomechanics X-A*, (edited by B. Jonsson). Human Kinetics, Champaign, Illinois, pp. 507-511.

Aura, O. and Viitasalo, J.T. (1989). Biomechanical characteristics of jumping. *International Journal of Sports Biomechanics*, 5, pp. 89-98.

Avela, J., Kyrolainen, H. and Komi, P.V. (1988). Changes in mechanical energy transfer and moment analysis during long jump take-off. *Scandinavian Journal Of Sports Sciences*, 10(1), pp. 1-5.

Bartlett, R.M. and Bowen, T. (1993). Kine System User Guide. Manchester Metropolitan University, Alsager, England.

Bartlett, R.M., Challis, J. and Yeadon, F. (1992). Cinematography / Video Analysis. In: Biomechanical Analysis of Performance in Sport (edited by R.M. Bartlett). British Association of Sport and Exercise Sciences, Leeds, England. pp. 8-23.

Bartlett, R.M. and Payton, C.J. (1991). Evaluating and reporting errors in biomechanical data and their possible effects. *Journal of Sports Sciences*, 9, pp. 393-4

Bedi, J.F. and Cooper, J.M. (1977). Take-off in the long jump – angular momentum considerations. *Journal of Biomechanics*, 10, pp. 541-548.

Biewener, A.A. (1997). Effects of elastic energy storage on muscle work and efficiency. *Journal of Applied Biomechanics*, 13(4), pp. 422-426.

Bobbert, M.F. and Ingen Schneau, G.J.van. (1988). Coordination in vertical jumping. *Journal of Biomechanics*, 21, pp. 249-262.

Bober, T. (1974). Investigation of the take-off technique in the triple jump. In: *Biomechanics IV* (edited by R.C. Nelson and C.A. Morehouse), University Park Press, Baltimore. pp. 149-154.

Bosco, C., Luhtanen, P., and Komi, P.V. (1976). Kinetics and kinematics of the take-off in the long jump. In: *Biomechanics V-B*. (edited by P.V. Komi). University Park Press, Baltimore, MD. pp. 174-180.

Bosco, C., Tarkka, I. and Komi, P.V. (1982a). Effect of elastic energy and myoelectrical potentiation of triceps surae during stretch-shortening cycle exercise. *International Journal of Sports Medicine*, 3, pp. 137-140.

Bosco, C., Viitasalo, J.T., Komi, P.V. and Luhtanen, P., (1982b). Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise. *Acta Physiologica Scandinavia*, 114, pp. 557-565.

Bruggeman, G.-P. (1990). Biomechanical analysis of the triple jump: An approach towards a biomechanical profile of the world's best triple jumpers. In *International Athletic Foundation / International Amateur Athletic Federation Scientific Research Project at the Games of the XXIVth Olympiad, Seoul, 1988; Final report* (edited by G.-P. Bruggeman and B. Glad). pp.306-362.

Bruggemann, P. and Susanka, P. (1987). The long jump. In *Scientific Report on the Second IAAF World Championships in Athletics, Rome 1987*. pp. 1-54. London: International Athletic Federation.

Challis, J.H. (1996). Accuracy of human limb moment of inertia estimations and their influence on resultant joint moments. *Journal of Applied Biomechanics*, 12(4), pp. 517-530

Challis, J.H. and Kerwin, D.G. (1992). Accuracy assessment and control point configuration when using the DLT for photogrammetry. *Journal of Biomechanics*, 25 (9), pp. 1053-1058.

Challis, J.H. and Kerwin, D.G. (1996). Quantification of the uncertainties in resultant joint moments computed in a dynamic activity. *Journal of Sports Sciences*, 14, pp. 219-231.

Chen, L., Armstrong, C.W.and Raftopoulos, D.D. (1994). An investigation on the accuracy of three-dimensional space reconstruction using the direct linear transformatiom technique. *Journal of Biomechanics*, 27 (4), pp. 493-500.

Clauser, C.E., McConville, J.T. and Young, J.W. (1969). Weight, volume and center of mass of segments of the human body. (AMRL-TR-69-70). Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory.

Costa, K., McNitt-Gray, J.L., Requejo, P., Mathiyakom, W., Eagle, J. and Marciniak, J. (1998). Gender differences in multijoint load distribution during the take-off phase of the long jump. In Proceedings of NACOB'98. The Third North American Congress on Biomechanics, Waterloo, August 14th-18th, 1998, pp. 419-420.

Dapena, J. and Chung, C.S. (1988). Vertical and radial motions of the body during the take-off phase in high jumping. *Medicine and Science in Sports and Exercise*, 20, pp. 290-302.

Dempster, W.T. (1955). Space requiremnts of the seated operator. WADC technical report, Wright-Patterson Air Force Base, OH. pp. 55-159.

Dempster, W.T. and Gaughran, G.R.L. (1967). Properties of body segments based on size and weight. *American Journal of Anatomy*, 120, pp. 33-54.

Edman, P.K.A. (1997). Force enhancement by stretch. *Journal of Applied Biomechanics*, 13(4), pp. 432-436.

Elashoff, J.D. (1999). nQuery Advisor Version 3.0, Study planning software. Los Angeles, CA.

Frigo, C. and Pedotti, A. (1978). Determination of muscle length during locomotion. In: *Biomechanics VI-A*. (edited by E. Asmussen and K. Jorgensen). University Park Press, Baltimore. pp. 355-360.

Fukashiro, S., Iimoto, Y., Kobayashi, H. and Miyashita, M. (1981). A biomechanical study of the triple jump. *Medicine and Science in Sports and Exercise*, 13 (4), pp. 233-237.

Fukashiro, S., Komi, P.V., Jarvinen, M. and Miyashita, M. (1995). In vivo achilles tendon loading during jumping in humans. *European Journal of Applied Physiology*, 71, pp. 453-458.

Fukashiro, S. and Miyashita, M. (1983). An estimation of the velocities of three take-off phases in 18-m triple jump. *Medicine and Science in Sports and Exercise*, 15 (4), pp. 309-312.

Fukashiro, S., Wakayama, A. (1992). The scientific research project at the III World Championships in athletics: preliminary report on the men's long jump. *New Studies in Athletics*, 7 (1). pp. 53-56.

Fukashiro, S., Wakayama, A., Kojima, T., Arai, T., Itoh, N., Ae, M., Kobayashi, K. and Matsui, H. (1993). World record long jump: three dimensional analysis of take-off motion of Powell and Lewis. In, Abstracts of the International Society of Biomechanics, XIVth Congress, Paris, 4th-8th July, 1993, vol. 1, pp. 434-435.

Ghena, D.R., Kurth, A.L., Thomas, M. and Mayhew, J. (1991). Torque characteristics of the quadriceps and hamstring muscles during concentric and eccentric loading. *The Journal of Orthopeadic and Sports Physical Therapy*, 14 (4), pp. 149-154.

Goubel, F. (1997). Series elasticity behaviour during the stretch-shortening cycle. *Journal of Applied Biomechanics*, 13(4), pp. 439-443.

Graham-Smith, P. and Lees, A. (1997). A comparison of the information quality between cinematography and videography for long jump technique analysis. *Biology of Sport*, 14 (3), pp. 213-225.

Grieve, D.W., Pheasant, S. and Cavanagh, P.R. (1978). Prediction of gastrocnemius length from knee and ankle joint posture. In: *Biomechanics VI-A*. (edited by E. Asmussen and K. Jorgensen). University Park Press. Baltimore. pp. 405-412.

Hanavan, E.P. (1964). A mathematical model of the human Body. (AMRL-TDR-63-18) Wright-Patterson Air Force Base, Ohio, Aerospace Medical Research Laboratory.

Harmen, E.A., Rosenstein, M.T., Frykman, P.N. and Rosenstein, R.M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise*, 22, pp. 825-833.

Hatze, H. (1981). A comprehensive model for human motion simulation and its application to the take-off phase of the long jump. *Journal of Biomechanics*, 14(3), pp. 135-142.

Hay, J.G. (1986). The biomechanics of the long jump. In K. Pandolf (Ed.), *Exercise and Sport Science Reviews*, pp. 401-446, New York: Macmillan.

Hay, J.G. (1992). The biomechanics of the triple jump: a review. *Journal of Sports Sciences*, 10, 343-378.

Hay, J.G. (1993). Citius, Altius, Longius (Faster, Higher, Longer): The biomechanics of jumping for distance. *Journal of Biomechanics*, 26 suppl 1. pp. 7-26.

Hay, J.G. and Miller, J.A. (1985). Techniques used in the triple jump. *International Journal of Sports Biomechanics*, 1, pp. 185-96.

Hay, J.G., Miller, J.A. Jr and Canterna, R.W. (1986). The techniques of elite male long jumpers. *Journal of Biomechanics*, 19, pp. 855-866.

Hay, J.G. and Nohara, H. (1990). Techniques used by elite long jumpers in preparation for take-off. *Journal of Biomechanics*, 23(3), pp. 229-239.

Hay, J.G. and Reid, J.G. (1988). Anatomy, Mechanics and Human Motion. 2nd edition. Prentice Hall Inc., Englewood Cliffs, N.J.

Hawkins, D. and Hull, M.L. (1990). A method for determining lower extremity muscle-tendon lengths during flexion / extension movements. *Journal of Biomechanics*, 23 (5), pp. 487-494.

Hinrichs, R.N., Cavanagh, P.R. and Williams, K.R. (1987). Upper extremity function in running 1: Centre of mass and propulsion considerations. *International Journal of Sports Biomechanics*, 3, pp. 222-241.

Hinrichs, R.N., Munkasy, B.A. and Chinworth, S.A. (1989). An analysis of angular momentum during the run-up and take-off in long jumping. In: *Congress Proceedings – XII International Congress of Biomechanics* (edited by Gregor, R.J., Zernicke, R.F. and Whiting, W.C.), abstract number 230, University of California, Los Angeles.

Horita, T., Kitamura, K. and Kohno, N. (1991). Body configuration and joint moment analysis during standing long jump in 6-yr-old children and adult males. *Medicine and Science in Sports and Exercise*, 23 (9), pp. 1068-1077.

Ingen Schenau, G.J.van, Bobbert, M.F., Huijing, P.A. and Woittiez, R.D. (1985). The instantaneous torque-angular velocity relation in plantar flexion during jumping. Medicine and Science in Sports and Exercise, 17 (4), pp. 422-426.

Ingen Schenau, G.J. van, Bobbert, M.F. and de Haan, A. (1997). Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics*, 13(4), pp. 389-415.

Johnson, C. (1996). The elastic strength development of Jonathan Edwards. *New Studies in Athletics*, 11(2), pp. 63-70.

Karayannis, M. (1987). The biomechanics of the triple jump. *Track and Field Quarterly Review*. 90 (4), pp. 18-23. Kalamazoo, Mich.

Kennedy, P.W., Wright, D.L. and Smith, G.A. (1989). Comparison of film and video techniques for three-dimensional DLT repredictions. *International Journal of Sports Biomechanics*, 5, pp. 457-460.

Kerwin, D.G. and Templeton, N. (1991). Cine-film and video: an assessment of digitisation accuracy. *Journal of Sports Sciences*, 9, p.402.

Koh, T.J. and Hay, J.G. (1990a). Landing leg motion and performance in the horizontal jumps I: the long jump. *International Journal of Sport Biomechanics*, 6, pp. 343-360.

Koh, T.J. and Hay, J.G. (1990b). Landing leg motion and performance in the horizontal jumps II: the triple jump. *International Journal of Sport Biomechanics*, 6, pp. 361-373.

Komi, P.V. (1986). The stretch-shortening cycle and human power output. In Human Muscle Power (edited by Norman L. Jones, Neil McCartney and Alan J. McComas) pp. 27-39. Human Kinetics, Champaign, IL.

Komi, P.V. and Gollhofer, A. (1997). Stretch reflexes can have an important role in force enhancement. *Journal of Applied Biomechanics*, 13(4), pp. 451-460.

Kilani, H.A., Palmer, S.S, Adrian, M.J. and Gapsis, J.J. (1989). Block of the stretch reflex of vastus lateralis during vertical jumps. *Human Movement Science*, 8, pp. 247-269.

Kreyer, V. (1993). About the female triple jump. *Modern Athlete and Coach*, 31(1), pp. 11-14.

Kyrolainen, H., Perttunen, J. and Komi, P.V. (1997). Kinetics and electromyography in the triple jump. In Abstracts of the Second Annual Congress of ECSS, August 20th-23rd, 1997, Copenhagen, Denmark.

Lees, A. (1980). An optimised film analysis method based on finite difference techniques. *Journal of Human Movement Studies*, 6, pp. 165-180.

Lees, A. and Barton, G. (1996). The interpretation of relative momentum data to assess the contribution of the free limbs to the generation of vertical velocity in sports activities. *Journal of Sports Sciences*, 14, pp. 503-511.

Lees, A. , Fowler, N. and Derby, D. (1993). A biomechanical analysis of the last stride, touch-down and take-off characteristics of the women's long jump. *Journal of Sports Sciences*, 11, pp. 303-314.

Lees, A. and Graham-Smith, P. (1994). The role of the arms in the long jump. Presented to the Sports Biomechanics Section of the British Association of Sport and Exercise Sciences Easter Meeting, West London Institute, 14th-15th April, 1994.

Lees, A., Graham-Smith, P. and Fowler, N. (1994). A biomechanical analysis of the last stride, touch-down, and take-off characteristics of the men's long jump. *Journal of Applied Biomechanics*, 10 (1), pp. 61-78.

Luhtanen, P. and Komi, P.V. (1979). Mechanical power and segmental contribution to force impulses in the long jump take-off. *European Journal of Applied Physiology*, 41, pp. 267-274.

McCaw, S.T. and De Vita, P. (1995). Errors in alignment of center of pressure and foot coordinates affect lower extremity torques. *Journal of Biomechanics*, 28, pp. 985-988.

Milburn, P.D. (1982). Triple Jump. *Track and Field Quarterly Review*, 82(4), pp. 16-19.

Miller, D.I. (1987). Resultant lower extremity joint moments in below-knee amputees during ruuning stance. *Journal of Biomechanics*, 20(5), pp. 529-541.

Miller, J.A. and Hay, J.G. (1986). Kinematics of a world record and other world-class performances in the triple jump. *International Journal of Sports Biomechanics*, 2, pp. 272-288.

Mungiole, M. and Martin, P.E. (1990). Estimating segment inertial properties: comparison of magnetic resonance imaging with existing methods. *Journal of Biomechanics*, 23(10), pp. 1039-1046.

Nixdorf, E. and Bruggeman, G.-P. (1990). Biomechanical analysis of the long jump. In *Scientific Research Project at the Games of the XXIVth Olympiad, Seoul, 1988.* (edited by G.-P. Bruggeman and B. Glad). pp.263-302. London: International Amateur Athletic Federation.

Palermo, R.A. (1980). Physics and biomechanics in long jumping. *Modern Athlete and Coach*, 18(3), pp. 35-36.

Pandy, M.G., Zajac, F.E., Sim, E. and Levine, W.S. (1990). An optimal control model for maximum-height human jumping. *Journal of Biomechanics*, 23 (12), pp. 1185-1198.

Perrin, D.H. (1993). Isokinetic exercise and assessment. Human Kinetics, Champaign, Illinois.

Pierrynowski, M.R. (1995). Analytic representation of muscle line of action and geometry. In: Allard, Stokes and Blanchi (eds) Three-dimensional analysis of human movement. Human Kinetics, Champaign, IL. pp. 215-256.

Pierrynowski, M.R. and Morrison, J.B. (1985). Length and velocity patterns of the human locomotor muscles. In *Biomechanics IX-A, International Series on Biomechanics* (edited by D.A. Winter, R.W. Norman, R.P Wells, K.C. Hayes, and A.E. Patla) vol 5B, Human Kinetics, Champaign, Ill. pp. 33-38.

Prilutsky, B.I., Zatsiorsky, V.M., Bravaji, D.Y. and Petrova, L.N. (1995). Comparison of maximal knee extension power during one-joint isokinetic movement and running long jump. In, Abstracts of the International Society of Biomechanics, XVth Congress, Tokyo, 1995, pp. 1072-3.

Ramey, M.R. (1970). Force relationships in the running long jump. *Medicine and Science in Sports*, 2(3), pp. 146-151.

Ramey, M.R. (1974). The use of angular momentum in the study of long jump take-offs. In: *Biomechanics IV* (edited by R.C. Nelson and C.A. Morehouse), Baltimore, University Park Press, 1974, pp. 144-148.

Ramey, M.R. and Williams, K.R. (1985). Ground reaction forces in the triple jump. *International Journal of Sports Biomechanics*, 1, pp. 233-239.

Requejo, P., McNitt-Gray, J.L., Eagle, J., Munkasy, B.A. and Smith, S. (1998). Multijoint load distribution and power generation during high velocity impact. In Proceedings of NACOB'98. The Third North American Congress on Biomechanics, Waterloo, August 14th-18th, 1998, pp. 459-460.

Robertson, D.G. and Fleming, D. (1987). Kinetics of standing broad and vertical jumping. *Canadian Journal of Sports Science*, 12, pp. 19-23.

Scheirman, G.L., Smith, S.L. and Dillman, C.J. (1989). Three-dimensional kinetic and kinematic relationships in the long jump. In: *Biomechanics XI-B. International Series on Biomechanics*, (edited by G. de Groot, A.P. Hollander, P.A. Huijing, and G.J. van Ingen Schenau), vol 7-B, Human Kinetics, Champaign, Ill. pp.561-564.

Shetty, A.B. and Etnyre, B.R. (1989). Contribution of arm movement to the force components of a maximum vertical jump. *Journal of Orthopeadic and Sports Therapy*, 11 (5), pp. 198-201.

Shorten, M.R. (1987). Muscle elasticity and human performance. *Med. Sport Sci.*, 25, pp. 1-18.

Smith, G. (1989). Padding point extrapolation techniques for the Butterworth digital filter. *Journal of Biomechanics*, 22, pp. 967-971.

Smith, S.L., Scheirman, G.L. and Dillman, C.J. (1989). Comparative analyses of decathlete and elite long jumpers. In: *Biomechanics XI-B. International Series on Biomechanics*, (edited by G. de Groot, A.P. Hollander, P.A. Huijing, and G.J. van Ingen Schenau), vol 7-B, Human Kinetics, Champaign, Ill. pp. 565-569.

Stefanyshyn, D.J. and Nigg, B.M. (1998). Contribution of the lower extremity joints to mechanical energy in running vertical jumps and running long jumps. *Journal of Sports Sciences*, 16, pp. 177-186.

Stewart, G. (1981). An analysis of long jump take-offs. *Modern Athlete and Coach*, 19(1), pp. 33-38.

Townend, M.S. (1984). Mathematics in Sport. Ellis Horwood, Chichester.

Thorpe, S.K.S., Li, Y., Crompton, R.H. and Alexander, R.M. (1998). Stresses in human leg muscles in running and jumping determined by force plate analysis and from published magnetic resonance images. *The Journal of Experimental Biology*, 201, pp. 63-70.

Tidow, G. (1989). Model technique analysis sheet for the horizontal jumps. Part 1 - The long jump. *New Studies in Athletics*, 3, pp. 47-62.

Unger, J. (1980). The take-off in jumping events. *Modern Athlete and Coach*, 18(4), pp. 7-9.

Van Gheluwe, B. (1978). Computerised three-dimensional cinematography for any arbitrary camera setup. In: *Biomechanics VI-A* (edited by Asmussen, E. and Jorgenson, K.). University Park Press, Baltimore. pp. 343-348.

Vincent, W.J. (1995). Statistics in Kinesiology. Human Kinetics, Champaign, Ill.

Visser, J.J., Hoogkamer, J.E., Bobbert, M.F. and Huijing, P.A. (1990). Length and moment arm of human leg muscles as a function of knee and hip joint angles. *European Journal of Applied Physiology*, 61, pp. 453-460.

Winter, D.A. (1990). Biomechanics and motor control of human movement. John Wiley, New York.

Witters, J., Bohets, W. and Van Coppenhole, H. (1992). A model of the elastic take-off energy in the long jump. *Journal of Sport Sciences*, 10, pp. 533-540.

Wood, G.A. and Marshall, R.N. (1986). The accuracy of DLT extrapolation in three-dimensional film analysis. *Journal of Biomechanics*, 19 (9), pp. 781-785.

Yeadon, M.R. and Challis, J.H. (1994). The future of performance-related sports biomechanics research. *Journal of Sport Sciences*, 12, pp. 3-32.

Yu, B. and Hay, J.G (1995). Angular momentum and performance in the triple jump: a cross sectional analysis. *Journal of Applied Biomechanics*, 11(1), pp. 81-102.

Zatsiorsky, V.M. (1997). The review is nice. I disagree with it. *Journal of Applied Biomechanics*, 13(4), pp. 479-483.

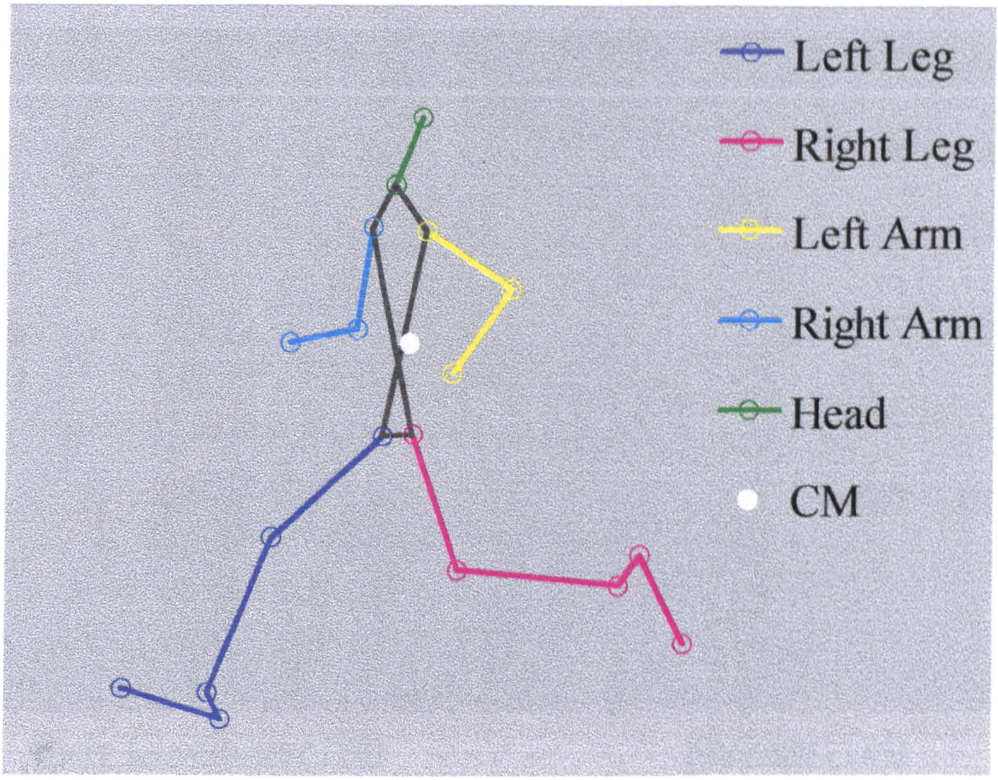
Zatsiorsky, V. and Seluyanov, (1983). The mass and inertia characteristics of the main segments of the human body. In: Biomechanics VIII-B (edited by H. Matsui and K. Kobayashi), Human Kinetics, Champaign, Ill. pp. 1152-1159.

Publications

Appendices

APPENDIX I

Segmental model for two-dimensional analysis.



<u>Body Landmarks (18)</u>

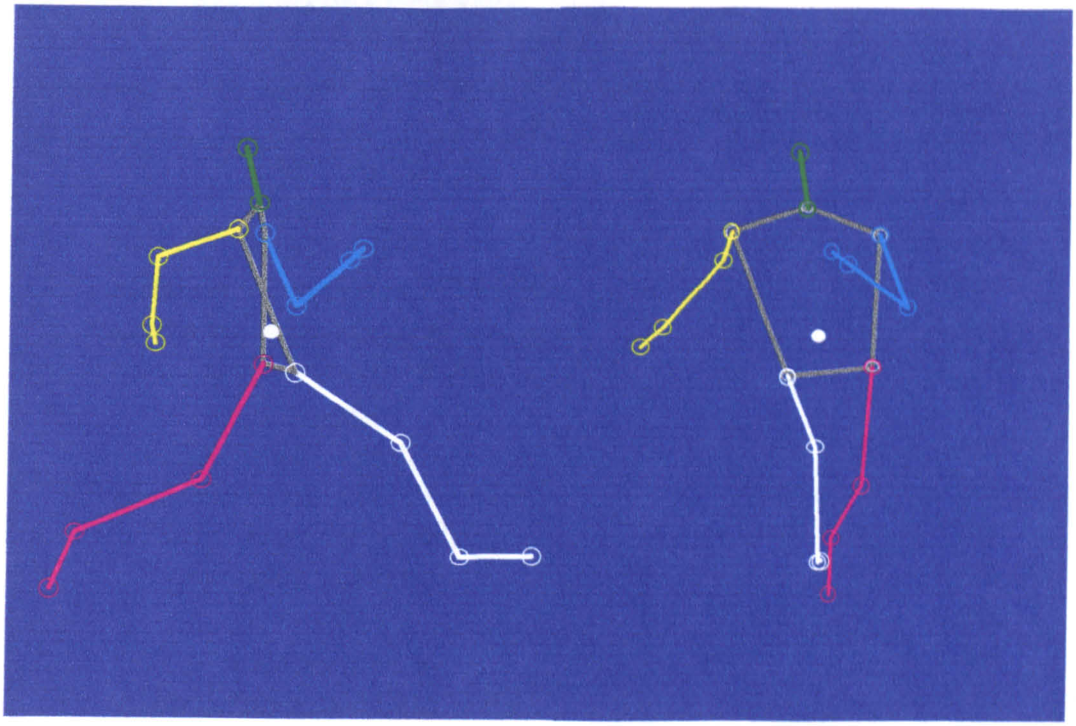
Vertex of head
Neck
Shoulder joint (left and right)
Elbow joint (left and right)
Wrist joint (left and right)
Hip joint (left and right)
Knee joint (left and right)
Ankle joint (left and right)
Heel (left and right)
Distal point of foot (left and right)

<u>Segments (11)</u>

Head and trunk
Upper arm (left and right)
Lower arm plus hand (left and right)
Upper leg (left and right)
Lower leg (left and right)
Foot (left and right)

APPENDIX II

Segmental model for three-dimensional analysis.



<u>Body Landmarks (18)</u>

Vertex of head
Neck
Shoulder joint (left and right)
Elbow joint (left and right)
Wrist joint (left and right)
3rd Metacarpel phalangeal joint (left and right)
Hip joint (left and right)
Knee joint (left and right)
Ankle joint (left and right)
Distal point of foot (left and right)

<u>Segments (14)</u>

Head
Trunk
Upper arm (left and right)
Lower arm (left and right)
Hand (left and right)
Upper leg (left and right)
Lower leg (left and right)
Foot (left and right)

APPENDIX III

Estimates of random error in kinematic variables

Estimates of error for variables included in the 3D analysis of the long jump. Results are for one performance digitised three times.

	mean (N=3)	mean deviation
Displacement		
Height $_{TD}$ (m)	0.956	0.004
Height $_{TO}$ (m)	1.241	0.002
Medio-lateral position of CM $_{TO}$ (m)	0.693	0.004
Touch-down distance (sagittal) Dx $_{TD}$ (m)	0.559	0.004
Touch-down distance (medio-lateral) Dz $_{TD}$ (m)	0.018	0.005
Angles		
Leg placement angle (sagittal) Ax $_{TD}$ (°)	33.713	0.351
Leg placement angle (frontal) Az $_{TD}$ (°)	1.225	0.313
Trunk angle $_{TD}$ (sagittal) (°)	-11.100	1.364
Trunk angle $_{TD}$ (frontal) (°)	-7.617	0.898
Pelvic tilt (°)	8.276	0.352
Hip rotation angle $_{TD}$ (°)	-20.507	2.440
Shoulder rotation angle $_{TD}$ (°)	14.912	1.631
3D Hip angle $_{MKF}$ (°)	94.152	0.895
3D Knee angle $_{MKF}$ (°)	133.839	0.883
Minimum Hip adduction angle (°)	89.116	1.061
Velocity		
Horizontal Velocity $_{TD}$ (m.s^{-1})	10.348	0.076
Horizontal Velocity $_{TO}$ (m.s^{-1})	9.061	0.038
Vertical Velocity $_{TD}$ (m.s^{-1})	-0.133	0.065
Vertical Velocity $_{MKF}$ (m.s^{-1})	2.306	0.044
Vertical Velocity $_{TO}$ (m.s^{-1})	3.216	0.064
Medio-lateral Velocity $_{TD}$ (m.s^{-1})	0.381	0.035
Medio-lateral Velocity $_{TO}$ (m.s^{-1})	0.084	0.087
Speed $_{TD}$ (m.s^{-1})	10.356	0.076
Speed $_{TO}$ (m.s^{-1})	9.616	0.036
Relative ankle velocity $_{TD}$ (m.s^{-1})	-5.755	0.216

APPENDIX IV

Correlation and coefficients of determination values for selected variables with the gain in vertical velocity from touch-down to take-off in the long jump.

Vertical Velocity $_{TD-TO}$	r	R^2 (%)
Speed $_{TD}$	-0.162	2.6
Ax $_{TD}$	0.335	11.2
Height $_{TD}$	-0.203	4.1
Height $_{TD-TO}$	0.335	11.2
Knee angle $_{TD}$	0.584	34.1
Hip flexion angle $_{TD}$	0.285	8.1
Hip extension $_{TD-TO}$	-0.608	37.0
Knee angle $_{TD-MKF}$	-0.065	0.4
Hip adduction $_{TD-MHA}$	-0.337	11.4
Free Limbs Total	0.360	13.0

Correlation and coefficients of determination values for selected variables with the loss in horizontal velocity from touch-down to take-off in the long jump.

Horizontal Velocity $_{TD-TO}$	r	R^2 (%)
Speed $_{TD}$	-0.398	15.8
Ax $_{TD}$	-0.562	31.6
Height $_{TD}$	0.376	14.1
Height $_{TD-TO}$	-0.717	51.4
Knee angle $_{TD}$	-0.347	12.0
Hip flexion angle $_{TD}$	-0.181	3.3
Hip extension $_{TD-TO}$	0.390	15.2
Knee angle $_{TD-MKF}$	0.238	5.7
Hip adduction $_{TD-MHA}$	0.801	64.1
Free Limbs Total	-0.443	19.6

APPENDIX V

Comparison of average and instantaneous velocity calculations at TD and TO.
Average horizontal and vertical velocities at touch-down and take-off were calculated using the equations of uniform acceleration, Miller and Hay (1986). This method requires the positional data of the CM at the frames of TO and the following TD and the time interval between them. Air resistance is assumed to be negligible and as such the horizontal velocity at TD is assumed to be equal to the horizontal velocity at TO in the previous take-off. Instantaneous velocity measures are calculated using direct differentiation, (Lees, 1980).

Touch-down and Take-off Velocities

	Hop TD		**Hop TO**		**Step TD**		**Step TO**		**Jump TD**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Horizontal Velocity										
Average	10.17	0.19	9.18	0.18	9.18	0.18	8.00	0.24	8.00	0.24
Instantaneous	9.94	0.18	9.02	0.12	9.07	0.27	8.07	0.37	7.87	0.38
Difference	**0.23**	**0.10**	**0.16**	**0.10**	**0.11**	**0.15**	**-0.07**	**0.26**	**0.13**	**0.23**
Vertical Velocity										
Average	-0.40	0.09	2.25	0.33	-2.43	0.37	1.92	0.23	-2.15	0.30
Instantaneous	-0.68	0.11	2.02	0.42	-2.43	0.30	1.73	0.27	-2.10	0.14
Difference	**0.28**	**0.06**	**0.22**	**0.14**	**-0.01**	**0.16**	**0.19**	**0.06**	**-0.05**	**0.21**

Note: Jump TO velocities could not be calculated using the average velocity approach because the landing phase (into the pit) was not analysed.

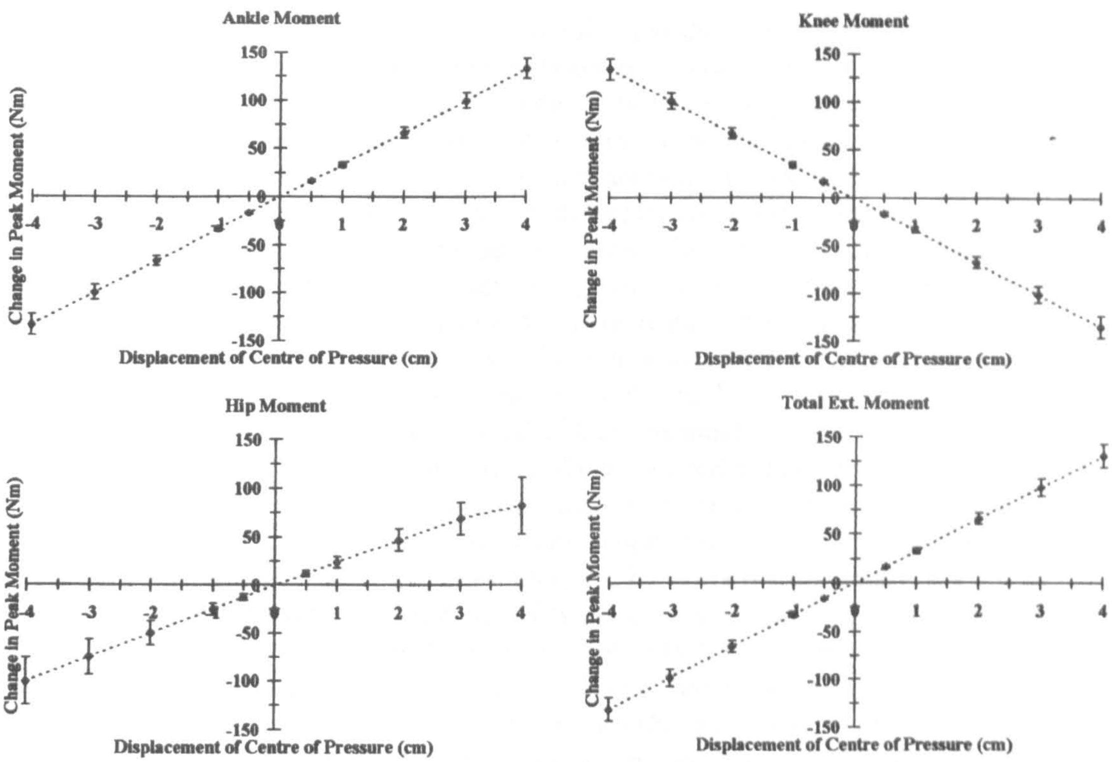
APPENDIX VI

Random error in muscle moment data

Variable	Random Error (Precision) in 1 Subject Mean (n=3)	Mean Deviation
Peak Joint Angles (°)		
Ankle	80.9	0.87
Knee	41.2	0.27
Hip	44.0	0.45
Peak Joint Angular Velocities (°.s^{-1})		
Ankle	14.7	0.16
Knee	11.0	0.04
Hip	12.2	0.20
Peak Joint Moments (N.m)		
Ankle	432.9	4.73
Knee	219.0	5.93
Hip	538.2	10.22
Total Extensor	1034.7	13.60
Peak Joint Power (W)		
Ankle	2047.0	30.13
Knee	918.7	25.76
Hip	1408.8	86.33

APPENDIX VII

Assessment of errors in peak extensor moments due to the alignment of the Centre of Pressure coordinates



Graphs showing the effect of misalignment of the Centre of Pressure on peak joint moments.

Summary data showing the effect of misalignment of the Centre of Pressure on peak joint moments (mean and mean deviation of data on 4 flat approach take-offs). Values given in N.m.

Joint		Displacement of Centre of Pressure (cm)									
		-4.0	-3.0	-2.0	-1.0	-0.5	0.5	1.0	2.0	3.0	4.0
Ankle	Mean	-133.6	-100.1	-66.7	-33.4	-16.7	16.7	33.4	66.7	100.0	133.3
	MD	11.0	8.1	5.4	2.7	1.4	1.3	2.7	5.4	8.0	10.6
Knee	Mean	133.7	100.4	66.9	33.5	16.8	-16.8	-33.6	-67.1	-100.7	-134.2
	MD	11.5	8.6	5.8	2.9	1.4	1.5	2.9	5.8	8.6	11.5
Hip	Mean	-100.8	-75.1	-49.8	-24.9	-12.5	12.3	24.0	46.7	68.6	81.5
	MD	24.5	18.5	12.2	6.0	3.0	2.9	5.7	11.4	16.5	29.1
Total Extensor	Mean	-131.1	-98.3	-65.5	-32.7	-16.4	16.4	32.8	65.6	98.3	131.0
	MD	11.9	8.9	5.9	3.0	1.4	1.5	2.9	5.9	9.0	12.0

MD = mean deviation

APPENDIX VIII

Assessment of errors in Net Joint Moments due to joint centre location, body segmental parameters, ground reaction forces and centre of pressure location

A sensitivity analysis was conducted on one subject at the frame of maximum knee flexion. The differences in net joint moments about the ankle, knee and hip joints following pertubation of joint centre location, body segmental parameters, ground reaction forces, centre of pressure location, and the combined effects of all these factors were determined. In the table it can be seen that shifting the joint centres by 1 cm horizontally and vertically creates a 38 N.m difference against the measured net joint moments. The same difference was found by moving the centre of pressure location by 1 cm. Moving the segment centre of mass location by 1 cm horizontally and vertically had almost zero effect on the net joint moments. An increase and decrease in segmental centre of mass acceleration of 5 $m.s^{-2}$ was found to have no effect on the ankle moment, a difference of 8 N.m in the knee moment and 14 N.m in the hip moment. Changes in segmental angular acceleration of $\pm$ 10 $rad.s^{-2}$ had a minimal effect on the joint moments, up to 2 N.m in the hip moment. The data of Zatsiorsky and Seluyanov (1983) and Clauser et al. (1969) were entered into the equations to examine the effects of segmental mass parameters on joint moments. The results revealed that segmental mass parameters have very little effect on ankle and knee moments, but there is a possibility of a 6 N.m difference in the hip moment compared to Clauser et al.'s (1969) data. The segmental moment of inertia data of Zatsiorsky and Seluyanov (1983) were entered into the equations and these were found to create a 21 N.m difference to the hip joint only. Changes of $\pm$ 1% in the ground reaction force data elicited only small changes to joint moments with a maximum of 4 N.m about the ankle joint. The major factors effecting net joint moment data therefore appears to be joint centre and centre of pressure locations, and to a lesser extent the body segmental parameters.

The combined effects of all these pertubations were also assessed. It was found that differences of up to 119 N.m in the ankle and knee joint moments and up to 153 N.m about the hip joint could be experienced if the joint centre and centre of pressure locations move in opposite directions, i.e. a net displacement of 2 cm. In contrast, if the joint centre and centre of pressure both have a 1 cm error in the same direction (zero relative displacement between them) then only small differences are observed in the net joint moments.

The results indicate that joint centre locations and aligning centre of pressure coordinates have the greatest effect on the resultant joint moments in comparison to body segmental parameters. The use of Dempster's (1955) body segmental parameters appear to be valid, but in comparison to Zatsiorsky and Seluyanov (1983) it underestimates the resultant hip joint moment by 21 N.m.

	Ankle Moment		Knee Moment		Hip Moment	
	Measured (N.m)	Difference (N.m)	Measured (N.m)	Difference (N.m)	Measured (N.m)	Difference (N.m)
Reference Measurement	**428**		**234**		**307**	
Joint centre + 1 cm (horizontal & vertical)	466	38	196	-38	345	38
Joint centre - 1 cm (horizontal & vertical)	390	-38	272	38	269	-38
Segment CM location + 1 cm error (horizontal & vertical)	428	0	234	0	307	-1
Segment CM location - 1 cm error (horizontal & vertical)	428	0	233	0	308	1
Segment CM acceleration + 5 m.s^{-2} error	428	0	225	-8	321	14
Segment CM acceleration - 5 m.s^{-2} error	428	0	242	8	294	-14
Segment angular acceleration + 10 rad.s^{-2} error	428	0	234	1	306	-2
Segment angular acceleration - 10 rad.s^{-2} error	428	0	233	-1	309	2
Segmental mass data of Zatsiorsky & Seluyanov (1983)	428	0	235	2	309	1
Segmental mass data of Clauser et al. (1969)	428	0	237	3	301	-6
Segmental MI data of Zatsiorsky & Seluyanov (1983)	428	0	233	0	329	21
Ground Reaction Force + 1% error	432	4	236	2	310	2
Ground Reaction Force - 1% error	424	-4	231	-2	305	-2
Centre of Pressure + 1 cm error	390	-38	272	38	269	-38
Centre of Pressure - 1 cm error	466	38	196	-38	345	38
Combined (all +ve errors)	432	4	229	-4	345	38
Combined (all -ve errors)	424	-4	241	7	312	5
Combined (all +ve errors & Centre of Pressure - 1 cm)	509	119	152	-119	422	153
Combined (all -ve errors & Centre of Pressure + 1 cm)	349	-41	316	45	237	-33